Chapter 4

Meditation

4.1 Introduction

Meditation provides an unexploited opportunity to advance neurobiological explorations of consciousness, as well as cognitive and affective neurosciences in general. The ability of humans to regulate their own mental states in ways which augment and refine focused attention, clarify introspective processes and improve abilities to identify personal and interpersonal issues (Varela et al. 1991) offers the potential to explain human experience in both its reflective and immediate aspects (Varela & Shear 1999). Mental training based on meditative techniques may also present an effective measure for the treatment of attentional disorders.

Changes in EEG activity during meditation have been widely reported by a number of studies (Aftanas & Golocheikine 2001, 2002; Baijal & Srinivasan 2009; Holzel et al. 2007; Kasamatsu & Hirai 1966; Kasamatsu et al. 1957; Kubota et al. 2001). The diverse collection of neurophysiological changes has been comprehensively reviewed (Cahn & Polich 2006; Opsina et. al. 2007) and many stimulating theoretical proposals have been offered (Austin 1998; Lutz et al. 2008; Raffone & Srinivasan 2009; Wallace 2003). Despite the abundance of research and the resulting evidence for meditation-related effects, very few studies have provided detailed phenomenological reports of meditative experiences and correlated these reports with neurophysiological data. After recovering from the legacy left by early behaviourists reducing the human subject to a “black box”, neuroscientists are beginning to explore the possibility of neural counterparts to subjective experience by emphasising first-person accounts (Varela 1996). The Buddhist contemplative traditions report phenomenologically distinctive and reproducible states during concentrative meditation.To assist in the interpretion of neurophysiological data, detailed descriptions of meditative states according to the Lifeflow Meditation Centre (§1.3.5) as well as post-study reports of subjective experiences during the experiment have been incorporated here. As outlined in §1.1, the Buddhist model for the way the external world and the individual interacts has the potential to guide interpretation of neurophysiological data. The five aggregates of form, sensation, perception, mental formations and consciousness (Table 1.1) are purportedly related directly to meditative states of absorption such that each successively deeper state corresponds with a specific aggregate. This diminished elaboration of perceptual and cognitive processes has been described as the "peeling back of layers" (Burston & Williams 2005).

4.2 Hypotheses

4.2.1 EEG activity

4.2.1.1 By frequency band

The following hypotheses regarding EEG activity are based on extant meditation literature (see §2.2 for review and discussion) and unpublished, preliminary findings (DeLosAngeles et al. 2007). Predictions firstly pertain to each EEG frequency band as defined in this project and then more specifically to each state.

Delta (0.5–3 Hz)

It is well-known that slow frequencies in the 0.5–3 Hz range are preponderant in stage 3 and particularly stage 4 of deep sleep (Rowan & Tolunsky 2003). Diffuse slow wave activity also characterises the onset of drowsiness, which is enhanced during the deepening of drowsiness (Niedermeyer & Lopes da Silva 1999). Reports of delta power changes in meditation studies have ordinarily been of increases while subjects have been asleep (Younger et al. 1975; Pagano et al. 1976, Fenwick et al. 1977; Mason et al. 1997). Dunn et al. (1999), however, reported less anterior and central delta activity during meditation when compared to relaxation, and less delta activity in concentration meditation when compared to mindfulness meditation.

Reflecting the alertness required to maintain vigilant focus during concentrative meditation, decreased delta EEG power was hypothesised for MEDITATORS during meditative states, relative to baseline conditions. Conversely, increased delta power was hypothesised in *controls* during meditative states, reflecting the levels of drowsiness and possibly stages of sleep, resulting from disinterest, lack of attention or inability to manage drowsiness.

Theta (3–8 Hz)

Increases in theta power generally (Aftanas & Golocheikine 2001; Kasamatsu & Hirai 1966; Kasamatsu et al. 1957) as well as frontal midline theta power (Aftanas & Golocheikine 2002; Baijal & Srinivasan 2009; Holzel et al. 2007; Kubota et al. 2001) are often reported during meditation practices involving concentration. In a number of studies, enhanced theta activation has also been correlated to meditation proficiency (Corby et al. 1978; Elson et al. 1977), lower state and trait anxiety scores (Inanaga 1998) and feelings of blissfulness and low thought content (Aftanas & Golocheikine 2001). Frontal midline theta activity is thought to be generated by attentional networks of the anterior frontal lobes, reflecting the alternating activation of the medial prefrontal cortex and anterior cingulate cortex during focused attentional processing (Baijal & Srinivasan 2009). This activity may be concomitant with the deactivation of "irrelevant networks for the maintenance of focused internalised attention and inhibition of inappropriate [distracting] information" (Aftanas & Golocheikine 2002).

Accordingly, we hypothesise theta increases (primarily frontally and frontocentrally) in MEDITATORS during early states of meditation (first and second), reflecting the attentional processing required to produce a meditative state. Theta power is then predicted to remain at those levels or increase further in deeper states, when MEDITATORS will maintain a state of focused attention and distraction inhibition. *Controls* are not expected to demonstrate changes in theta power.

Alpha (8–13 Hz)

The paradox of enhanced alpha activity reflecting the brain's state of idling and relaxation (Niedermeyer & Lopes da Silva 1999) and also being a correlate of meditative states of internalised attention (Kasamatsu & Hirai 1966; Murata et al. 2004) has yet to be resolved in the EEG literature in general, and in meditation literature in particular (Buzsáki 2006). Many meditation studies report an increase in both the power and spatial extent of alpha oscillations during meditation, especially in the practices of Zen and yoga (Anand et al. 1961; Cahn & Polich 2006; Shapiro 1981).

Alpha activity is hypothesised to initially increase in amplitude in MEDITATORS, then decrease during deeper states of meditation, consistent with previous meditation studies and unpublished, preliminary findings (DeLosAngeles et al. 2007). The initial increase will reflect the greater levels of effortful concentration required to initially enter and sustain a meditative state and the subsequent decreases will reflect deeper states becoming less effortful in regards to concentration, "with the practitioner being *settled* in a state of decreased mental effort but alert focus" (Brefczynski-Lewis et al. 2007). Alpha power levels in *controls* are hypothesied to remain unchanged across meditative states.

Beta (13–25 Hz)

Increases in beta power have often been reported in connection with deep meditation or states of ecstasy or intense concentration (Anand et al. 1961; Banquet 1973; Corby et al. 1978; Das & Gastaut 1957; Kasamatsu & Hirai 1966). In keeping with earlier discussions on high frequency EEG activity (§2.1.2), the interpretation of beta and gamma findings will be influenced by circumferential electrodes representing EMG and central electrodes likely to be reflecting EEG, especially at lower frequencies in the beta-gamma range (Whitham et al. 2007). More specifically, as circumferential electrodes were found to be greatly contaminated by EMG at frequencies above 20 Hz (Figures 2.5 and 2.6, §2.1.2), beta1 (13–20 Hz) is regarded as EEG, while beta2 (20–25 Hz) is considered to be representative of muscle activation. However, centrally, frequencies up to 50 Hz were found to have a significantly diminished contribution of EMG, such that both beta1 and beta2 ranges are regarded as EEG.

During states of meditation, beta2 power is hypothesised to decrease in MEDITATORS, reflecting a more relaxed state and increase in *controls,* reflecting tension.

Gamma (25–80 Hz)

Extending the above discussion on high frequencies, both gamma1 (25–48 Hz) and gamma2 (52–80 Hz) are interpreted as EMG at circumferential sites. However, as stated above, only frequencies above 50 Hz at central channels were contaminated by EMG, such that gamma1 is regarded as EEG and gamma2 as EMG. Exact frequencies of the two gamma frequency bands were chosen to avoid electrical DC interference at 50 Hz and the 100 Hz harmonic.

Decreases in gamma1 and gamma2 are hypothesised in MEDITATORS to reflect greater muscle relaxation, particularly in posterior electrodes, due to the contribution from cervical muscles holding the head upright and motionless. Gamma1 and gamma2 are hypothesised to increase in *controls*, reflecting continuous or intermittent thought occurrence and concomitant muscle tension.

4.2.1.2 By experimental state

Baseline

A reading of the literature with regard to long-term effects of meditation indicates that experienced MEDITATORS demonstrate up to 20% more power in both theta and alpha frequency bands (Baijal & Srinivasan 2009; Hardt 1994; Kasamatsu & Hirai 1966). In this experiment, therefore, we predicted a 20% power increase in theta and alpha bands in MEDITATORS during the baseline state compared to *con-*

trols in the same state. It is expected that activity in theta and alpha bands will be altered by long-term (trait) effects of meditation. In order to determine the necessary sample size required to reach this significance, a sample size (two-samples) was calculated online (http://www.dssresearch.com/toolkit/sscalc/size_a2.asp) using mean values taken from unpublished, preliminary work (DeLosAngeles et al. 2007) for theta and alpha frequency bands. In these preliminary studies, MEDITATORS were found to have a baseline EEG theta power of (1.57 $\mu V^2 \pm 0.252$). Therefore, expecting 20% less theta power in *controls* (1.256 $\mu V^2 \pm 0.252$) with $\alpha = 0.05$ and $\beta = 0.20$, the sample size required was calculated to be 8 for both samples. Unpublished, preliminary results also revealed MEDITATORS with a baseline alpha EEG power of 2.3 $\mu V^2 \pm 0.45$. Therefore, expecting 20% less alpha EEG power in *controls* (1.86 $\mu V^2 \pm 0.45$) with $\alpha = 0.05$ and $\beta = 0.20$, the sample size required was calculated to be 13 for both samples.

