Electroencephalographic, Cognitive and Autonomic Correlates of States of Concentrative Meditation

by

Dylan DeLosAngeles B.Sc. (B.Sc. Hons)

School of Medicine
Faculty of Health Sciences
Flinders University of South Australia, Adelaide

AUSTRALIA

14th October, 2010

A thesis presented to the
Flinders University of South Australia
in total fulfillment of the requirements for the degree of
Doctor of Philosophy
Abstract

Meditation is generally characterised as “a family of complex emotional and attentional regulatory strategies developed for various ends, including the cultivation of well-being and emotional balance” (Lutz et al. 2008). Although specific methods vary, most meditative techniques strive for and report states of mental alertness and focus, as well as simultaneous states of physical and emotional relaxation. This project investigated distinct states or absorptions of Buddhist concentrative meditation as transliterated from traditional texts into clear and comprehensible descriptions and explanations which are amenable to science.

The way meditative states and traits are classified and characterised in the scientific literature is appraised, including a discussion on the definitions and technical terms associated with meditation. In addition, an explication of the concentrative meditation technique investigated in this project discusses the cognitive and psychological processes in meditation, descriptions of meditative states and how meditators enter and maintain each state. The history and philosophy of Buddhism is also briefly discussed. After relevant background information is supplied with regard to electroencephalography (EEG), the evidence for the effects of meditation is reviewed.

This project involved four experiments which were run in a counterbalanced order during a single day, however each subject came in on a different day. Thirteen meditators and thirteen non-meditator controls were recruited, however due to subject and equipment complications, the number of subjects used in analysis varies between experiments. These details are given in each chapter.

Experiment 1. To assess whether concentrative meditation influences early sensory processing and attentional resource allocation, event-related potentials (ERP)s and behavioural responses were recorded from ten meditators and ten pair-matched non-meditator controls during an audiovisual continuous performance task, performed before and after a meditation condition. This task required subjects to respond to audio and/or visual target stimuli interspersed among distractor and non-target stimuli by pressing a button. An improvement
in response speed and accuracy in both groups after meditation was interpreted as the ability of both groups to enter a light state of meditation between attention tasks. Consistently larger P2 mean amplitudes were found in meditators, compared to controls, suggesting that extended practice of meditation can influence the long-term capacity to selectively attend. In addition, larger P3 mean amplitudes in occipital electrodes were found in meditators. This result is likely to represent a long-term enhancement of target detection, precipitated by the practice of meditation.

**Experiment 2.** Additionally, five different meditative states were examined using measures of EEG and autonomic activity in twelve meditators and twelve pair-matched non-meditator controls. During the experiment, meditators were found to demonstrate significant changes in theta and gamma EEG activity which intimate enhanced focus and mental quiescence during meditative states. In addition, changes in autonomic activity were indicative of decreased sympathetic tone, in other words physical, mental and emotional relaxation.

**Experiments 3.** The perception of external stimuli during meditation was examined in twelve meditators and twelve pair-matched non-meditator controls. Subjects responded with a button-press when they became aware of an auditory, visual or tactile stimulus. No changes in any group or condition were found that could be interpreted as a significant effect from meditation.

**Experiment 4.** Cortical steady-state responses were recorded from eight meditators and eight pair-matched non-meditator controls during meditation. No changes in any group or condition were found that could be interpreted as a significant effect from meditation.

In summary, contributions have been made to the scientific understanding of meditation by providing evidence for the efficacy of meditation to induce states of physical relaxation, mental and emotional calm, enhanced concentration and diminished thought activity.
Each of us literally chooses by way of his attending to things what sort of universe he shall appear to himself to inhabit.\(^1\)

William James (1842 – 1910 AD)

All that we are is the result of what we have thought: it is founded on our thoughts, it is made up of our thoughts.\(^2\)

Siddhattha Gotama (the Buddha) (563 – 483 BC)