Mind-wandering

As outlined in §2.7, mind-wandering, like the baseline, is also a non-meditative control state including additional instructions to actively engage in thinking, that is, to "let their minds wander freely without remaining on one thing."

Hypotheses made for the baseline apply equally to this state, that is, theta and alpha EEG power will be greater for MEDITATORS, compared to *controls*. Circumferential scalp gamma1 and gamma2 are hypothesised to decrease in MEDITATORS and increase in *controls*.

First absorption

The first absorption requires a change in mental behaviour from scattered attention and mental wandering to heightened awareness and focused attention on an object, typically the breath. This process necessitates an alert and vigilant state in order maintain stability and clarity of focus (see §1.3.4).

A reduction in delta power is hypothesised for MEDITATORS, reflecting diminished drowsiness, whereas an increase in delta power is hypothesised for *controls*, indicating an onset of drowsiness (Dunn et al. 1999). Theta power increases (midline frontal and fronto-central) in MEDITATORS are hypothesised to represent internalised concentration involving the recruitment of attentional networks of the medial prefrontal cortex and the anterior cingulate cortex (ACC). Only slight changes, if any, in theta power are hypothesised for *controls*, as meditation-naïve individuals are anticipated to be ineffective at completely engaging in this meditative state, although may attend intermittently. An increase in alpha power in parietal and occipital regions is hypothesised for MEDITATORS in this state, compared to non-meditative states, reflecting an increase in attentional effort (Brefczynski-Lewis et al. 2007). No increases in alpha EEG power are hypothesised for *controls*.

Commencing concentrative meditation not only reduces (and eventually inhibits) thought occurrence, but also induces a deeper state of relaxation due to the diminished occurrence of thoughts and subsequent emotional associations. In a manner of simple positive feedback loops, changes in muscle activity (EMG) concomitant with reduced thinking assist further relaxation which in turn diminishes thinking and enhances the degree and quality of focus (Figure 4.1). This meditative process of "settling the mind", eventuating in the reduction of EMG, is a gradual process for beginners and depends on numerous factors such as hyper-arousal and drowsiness (§1.3.4). Experienced MEDITATORS, however, are expected to accomplish this process rapidly.

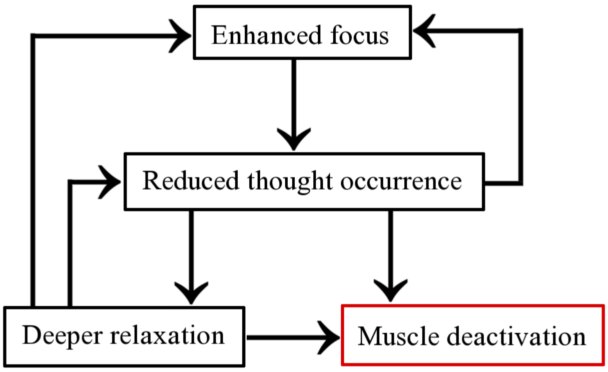

Figure 4.1: **Simple positive feedback model** to explain how interactions between enhanced focus, reduced thought occurrence and deeper relaxation contribute to reduced EMG.

Consequently, the most significant decreases in high frequency EMG activity (beta2, gamma1 and gamma2) are predicted for MEDITATORS in this state, localised posteriorly (discussed above).

Second absorption

In the second absorption, focused attention is achieved with a greater degree of intensity and imperturbability, and all thought activity ceases. Consequently, attentional networks are expected to remain engaged (or engage more fully) in MEDITATORS during this state. Prefrontal brain structures are involved in isolating, differentiating and analysing the world around us and frontal network theta oscillations during meditation are thought to "mediate suppression of distracting effects of the environment (internal thoughts and external stimulation)" (Baijal & Srinivasan 2009). In accordance with the aforementioned model of perception, one is no longer involved with thoughts, ideas, opinions and prejudices (Govinda 1976).

Therefore, elevated or increasing frontal/central theta power is hypothesised in MEDITATORS, reflecting attentional engagement and the complete inhibition of thought occurrence during this state. MEDITATORS are also hypothesised to exhibit reduced alpha EEG power, reflecting diminished attentional effort required to maintain focus on the breath. Delta is expected to increase further in *controls* due to increased drowsiness associated with disinterest and unsuccessfully engaging in meditation, however MEDITATORS are expected to remain alert and exhibit lower levels of delta power.

Third absorption

MEDITATORS maintain focused attention and thought suppression in the third absorption, therefore preserved or increased levels of theta power are hypothesised. A continued reduction in both alpha and delta power in MEDITATORS is also hypothesised, representing a maintenance of increased arousal, whereas increased delta power in *controls* is hypothesised to reflect continuing levels of drowsiness. MEDITATORS generally only experience what is referred to in the second aggregate as sensation or feeling, that is, the experience resulting from interaction with an object.

Fourth absorption

The fourth absorption is the deepest state of meditation and a continued reduction in alpha and delta activity as well as a maintenance of elevated theta activity is hypothesised for MEDITATORS, while *controls* are hypothesised to demonstrate continued drowsiness and concomitant increases in delta. This state is proposed to correspond to the most fundamental operation of perception, that is, the physical sense organs interacting with the external world. Interestingly, a few studies report changes in brain potentials (McEvoy et al. 1980; Telles et al. 1994; Zhang et al. 1993) suggesting meditation may affect initial sensory processing.

Formless absorption

Changes in delta, theta and alpha activity hypothesised for both groups in the fourth absorption are also expected in the formless absorption as this state represents an extension or expansion of the fourth absorption (§1.3.5). However, in addition to maintaining a deep meditative state, MEDITATORS also expand their minds into space, often experienced by imagining themselves expanding out into infinite space. This supplementary conceptual or imaginary aspect could conceivably generate EEG activity in frontal or occipital cortices.

4.2.2 Autonomic activity

The predicted changes for autonomic activity below are derived from phenomenological reports of MEDITATORS and commonly reported changes in the literature. A more detailed discussion on each autonomic measure is given in the literature review in §2.3.

Heart rate

Meditation has been referred to as a "hypometabolic state" (Jevning et al. 1988), although little reliable evidence for reduced heart rate exists (Goleman & Schwartz

1976; Solberg et al. 2004). Be that as it may, decreases in heart rate are hypothesised for MEDITATORS during meditative states (particularly deep states such as the third, fourth and formless) which will indicate a relaxed physiological state as a result of reduced sympathetic tone. *Controls* are predicted to have minimal decreases in heart rate, not exceeding those in MEDITATORS.

Blood pressure

Controlled studies generally report no change in blood pressure (Holmes et al. 1983; Morse et al. 1977; Solberg et al. 2004), even though a considerable number of uncontrolled and case studies have found decreases in blood pressure in normal and hypertensive patients during meditation. Keeping with the idea that MEDITATORS are more effective at mentally and physically relaxing during meditation, MEDITATORS are hypothesised to have lower blood pressure measures during meditation, compared to *controls*.

Respiration

The rate and depth of unconscious breathing is automatically regulated by specialised centres in the brainstem, depending on the body's needs and carbon dioxide levels in the blood. Decreases in respiration rate are hypothesised to be concomitant with relaxation (when the level of carbon dioxide is lower). As discussed above, MEDITATORS are expected to be more relaxed due to decreased thought activity and muscle activation.

We therefore hypothesise decreased rates of respiration in MEDITATORS during meditative states (particularly deep states such as the third, fourth and formless) as well as minimal decreases in *controls*.

As instructions for certain meditative states direct the subject to alter the rate of their breathing, a decrease in respiratory rate is hypothesised to positively correlate with descending states of meditation in both groups. An increase in respiration rate is hypothesised to positively correlate with ascending states of meditation.

Peripheral blood oxygen saturation

During ordinary periods of rest, it is anticipated that a degree of sympathetic tone maintains a general level of arousal and readiness, in the event a fight or flight response is required. This preservation of arousal requires a certain level of oxygen to facilitate metabolism. Meditation is an intentional mental strategy of moving attention from thoughts to bodily sensations in order to focus attention and abate tension. Therefore, it is feasible that meditation may lower the set-point of oxygen required by the body through decreased sympathetic tone and voluntary respiratory reductions.

Due to a more relaxed psychological and physiological condition during meditation, MEDITATORS are predicted to demonstrate lower blood oxygen saturation, relative to non-meditative states and relative to *controls* during meditation.

Skin temperature

Skin plays an important role in thermoregulation, primarily via vasoconstriction and vasodilation which are controlled by the autonomic nervous system. Decreased sympathetic tone precipitates increased cutaneous blood flow and subsequently increased skin temperature and is generally considered one reliable index of physical and psychological relaxation (Blessing 1997).

MEDITATORS are hypothesised to demonstrate greater reductions in sympathetic tone and therefore increased skin temperature during meditation relative to non-meditative states, while *controls*' temperatures are not hypothesised to change during meditation. MEDITATORS are also expected to demonstrate higher skin temperatures overall than *controls* during meditation.

Electrodermal activity

There exists a close relationship between electrodermal activity and skin temperature. Activation of sympathetic vasomotor fibres alters skin temperature via constriction of cutaneous blood vessels and subsequently through radiation, conduction and convection. Increased sympathetic tone also affects sweat gland activity. Perspiration can occur during two situations: physical heat (exercise or ambient temperature) or emotional strain (nervousness or an arousal or orienting response). Anxiety-induced perspiration leads to low skin resistance (increased conductance or decreased electrodermal activity) and is generally thought to be a reliable indicator of stress (Boucsein 1992).

Therefore, MEDITATORS are predicted to have a reduction in electrodermal activity during meditation, relative to non-meditative states, reflecting greater psychological calm. MEDITATORS are also expected to demonstrate overall lower electrodermal levels than *controls* during meditation, while *controls* are not expected to demonstrate a change in electrodermal activity during meditation.

4.3 Methods

4.3.1 Subjects

Out of the twenty-six subjects recruited for the project, one MEDITATOR was excluded from the meditation experiment due to equipment malfunction. The *control* paired to this subject also had to be excluded to ensure that only pair-matched subjects were included in analyses. Therefore, twelve MEDITATORS (♀ 5, ♂ 7, age: $\bar{x}$=47.81 years, range 29–64 years) with 3–30 years meditation experience ($\bar{x}$=14 years) from the Lifeflow Meditation Centre in Adelaide, South Australia participated in the meditation experiment (Table 3.1) and all MEDITATORS were pair-matched with non-meditator *controls* for age (± 6 years), gender, handedness and education level (§2.7.2.2).

4.3.2 Measurements

During the experiment, the following measures were taken to assess brain and autonomic activity.

4.3.2.1 EEG activity

EEG acquisition

Please refer to §3.3 for information about EEG acquisition.

EEG processing

After acquisition of EEG, data were re-referenced using a common-average head reference algorithm where an average of EEG activity at every electrode site is used as a reference (thereby removing noise common to all sites). EEG data were then lowpass filtered (100 Hz, 96 dB/oct) using NeuroScan software (El Paso, TX, USA). All muscle artefact was marked out by hand and any channels overly contaminated with muscle activity and/or 50 Hz electrical interference were rejected. Further processing of data was undertaken in Matlab (The Mathworks, Natick, Massachusetts, USA) where data were epoched and baselined. Any epochs containing segments marked-out due to muscle contamination were excluded from subsequent analysis.

EEG analysis

Data were divided into one second epochs, transformed to the frequency domain using a fast Fourier transform with a Hamming window and averaged to yield spectra. EEG spectra were analysed using the mean power from the following frequency bands adapted from EEG literature (Niedermeyer & Lopes da Silva 1999; Rowan & Tolunsky 2003): delta 0.5–3 Hz, theta 3–8 Hz, alpha 8–13 Hz, beta1 13–20 Hz, beta2 20–25 Hz, gamma1 25–48 Hz and gamma2 52–80 Hz. Data were exported from Matlab into .csv files for analysis in SPSS (Chicago, Illinois).

In considering approaches to the analysis of EEG changes in meditation, one might hypothesise uniform, regional or even small areas of specific changes. One might consider the brain as a uniform organ and therefore be somewhat justified in examining global changes found across all electrodes, however, it is well-known that the brain has many heterogenous structures and oscillatory activity varies topographically depending on frequency and mental condition. As such, analysing the brain as a whole would be unsophisticated. One might also consider each cortical region or lobe as a discretely operating structure and consequently group electrodes according to these regions. However, this method is likely to be flawed in the same way as the aforementioned. Finally, although adjacent electrodes are highly correlated and even distant electrodes are somewhat correlated, no two electrodes record from the exact same population of neurons in the brain (Buzsáki 2006). EEG activity recorded by scalp electrodes reflects the summation of the synchronous activity of millions of discharging neurons that have similar spatial orientation, radial to the scalp (Niedermeyer & Lopes da Silva 1999). Thus, high-density arrays are often used when research or clinical application demands increased spatial resolution for proximate areas of the brain (for example, the somatosensory cortex or the motor cortex). Here, interest is in particular frontal and frontal midline regions of the cortex, so that a topographic map is essential for determining changes in these areas.

Exploratory analyses were done on brain regions, by grouping electrodes into hemispheres and cortices (Figure 4.2): left frontal (73, AF7, AF3, 75, 76, F7, F5, F3, F1, Fz, 79, 80, 81, 82, 83, FC5, FC3, FC1, FCz, 92, 93, C1 and Cz), right frontal (74, AF4, AF8, 77, 78, Fz, F2, F4, F6, F8, 84, 85, 86, 87, 88, FCz, FC2, FC4, FC6, 94, 95, Cz and C2), left parietal (91, C3, 100, 101, 102, CP3, CP1, CPz, 109, 110, 111, P5, P3, P1, Pz, 118 and PO7), right parietal (96, C4, 103, 104, 105, CPz, CP2, CP4, 112, 113, 114, Pz, P2, P4, P6, 121 and PO8), left temporal (FT9, FT7, 89, 90, T7, C5, 99, TP9, TP7, CP5, 107, 108 and 117), right temporal (FT8, FT10, 97, 98, C6, T8, 106, CP6, TP8, TP10, 115, P8 and 122), left occipital (119, PO3, POz, 124, O1 and Oz) and right occipital (120, POz, PO4, 125, Oz and O2).

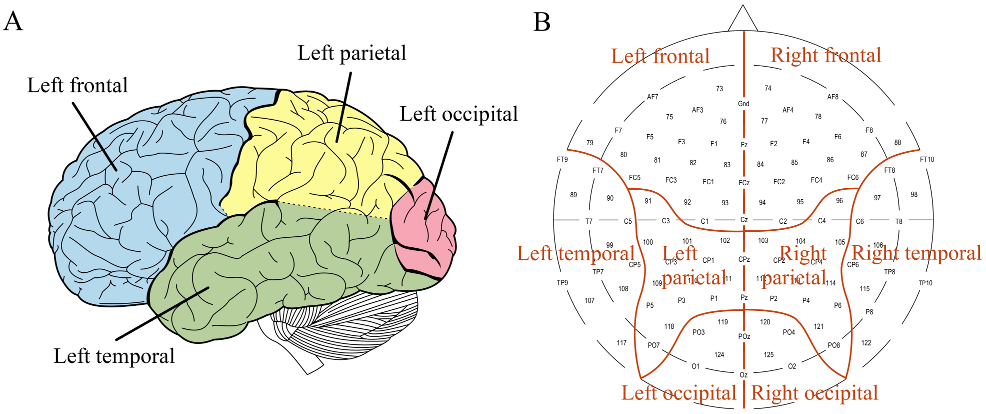

Figure 4.2: Lateral view of the brain showing the four regions (cortices) of the left hemisphere (A) (adapted from http://commons.wikimedia.org/wiki/File:Lobes_of_the_brain_NL.svg). (B) shows a 128-channel EEG montage clustered into electrode groups reflecting cortices and hemispheres of the brain. Adapted from http://www.easycap.de/easycap/e/electrodes/11_M15.htm.

In preliminary evaluation of results, a general linear model repeated measures ANOVA with group, electrode and state as factors revealed highly significant main effects for electrodes in certain brain regions (notably left and right frontal), supporting the argument that grouping electrodes is too coarse an approach to appropriately test the experimental hypotheses. Hence, repeated measures ANOVAs were undertaken on each electrode with group and state as factors. To test the hypotheses concerning meditative state-dependent changes in EEG power, contrasts were constructed estimating the group-by-state interaction associated with baseline and each subsequent state. These contrasts determined if the differences in means between groups at a particular state (for example the second absorption) were significantly different from the difference between group means. Greenhouse-geisser values were recorded without correction. Descriptive statistics were exported from SPSS and saved (see Appendix F on cd), including group-by-state contrast effects, profile plots, and means and standard errors for group, state and group-by-state.

Heat maps

An $\alpha = 0.05$ was chosen for the critical level of significance. P-values for group-by-state contrasts on each electrode were used to create heat maps for each frequency band (Figures 4.5 through 4.11 under Results). Six "temperatures" were designated to illustrate degrees of increase (warmer colours) and decrease (cooler colours) of EEG power, with lighter colours (yellow and light blue) representing p-values less than 0.05, medium colours (orange and mid-blue) representing p-values less than 0.01 and the darkest colours (red and dark blue) representing p-values less than 0.001. In this way, the larger the effect from the group-by-state interaction associated with baseline and a particular state at an electrode, the "hotter" or "colder" the colour of that electrode will be. Increases and decreases were determined based on changes in electrode profile plots (Figure 4.16). If both groups demonstrated reasonable EEG power changes in inverse directions (that is, meditators increased and controls decreased), both groups would be noted as having a significant change on the heat map. As graphical representation of the data, heat maps are convenient for communicating results quickly, however, for means, standard errors and exact p-values, the reader is asked to refer to Appendix F.

4.3.2.2 Autonomic measures

Placement of electrodes for autonomic measures was arranged to permit one unconstrained hand for task response (Figure 4.3). This arrangement also meant that any interference to autonomic measures from the somatosensory stimulation of the response hand was reduced (§6.3). This placement was reversed for left-handed subjects.

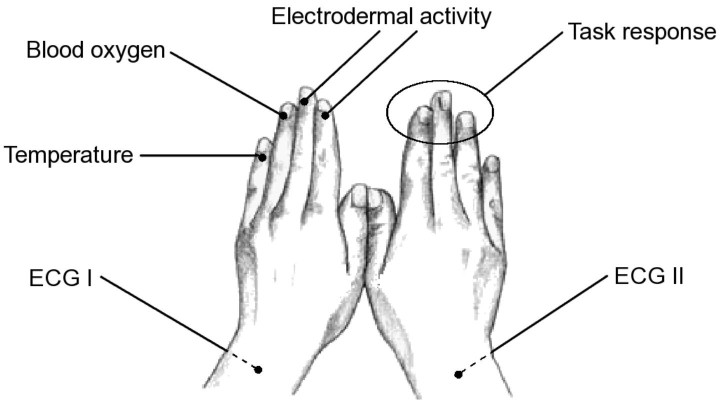

Figure 4.3: **Placement sites for autonomic measures.** This example shows the non-dominant hand as the left hand and the dominant hand as the right hand.