\(^1\)Principles of Psychology (1890)  
\(^2\)The Dhammapada
Contents

Abstract ii

List of Figures x

List of Tables xi

Declaration xiii

Acknowledgments xiv

List of Abbreviations xvi

Executive Summary xviii

1 Explication of Meditation 1

1.1 Introduction 1

1.1.1 Toward an operational definition 3

1.2 Definitions and descriptions 6

1.2.1 Concentration, mindfulness and a new classification 7

1.3 Buddhist concentrative meditation: techniques and states 13

1.3.1 Introduction 13

1.3.2 Meditation in traditional literature 14

1.3.3 Philosophical framework of Buddhism 15

1.3.4 Mental strategies of meditation 20

1.3.5 Description of states 26

2 Review of the Literature 36

2.1 Aspects of electroencephalography 36

2.1.1 Continuous EEG 36
2.1.2 EEG frequencies ........................................... 37
2.1.3 Evoked and event-related potentials ...................... 44

2.2 Neuroelectrical studies in meditation ......................... 46
  2.2.1 Continuous EEG ......................................... 46
  2.2.2 Evoked potentials and event-related potentials .......... 59

2.3 Autonomic measures ......................................... 60
  2.3.1 Heart rate .................................................. 61
  2.3.2 Respiration ............................................... 61
  2.3.3 Temperature ............................................... 61
  2.3.4 Electrodermal activity ................................... 64

2.4 Cognitive measures ........................................... 65
  2.4.1 Perception .................................................. 66
  2.4.2 Attention ................................................... 69

2.5 Psychological phenomena ...................................... 72
  2.5.1 Expectation ............................................... 72

2.6 Neurophenomenology ........................................... 73

2.7 Considerations of the investigation of distinct meditative states . 76
  2.7.1 Neurophenomenological considerations .................... 76
  2.7.2 Lack of control protocols .................................. 78

3 Attention ......................................................... 80
  3.1 Introduction .................................................. 80
  3.2 Hypotheses .................................................... 83
    3.2.1 Trait and state effects (behavioural) .................... 83
    3.2.2 Event-related potentials ............................... 83
  3.3 Methods ....................................................... 84
    3.3.1 Experimental sequence ................................... 84
    3.3.2 Attentional processes ................................... 85
    3.3.3 Subjects ................................................. 85
    3.3.4 Neurological evaluation .................................. 86
    3.3.5 Pre-study respite ....................................... 87
    3.3.6 Phenomenological reports ................................ 87
    3.3.7 Stimuli .................................................. 88
    3.3.8 Experimental protocol ................................... 89
3.3.9 Behavioural response analysis ........................................... 92
3.3.10 EEG acquisition and analysis ........................................... 93
3.3.11 ERP processing ............................................................... 94
3.3.12 ERP analysis ................................................................. 97

3.4 Results ........................................................................... 99
3.4.1 Behavioural data ............................................................. 100
3.4.2 Event-related potentials .................................................... 100

3.5 Discussion ................................................................. 110

4 Meditation ...................................................................... 113
4.1 Introduction ................................................................. 113
4.2 Hypotheses .................................................................. 114
4.2.1 EEG activity ............................................................... 114
4.2.2 Autonomic activity ....................................................... 121
4.3 Methods .................................................................... 124
4.3.1 Subjects ................................................................. 124
4.3.2 Measurements .......................................................... 124
4.3.3 Experimental protocol .................................................. 131
4.4 Results .................................................................... 133
4.4.1 Phenomenological reports ........................................... 133
4.4.2 EEG ................................................................. 135
4.4.3 Autonomic function ..................................................... 144
4.5 Discussion ................................................................. 149
4.5.1 EEG ................................................................. 149
4.5.2 Autonomic function ..................................................... 157
4.5.3 Summary ................................................................. 160

5 Perception ...................................................................... 161
5.1 Introduction ................................................................. 161
5.1.1 Perceptual acuity .......................................................... 163
5.2 Hypotheses ................................................................. 164
5.3 Methods .................................................................... 164
5.3.1 Subjects ................................................................. 164
5.3.2 Experimental protocol .................................................. 165
6 Sensory Processing

6.1 Introduction ........................................... 172
6.2 Hypotheses .............................................. 173
6.3 Methods .................................................. 174
  6.3.1 Subjects ............................................. 174
  6.3.2 Steady-state response ............................... 174
  6.3.3 Experimental protocol .............................. 177
6.4 Results .................................................. 180
  6.4.1 Auditory (ASSR) .................................... 182
  6.4.2 Visual (VSSR) ....................................... 182
  6.4.3 Somatosensory (SSSR) ............................. 182
6.5 Discussion .............................................. 182