Heart rate Heart rate was measured using ECG, recorded via three electrodes attached to each inner wrist and the left inner ankle using 'Red Dot' Ag/AgCl monitoring electrodes (3M Health Care, Ontario, Canada). Electrodes were arranged according to Einthoven's triangle and positions were chosen on the advice of our collaborating cardio-neurophysiologist.

Blood pressure Blood pressure was taken automatically after each of the first six meditative states (see below) using a Dinimap Vital Signs Monitor (Critikon, Florida, USA) controlled using Presentation computer software (Neurobehavioral Systems, California, USA).

Respiration Thoracic respiration was measured with a Piezo Crystal Transducer Respiratory Effort Sensor (Pro-Tech, Mukilteo, WA, USA) fastened around the thorax of the subject using stretch Velcro straps (Pro-Tech, Mukilteo, WA, USA).

Peripheral blood oxygen saturation (SpO_2) SpO_2 was measured using the ratio of absorption of red and infrared light between oxyhemoglobin and its deoxygenated form via a pulse oximeter device (Criticare Systems Inc., Bad Homburg, Germany) attached to the ring or third finger (digitus IV) of the non-dominant hand.

Temperature A custom-made four channel thermistor interface (Flinders Biomedical Engineering, Flinders Medical Centre, Bedford Park, Australia) facilitated three measures of skin temperature: 1) the dorsal surface of the little finger (digitus V); 2) the dorsal surface of the fifth or little toe; and 3) the medial surface of the outer ear. One measure of ambient air temperature was taken centrally from the Faraday cage. The thermistor interface output to the Synamps EEG recording system was set to 0.800 mV/°C and optimised for the range of 15°C to 45°C. Following acquisition and data integrity verification, temperature recordings were converted into degrees Celsius using Matlab.

Electrodermal activity A custom-made device (Flinders Biomedical Engineering, Flinders Medical Centre, Bedford Park, Australia) measured the electrical resistance of the skin by passing a small amount of current from the index finger (digitus II) to the middle finger (digitus III) of the non-dominant hand. Results were recorded in mhos,[1] the SI-derived unit of electrical conductance, equal to one Ampere per volt.

For peripheral blood oxygen saturation, temperature and electrodermal activity, measures of mean and slope temperature change were calculated for each descending and ascending meditative and non-meditative state. Due to the way the data were recorded[2], all measures were relative to the baseline, that is, the mean values for the first state (descending baseline) were subtracted from each subsequent state. This adjustment also compensated for any initial baseline differences between groups. For slope, two positions were chosen along a first order polynomial curve fitted to the data from each state and the coordinates of each of these points on the chosen line was found. Slope was then calculated as the difference in the two y-coordinates divided by the difference in the x-coordinates. Means and slopes were subjected to ANOVAs with state and group as factors.

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[1] Mho is equivalent to the reciprocal of the Ohm unit, formerly called Siemens.

[2] The measuring devices performed numerous DC corrections prior to recording, thus shifting the initial recorded measures from zero to unknown, arbitrary values.

4.3.3 Experimental protocol

Given the natural progression of meditation from the first absorption to the formless absorption and the customary routine in which the meditative states are practised at the Lifeflow Meditation Centre, a counterbalanced design (Figure 4.4) was utilised to minimise the effects of time and disruption to standard meditation practices. Both MEDITATORS and *controls* were presented with the same experimental protocol. The upper half of Figure 4.4 (A) shows the first division of the experiment, in which states are designated "descending" for clarity, and the lower half of Figure 4.4 (B) shows the remaining division of the experiment, in which states are designated "ascending".[3]

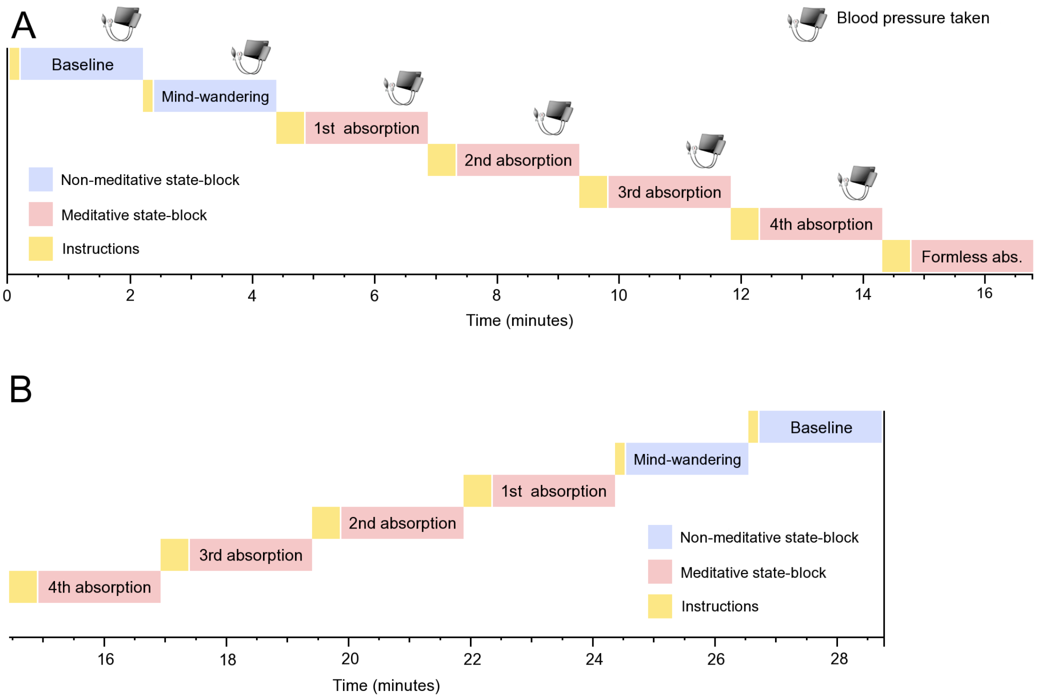

Figure 4.4: **Meditation experiment protocol.** The top half of the figure shows descending experimental states (A) while the bottom half shows the ascending states (B). Blood pressure was only taken during the first six states to prevent disruption to ascending states. Meditative (blue) and non-meditative state-blocks (pink) are preceded by instructions (orange).

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[3] The descriptions *descending* and *ascending* characterise the progression of meditative states during the experiment in a way reminiscent of sleep stages and are used primarily to aid the description of the experiment.

Baseline

The baseline condition was the first (Figure 4.4, A) and the last state (Figure 4.4, B) which subjects underwent in this experiment. Each baseline was two minutes in duration and was prefaced with the instruction to "sit quietly with your eyes closed". Baseline states are considered *passive*, non-meditative states. Although subjects may be engaged in specific mental activity during this time, such as mind-wandering or even light meditation, as far as experimental design is concerned, the expectation is they will be in a *passive,* non-meditative state, as opposed to an *active,* non-meditative state (see below).

Mind-wandering

The descending mind-wandering state followed the first baseline and the ascending mind-wandering state preceded the last baseline. Each mind-wandering state was two minutes in duration and differed from the baselines in the instruction to "relax, breathe naturally and let the mind wander freely without remaining on one thing". Mind-wandering states were therefore considered *active*,[4] non-meditative[5] states. In order to prevent any influence on the first baseline from the *active* mind-wandering state, the baseline was ordered first in the experiment.

Meditative absorptions

All subjects (MEDITATORS and *controls*) were guided through the meditative absorptions with identical instructions (Appendix D) by the voice of a colleague. The voice was unidentifiable to both MEDITATORS and *controls* and as such no specific emotional responses were anticipated to be elicited in any individuals.[6] Subjects were asked to enter each meditative state beginning with the first absorption. The order of the meditative absorptions was as follows: (D)escending

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[4] This term indicates the expected mental state during this state, that is, subjects were expected to *actively* wander from thought to thought as opposed to a *passive* non-meditative state (baseline).

[5] In addition to the baseline, this state was also considered *non-meditative*, as mind-wandering, or the event of being locked in thoughts (also called states of emotional conflict, see §1.3.5), is not considered to be a meditative state.

[6] This fact is particularly important with respect to a conditioning and placebo effect (see §2.5)

first, (D) second, (D) third, (D) fourth, formless, (A)scending fourth, (A) third, (A) second, (A) first.

Blood pressure (BP) was recorded at the end of meditative states to reduce the impact on meditation and only for the descending baseline, mind-wandering and first four absorptions. In preliminary studies, MEDITATORS indicated that recording BP was quite invasive to meditation, so by taking BP on the way down, the last five meditative absorptions were uninterrupted by mechanical intrusion and subject expectation.

4.4 Results

All subjects reported the experiment being taxing but were able to follow all instructions successfully.

4.4.1 Phenomenological reports

Two MEDITATORS reported meditating at an unsatifactory level during the experiment, one of which reported minor distractions during absorptions while the other felt a little drowsy in the first and second absorptions, and had slightly aching neck and shoulders. Nevertheless, both MEDITATORS still reported being mentally clear and deeply relaxed during meditation. All other MEDITATORS reported experiences (Table 4.1) which were in line with phenomenological decriptions of states given in §1.3.5.