7 Conclusion

7.1 General discussion .................................... 185
  7.1.1 Attention .......................................... 186
  7.1.2 Meditation ........................................ 187
  7.1.3 Perception ......................................... 189
  7.1.4 Sensory processing ................................ 190
  7.1.5 Summary of contributions of this thesis .......... 190
7.2 Future work ........................................... 190
  7.2.1 Investigation of disparate meditation techniques 190
  7.2.2 Alpha-blocking and habituation ................... 191
  7.2.3 Correlating autonomic function and meditation .... 192
  7.2.4 Sensory processing during meditation .............. 193
  7.2.5 Refined temporal studies of meditative states .... 193

References ............................................. 195

A Meditation competency questionnaire ................. A-1
B  Pre-study report

C  Post-study report

D  Instructions for meditative absorptions

E  Statistics from attention experiment

F  Statistics from meditation experiment

G  Statistics from perception experiment
List of Figures

2.1 International 10-20 electrode reference system .................. 37
2.2 120-electrode EEG montage ........................................... 38
2.3 Examples and descriptions of EEG bands .......................... 39
2.4 Frequency spectra of normal EEG .................................... 40
2.5 EEG frequency spectra at electrode Cz ............................. 43
2.6 EEG frequency spectra at electrode Oz ............................. 43
2.7 Event-related potential example ........................................ 45
2.8 EEG topographic maps .................................................. 56

3.1 Example of audio attention task ........................................ 89
3.2 Protocol for the attention experiment ................................. 89
3.3 Electrode selection for ERP analysis ................................. 94
3.4 ERP pre-grand averages ............................................... 96
3.5 ERP grand average ..................................................... 96
3.6 ERP peak picking example ............................................. 98
3.7 Discarded ERP waveforms ............................................. 99
3.8 ERPs recorded from electrode F3 ..................................... 101
3.9 ERPs recorded from electrode Fz ..................................... 101
3.10 ERPs recorded from electrode F4 .................................... 102
3.11 ERPs recorded from electrode FCz ................................... 102
3.12 ERPs recorded from electrode C3 .................................... 103
3.13 ERPs recorded from electrode Cz .................................... 103
3.14 ERPs recorded from electrode C4 .................................... 104
3.15 ERPs recorded from electrode TP7 ................................... 104
3.16 ERPs recorded from electrode TP8 ................................... 105
3.17 ERPs recorded from electrode O1 .................................... 105
3.18 ERPs recorded from electrode O2 .................................... 106
# List of Tables

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Buddhist and scientific models of consciousness</td>
<td>17</td>
</tr>
<tr>
<td>1.2</td>
<td>States of meditation and the qualities present therein.</td>
<td>24</td>
</tr>
<tr>
<td>2.1</td>
<td>Controlled studies on autonomic activity</td>
<td>62</td>
</tr>
<tr>
<td>3.1</td>
<td>Subject pairs used in experiments</td>
<td>86</td>
</tr>
<tr>
<td>3.2</td>
<td>Audio attention task stimuli</td>
<td>90</td>
</tr>
<tr>
<td>3.3</td>
<td>Visual attention task stimuli</td>
<td>90</td>
</tr>
<tr>
<td>3.4</td>
<td>Audiovisual attention task stimuli</td>
<td>91</td>
</tr>
<tr>
<td>3.5</td>
<td>Bookmaker confusion matrix</td>
<td>93</td>
</tr>
<tr>
<td>3.6</td>
<td>ERP mean amplitude summary</td>
<td>107</td>
</tr>
<tr>
<td>3.7</td>
<td>ERP peak latency summary</td>
<td>108</td>
</tr>
<tr>
<td>4.1</td>
<td>Meditative phenomenological reports</td>
<td>134</td>
</tr>
<tr>
<td>4.2</td>
<td>P-values for autonomic measurements</td>
<td>145</td>
</tr>
</tbody>
</table>
Declaration

I certify that this thesis does not incorporate without acknowledgement any ma-
terial previously submitted for a degree or diploma in any university; and that to
the best of my knowledge and belief it does not contain any material previously
published or written by another person except where due reference is made in the
text.