One *control* subject felt “fidgety” and distracted during the entire meditation while another *control* became drowsy and drifted in and out of consciousness. The drowsy subject reported being in a surreal dream state and nearly dropping the response panel three times during the fourth absorption. All other *controls* reported being relaxed and focused, and occasionally described similar experiences to MEDITATORS, however, these descriptions varied widely across *control* subjects for each state with more mind-wandering and mental distraction occurring during meditative states. Neither MEDITATORS nor *controls* reported difficulties with the blood pressure monitoring.

Meditative absorption	Phenomenological reports from MEDITATORS	Phenomenological reports from *controls*
First	“physically and mentally relaxed but alert”, “emotionally calm”, “mentally clear”, “steady”, “mental relaxation”, “still”	“distracted”, “relaxed”, “felt physically relaxed”, “mentally and emotionally calm”, “started to relax”, “tired”
Second	“mentally clear and focused”, “feelings of joy and happiness”, “pleasant emotion”, “mentally still”, “bliss over skin and in central channel”, “enjoyable sensations”, “letting go of thoughts”	“continued to relax”, “mind slightly wandering”, “relaxed”, “emotionally and physically normal”, “relaxed and focused”, “calm”, “stiff”, “trying to concentrate”
Third	“very still”, “heavy”, “mentally clear and focused”, “losing feeling of body edges”, “lack of body boundaries”, “openness”, “sinking feeling”, “feeling of spaciousness”, “expansive”, “opening out”, “anchored”	“becoming more focused”, “head and shoulders feeling heavy”, “focused and relaxed”, “heavy limbs”, “numb but feeling body”, “calm”, “body spasms”
Fourth	“well focused”, “single pointed concentration”, “still”, “settled”, “little registration of anything physical”, “losing mental processes”, “still no bodily awareness”	“more at ease”, “deeply relaxed”, “some thoughts in mind”, “heavy limbs”, “drifting”, “focused and relaxed”, “emotionally even”, “in and out of consciousness”
Formless	“feeling of floating in space”, “spacious”, “sense of spaciousness”, “expansive”, “lost sense of the body as attention was drawn into space”, “opening out into no particular direction”	“relaxed but fidgety”, “mentally anxious”, “physically relaxed”, “very relaxed”, “completely blank in mind”, “mind wandered more”, “disconnected”, “surreal”

Table 4.1: **Phenomenological reports for meditators and controls in meditative states.** Descriptions are given for each meditative state for each group. Subjects’ own words are given in order to provide an accurate account of experiences during the experiment.

4.4.2 EEG

Significant increases in central and fronto-central theta power were found in MEDITATORS during meditation. Additionally, significant changes in high-frequency activity were found posteriorly in both MEDITATORS and *controls*, and centrally in MEDITATORS only during meditation. Few other results were as clear.

As a result of operator error and subject task misunderstanding, there was no EEG data for six states of three subjects. While it was intended to compare all descending and ascending states, because of some missing data it was necessary to use only one measure for some states. Where two measures were available, averaged descending and ascending values were used. As identical descending and ascending meditative states were assumed to induce equivalent EEG changes, averaging states was not expected to adversely affect the outcome of analyses. Consolidating the thirteen states into seven would remove any time-dependant trend and as such, any changes found would support the hypothesis regarding a correlation between meditative states and changes in EEG. This method was only necessary for EEG data due to software requirements.

Group differences

No differences between groups in the baseline state were found.

Holmes (1984) cautioned against interpreting the effects of meditation when initial differences between experimental groups had not been analysed and taken into account. His concern was that any significant differences found during a meditation condition may have been present from the beginning and therefore would not reflect acute changes resulting from meditation, but rather may be a consequence of biological variability or even long-term effects of meditation. Hence, we performed unpaired t-tests comparing the baseline states between groups to identify any long-term, pre-experimental effects of meditation. All tests, except one, failed to reveal a significant difference between the two groups during the baseline state. A p-value of 0.029 was found for electrode 111 in the delta band, where larger delta power was revealed in *controls* (21.113 $\mu V^2 \pm 0.543$), compared to MEDITATORS (19.580 μV^2 ± 0.347). This result is not noteworthy as 6 significant results out of the 120 tests performed were expected by chance alone.

Effects of control and meditative states

Repeated measures ANOVAs were performed in SPSS on each electrode for each frequency band with group and state as factors. Results are graphically represented in heat maps (Figures 4.5 to 4.11). MEDITATORS are displayed in the top half of the figures and *controls* in the bottom half. The two large topographic heat maps on the left were created by selecting the lowest p-values across states. The right side of the figures shows individual heat maps for each state.

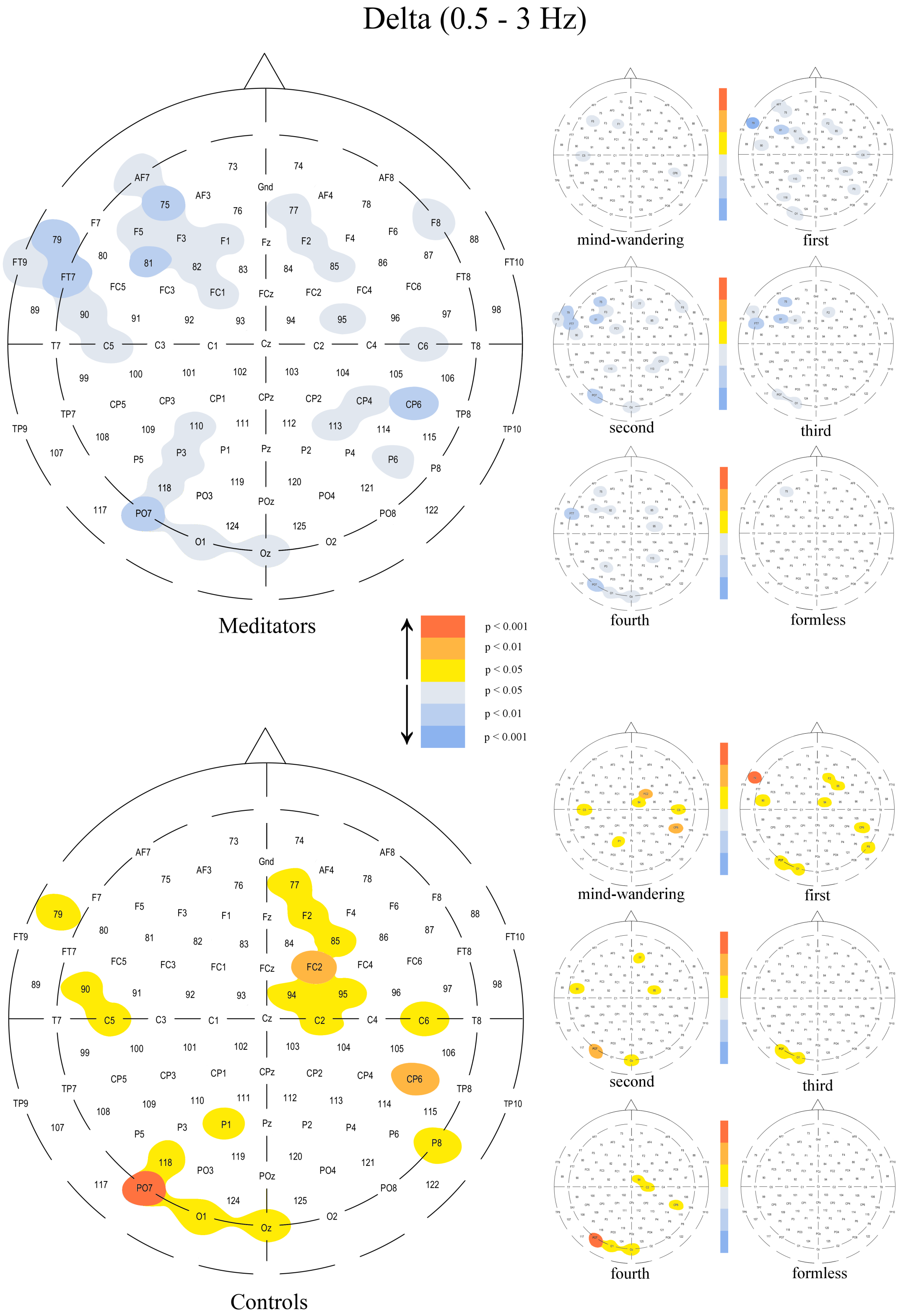

Figure 4.5: **Heat maps of p-values for delta (0.5–3 Hz)** from repeated measures contrasts, showing individual (right) and combined (left) maps for states for MEDITATORS (top) and *controls* (bottom).

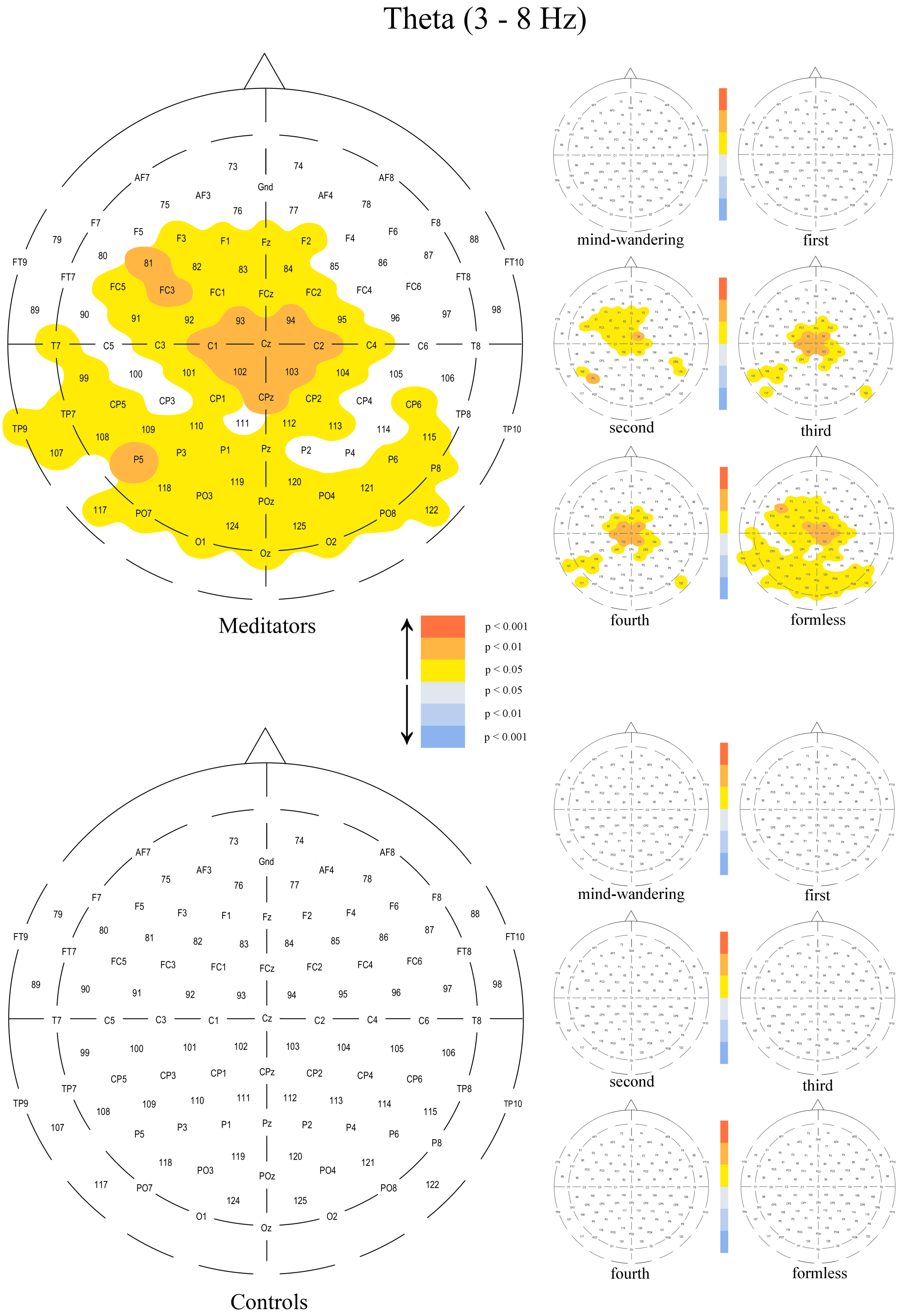

Figure 4.6: **Heat maps of p-values for theta (3–8 Hz)** from repeated measures contrasts, showing individual (right) and combined (left) maps for states for MEDITATORS (top) and *controls* (bottom).

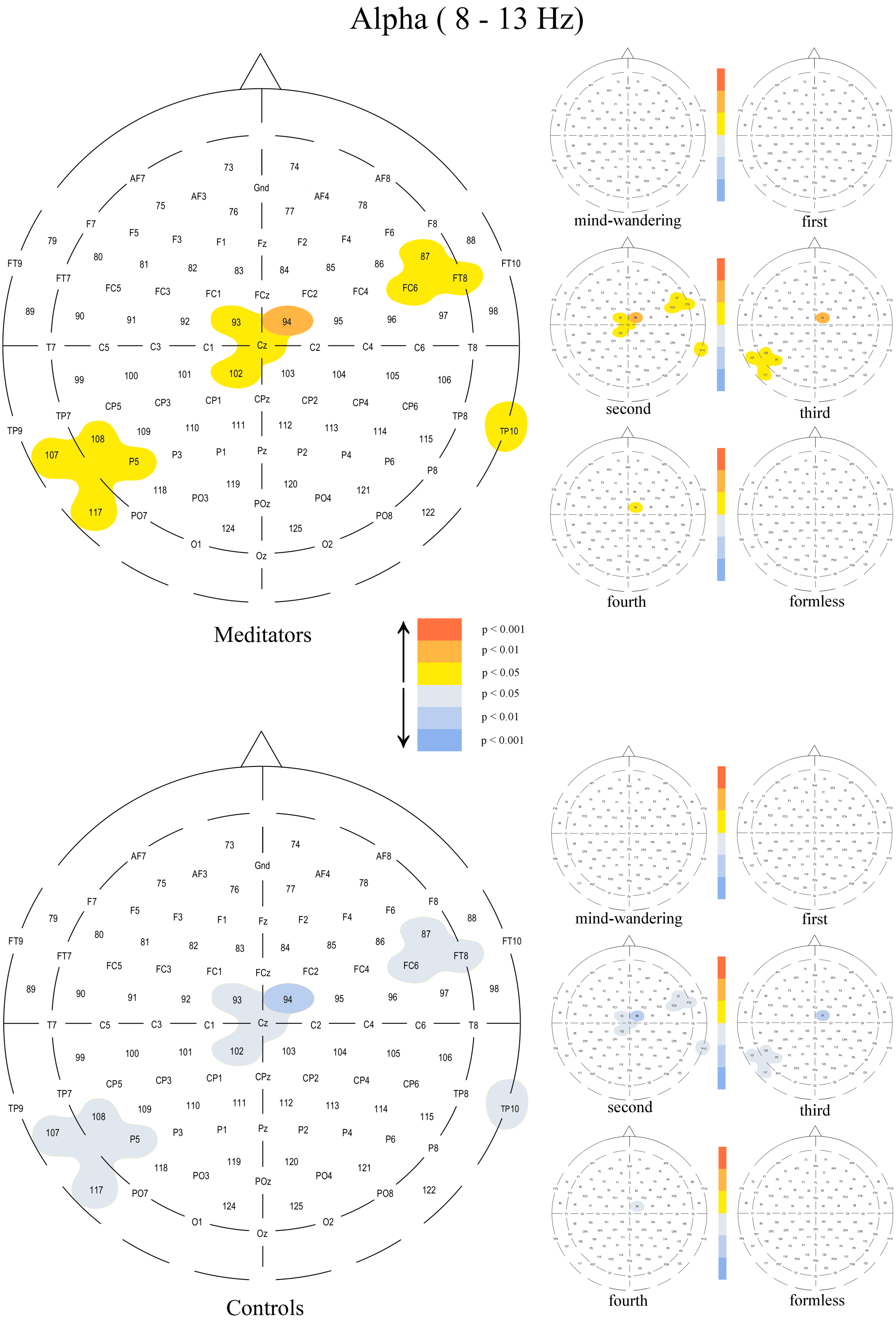

Figure 4.7: **Heat maps of p-values for alpha (8–13 Hz)** from repeated measures contrasts, showing individual (right) and combined (left) maps for states for MEDITATORS (top) and *controls* (bottom).