As requested under Clause 14 of Appendix D of the Flinders University Re-
search Higher Degree Student Information Manual I hereby agree to waive the
conditions referred to in Clause 13(b) and (c), and thus:

- Flinders University may lend this thesis to other institutions or individuals
  for the purpose of scholarly research;

- Flinders University may reproduce this thesis by photocopying or by other
  means, in total or in part, at the request of other institutions or individuals
  for the purpose of scholarly research.
Acknowledgements

This PhD was supported by a State Government Department of Health scholarship. None of this thesis would have been possible without the support and help of a great many people whom I would like to sincerely thank:

- My supervisors—Professor John Willoughby, Dr Kenneth Pope, Professor Richard Clark, Dr Graham Williams and Mr John Burston. You have all helped me come a very long way since I nervously sat in the lab and described my ideas those many years ago. Firstly and most importantly, thank you John W. for your generous counsel and support. Over the last five years, you have been both a cherished mentor and a dear friend (I thoroughly enjoyed lampooning religion with you) and I could not have asked for a better one of either. Thank you Kenneth for your indefatigable generosity, equable advice and coding assistance—you really did spoil me. Thank you Richard for helping me with experimental design and last minute assistance, it was greatly appreciated. Graham and John B. (also director and general manager of the Lifeflow Meditation Centre), I would like to thank you both for your constant support, your friendship and your very generous provision of time, advice, resources and teachings. Thank you also for your clear elucidations of the very tricky concepts of meditation and for your necessary assistance in the design of our experiments. It is my hope that our relationship will continue into the future.

- Dr Sean Fitzgibbon and Dr Trent Lewis—Thank you both for your generous and much-needed coding assistance. Your camaraderie gave me the confidence and stimulation to achieve more than I could have hoped to achieve without you.

- Lifeflow meditators—I readily admit that you had one of the toughest jobs of all in this project—completing the experiments. Thank you all for your hard work, commitment and for tolerating all of my experiments so calmly and gracefully. I appreciate you allowing me to indulge my inner “mad
scientist”.

- Professor John Plummer for your patient counsel regarding statistical questions, which often came randomly and unexpectedly.

- Mathias Baumert at the University of Adelaide for your assistance with analyses of autonomic activity.

- All involved BME staff at the Flinders Medical Centre for accommodating my biomedical engineering requests, as strange as they seemed at the time.

- Dr Martin Donnelley for your thesis template and your much appreciated last minute assistance.

- To my friends—for all of your extracurricular support, especially those who shared comparable experiences trudging through their own doctorates.

- To my family—Wal, Robyn, Ward, Adam and Merran for your continued encouragement and support. Mum and Dad, thank you especially for your love.

- To Tamara—I think it was you who had the toughest job of all. Thank you so much for your constant love, patience and support—I could not have done it without you. *Es a ti a la que adoro, mi amor.*
### List of Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACC</td>
<td>Anterior cingulate cortex</td>
</tr>
<tr>
<td>AM</td>
<td>Amplitude-modulated</td>
</tr>
<tr>
<td>ASSR</td>
<td>Auditory steady state response</td>
</tr>
<tr>
<td>ANS</td>
<td>Autonomic nervous system</td>
</tr>
<tr>
<td>BP</td>
<td>Blood pressure</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon dioxide</td>
</tr>
<tr>
<td>DCx</td>
<td>(Non-linear) dimensional complexity</td>
</tr>
<tr>
<td>ECG</td>
<td>Electrocardiography</td>
</tr>
<tr>
<td>EDL</td>
<td>Electrodermal level</td>
</tr>
<tr>
<td>EDR</td>
<td>Electrodermal response</td>
</tr>
<tr>
<td>EEG</td>
<td>Electroencephalography</td>
</tr>
<tr>
<td>EMG</td>
<td>Electromyography</td>
</tr>
<tr>
<td>EOG</td>
<td>Electro-oculography</td>
</tr>
<tr>
<td>EP</td>
<td>Evoked potential</td>
</tr>
<tr>
<td>ERP</td>
<td>Event-related potential</td>
</tr>
<tr>
<td>Fm</td>
<td>Frontal midline</td>
</tr>
<tr>
<td>fMRI</td>
<td>Functional magnetic resonance imaging</td>
</tr>
<tr>
<td>GSR</td>
<td>Galvanic skin response</td>
</tr>
<tr>
<td>HRV</td>
<td>Heart rate variability/variation</td>
</tr>
<tr>
<td>ISI</td>
<td>Inter-stimulus interval</td>
</tr>
<tr>
<td>LORETA</td>
<td>Low resolution brain electromagnetic tomography</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------</td>
</tr>
<tr>
<td>mPFC</td>
<td>Medial prefrontal cortex</td>
</tr>
<tr>
<td>O$_2$</td>
<td>Oxygen</td>
</tr>
<tr>
<td>OBAMA</td>
<td>Object-based attentional meditation approach</td>
</tr>
<tr>
<td>NOBAMA</td>
<td>Non-object-based awareness meditation approach</td>
</tr>
<tr>
<td>PET</td>
<td>Positron emission tomography</td>
</tr>
<tr>
<td>PFC</td>
<td>Prefrontal cortex</td>
</tr>
<tr>
<td>PhC</td>
<td>Phenomenological clusters</td>
</tr>
<tr>
<td>SAM</td>
<td>Sinusoidally amplitude-modulated</td>
</tr>
<tr>
<td>SCR</td>
<td>Skin conductance response</td>
</tr>
<tr>
<td>SPECT</td>
<td>Single positron emission computed tomography</td>
</tr>
<tr>
<td>SSEP</td>
<td>Steady state evoked potential</td>
</tr>
<tr>
<td>SSSR</td>
<td>Somatosensory steady state response</td>
</tr>
<tr>
<td>SpO$_2$</td>
<td>Peripheral blood oxygen saturation</td>
</tr>
<tr>
<td>SSR</td>
<td>Steady state response</td>
</tr>
<tr>
<td>SSVER</td>
<td>Steady state visual-evoked response</td>
</tr>
<tr>
<td>TM</td>
<td>Transcendental Meditation</td>
</tr>
<tr>
<td>VSSR</td>
<td>Visual steady state response</td>
</tr>
</tbody>
</table>
Executive Summary