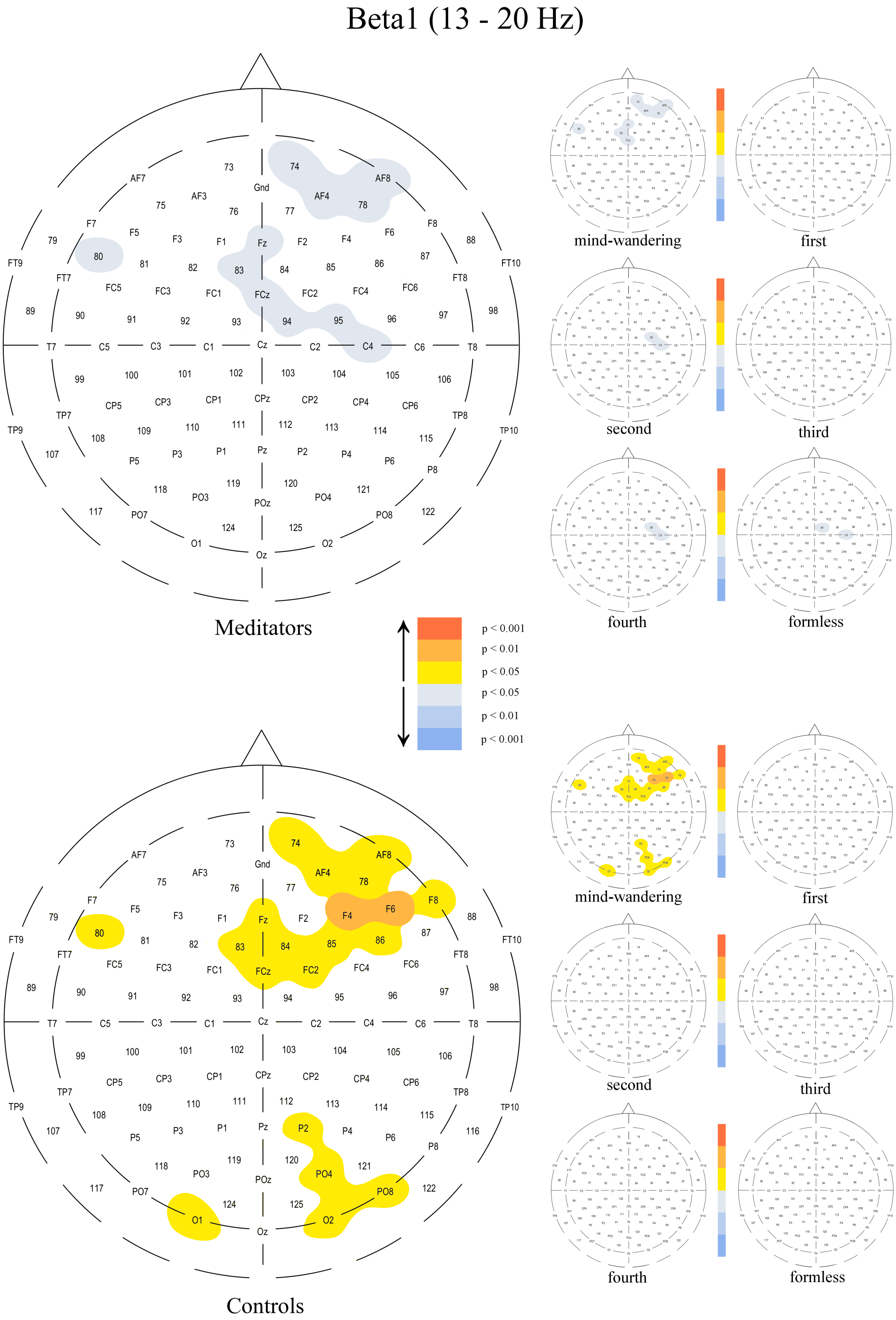

Figure 4.8: **Heat maps of p-values for beta1 (13–20 Hz)** from repeated measures contrasts, showing individual (right) and combined (left) maps for states for MEDITATORS (top) and *controls* (bottom).

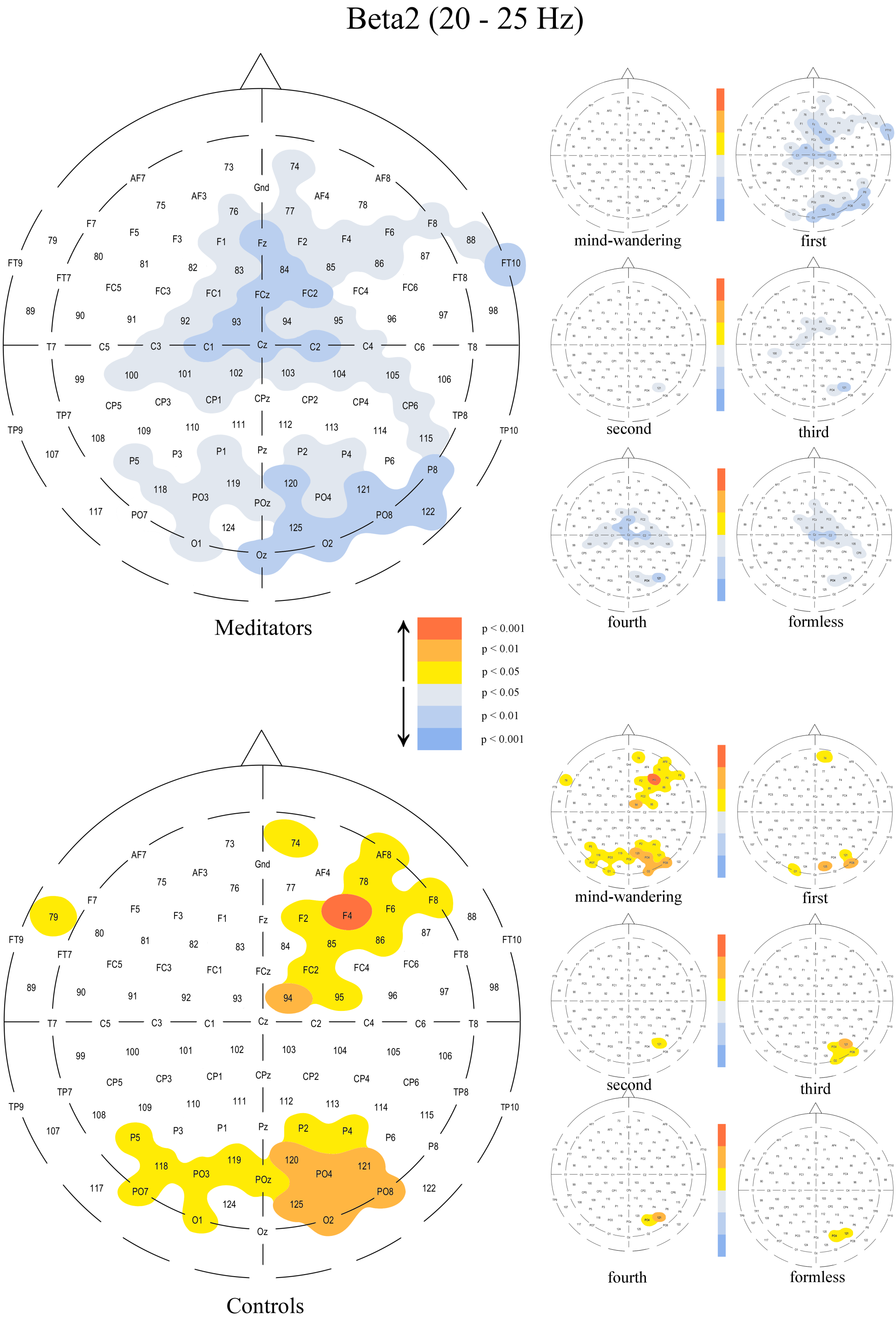

Figure 4.9: **Heat maps of p-values for beta2 (20–25 Hz)** from repeated measures contrasts, showing individual (right) and combined (left) maps for states for meditators (top) and *controls* (bottom).

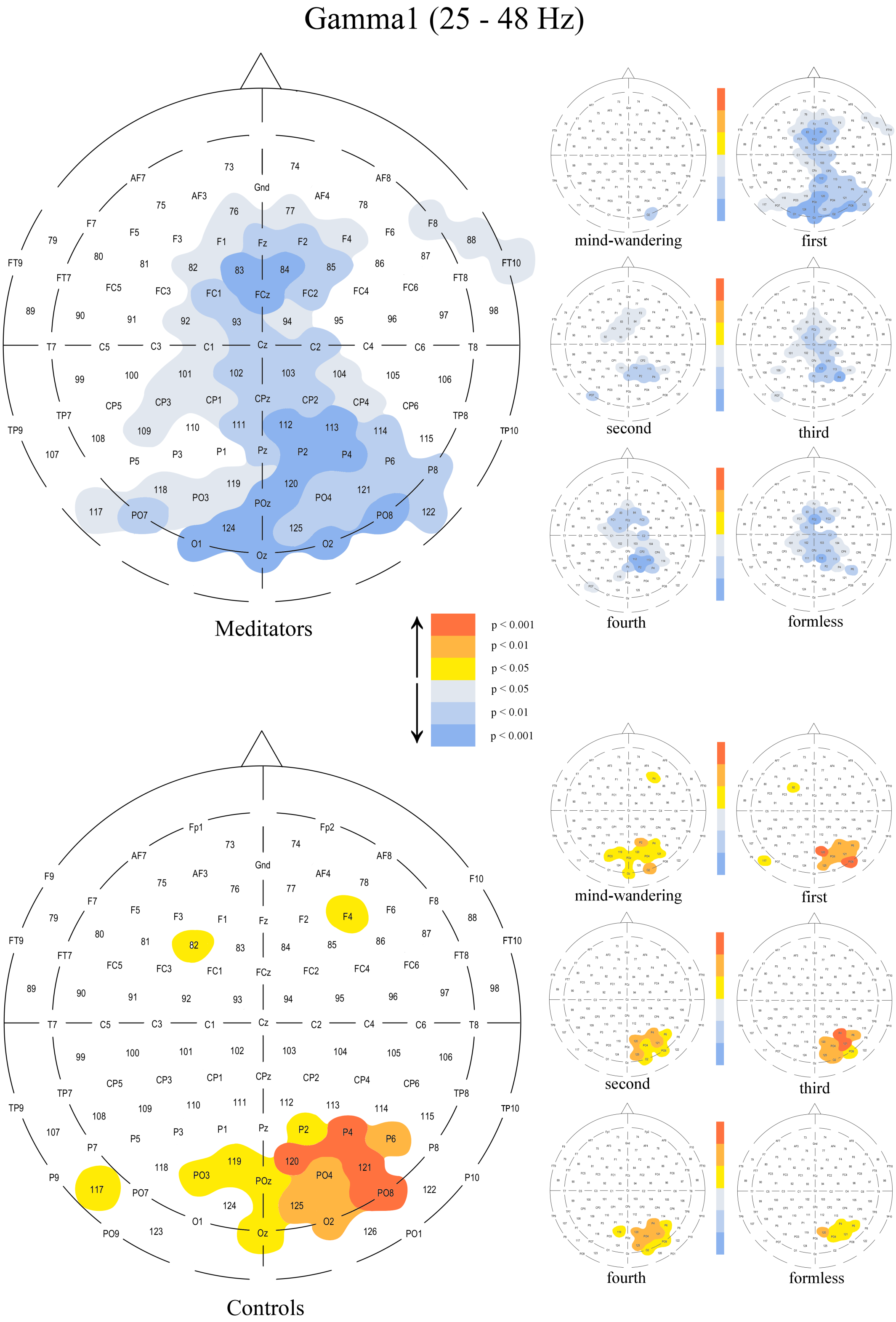

Figure 4.10: **Heat maps of p-values for gamma1 (25–48 Hz)** from repeated measures contrasts, showing individual (right) and combined (left) maps for states for MEDITATORS (top) and *controls* (bottom).