This project comprises of four experiments which examine 1) the influence of meditation on attentional performance as measured by event-related potentials (ERPs) and behavioural responses during a continuous performance task, 2) the effects of meditative states on electroencephalographic (EEG) and autonomic activity, 3) perception of external auditory, visual and somatosensory stimuli during states of meditation and 4) the sensory processing of continuous auditory, visual and somatosensory stimuli during different focus conditions. All four experiments were carried out on meditating and non-meditating control subjects.

Chapter 1 begins with an appraisal of the way meditative states and traits are classified and characterised in the scientific literature. This first chapter will include a discussion on the definitions and technical terms associated with meditation methods. This chapter also includes an explication of the concentrative meditation technique investigated in this project, as explained and practiced by our colleagues at the Lifeflow Meditation Centre. The explication will discuss the cognitive and psychological processes involved in meditation, descriptions of meditative states and how meditators use the adopted object of meditation (viz. the breath) to enter and maintain each state. A brief section on the history and philosophy of Buddhism is also included to provide information about the motivations and concepts behind the practice of meditation. Chapter 2 begins by outlining aspects of electroencephalography relevant to this research project, including event-related potentials and steady state responses. The evidence for the effects of meditation is then reviewed, concentrating on research involving neuroelectric, neuroimaging and autonomic measures, as well as studies on aspects of cognition and psychology. Chapters 3, 4, 5 and 6 concern the four experiments and are classically structured with sections of Introduction, Hypotheses, Methods, Results and Discussion. The first experiment, covered in Chapter 3, investigated if meditation methods employing focused attention could alter early sensory processing and attentional resource allocation in ways which were detectable using ERPs and behavioural measures. Continuous performance attention tasks using
auditory and visual stimuli were undertaken in which subjects were asked to respond to targets among non-targets and distractors. This task was followed by a condition in which subjects were asked to meditate, and then the attention tasks were repeated. Chapter 4 regards the second experiment in which 120-channel EEG, in addition to autonomic measures of heart rate, respiration, electrodermal activity, skin temperature, blood oxygen saturation and blood pressure, were recorded during five phenomenologically distinct states of Buddhist concentrative meditation. The chapter 5 experiment on perception involved presenting auditory, visual and somatosensory stimuli at varying intensities to subjects while meditating in order to determine if meditation alters perception of external stimuli. The last experiment on sensory processing (Chapter 6) examined if changes in attentional focus affect steady-state responses in the brain, by presenting continuous stimuli during different conditions in which subjects focused on either their thoughts, their breath or the stimulus. The last chapter summarises the contributions of this thesis and suggests future research directions.