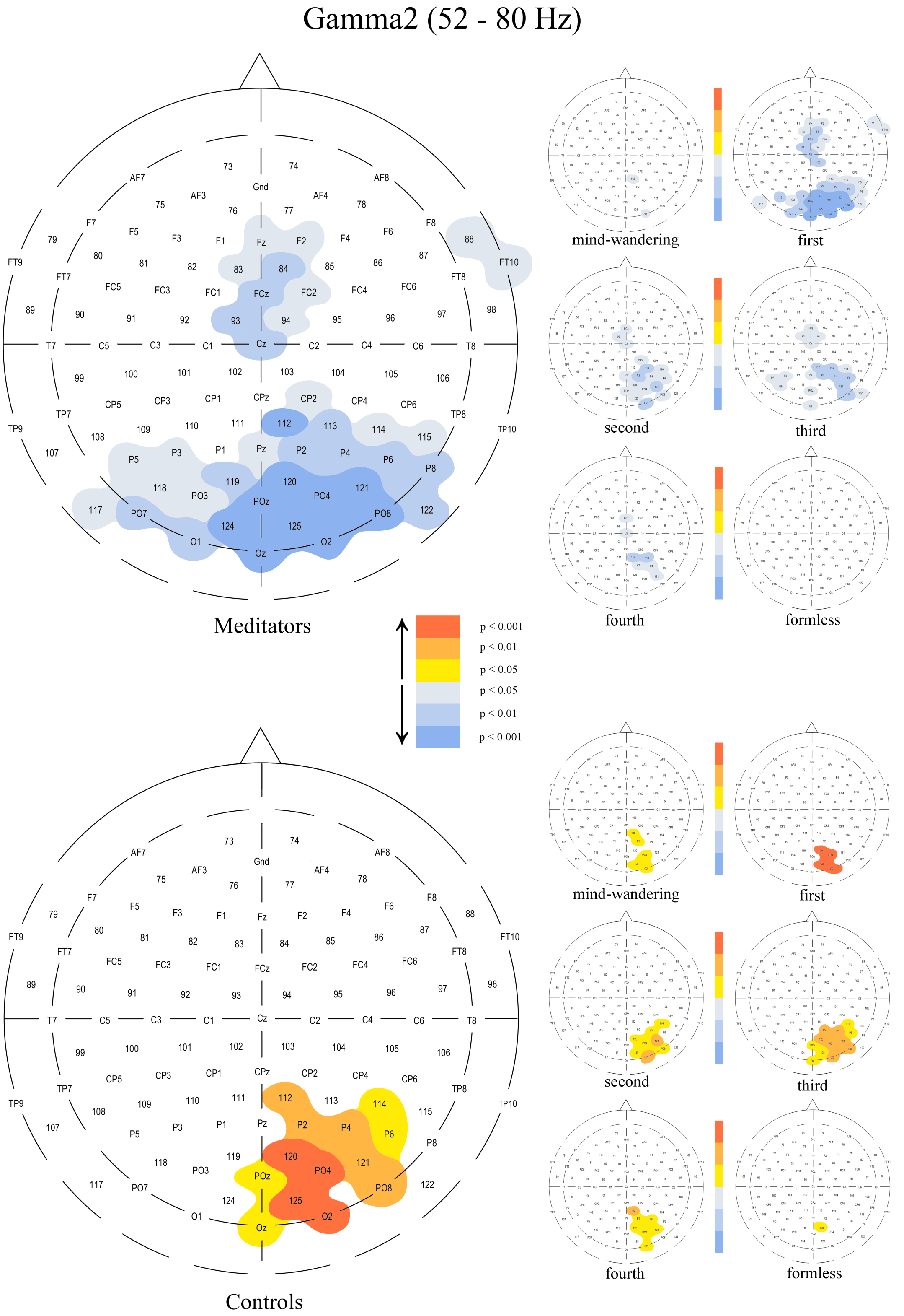

Figure 4.11: **Heat maps of p-values for gamma2 (52–80 Hz)** from repeated measures contrasts, showing individual (right) and combined (left) maps for states for MEDITATORS (top) and *controls* (bottom).

4.4.3 Autonomic function

Heart rate

No significance group differences or state effects were found for RR intervals in ECG timing.

Blood pressure

No significance group differences or state effects were found for blood pressure.

Respiration

Analysis revealed significant differences between groups, with MEDITATORS exhibiting a slower baseline breathing rate, compared to *controls* (Figure 4.12). A meditation effect was also found, with decreases in both groups positively correlating to descending states and increases positively correlating to ascending states. Finally, using a simple t-test, the difference between groups in the respiratory frequency during baseline was found to be statistically significant ($p < 0.0002$).

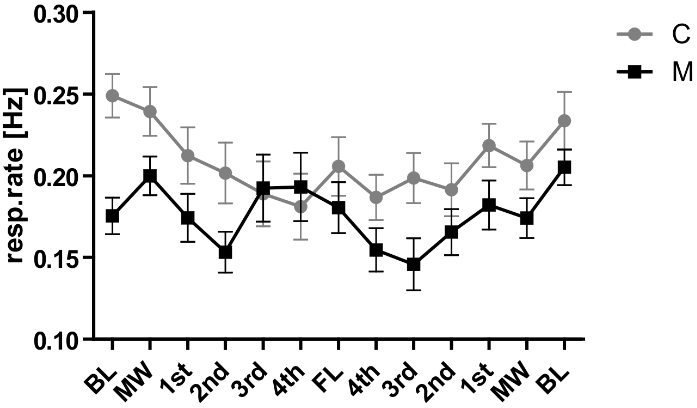

Figure 4.12: **Respiration rate**s for MEDITATORS (black squares) and *controls* (grey circles) across all meditative states. BL - baseline, MW - mind-wandering and FL - formless.

Peripheral blood oxygen saturation (SpO_2)

Overall, MEDITATORS exhibited lower blood oxygen saturation levels, compared to *controls*. SpO_2 levels in MEDITATORS during meditation also decreased more rapidly than *controls* (Figure 4.13).

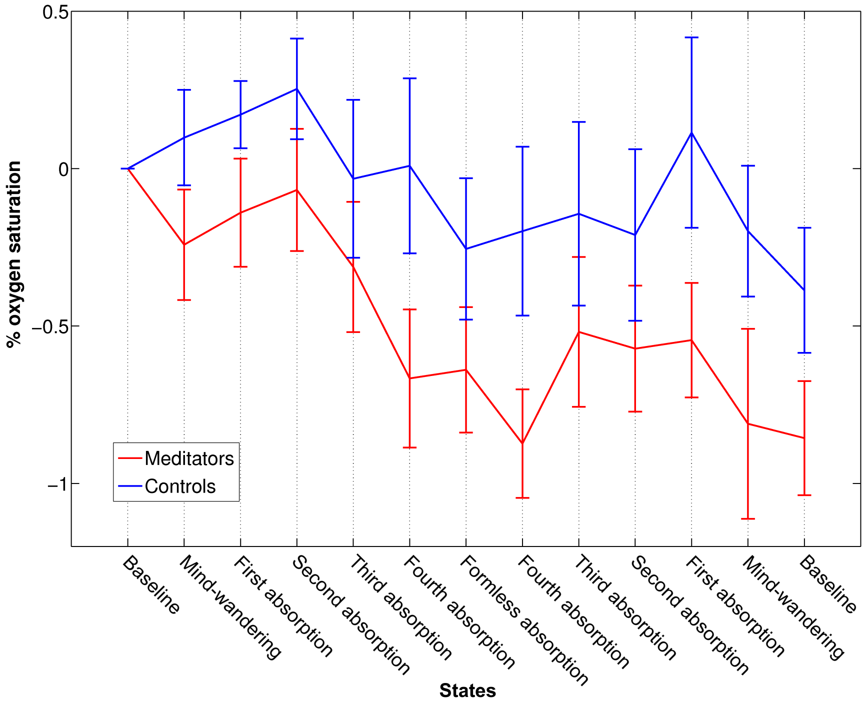

Figure 4.13: **Peripheral blood oxygen saturation** changes in percentage oxygen saturation relative to baseline in MEDITATORS (red) and *controls* (blue) plotted over all states.

Significance values for peripheral blood oxygen saturation, temperature and electrodermal activity are shown in Table 4.2.

	Means			Slopes		
Autonomic measure	State	Group	State x group	State	Group	State x group
Finger temperature	0.0001	0.0006	0.2486	0.0013	0.9355	0.0011
Toe temperature	0.6599	0.7279	1	0.003	0.661	0.9896
Ear temperature	0.2738	0.0015	0.779	0.0059	0.2756	0.78
Air temperature	0.0002	0.1528	0.5698	0.0001	0.7999	0.0656
Blood oxygen saturation	0.0072	<0.0001	0.9548	0.2537	0.0177	0.5034
Electrodermal level	0.5114	<0.0001	0.6363	0.9361	0.0003	0.2208

Table 4.2: **P-values for autonomic measurements.** Significant p-values are in green and non-significant p-values are in grey. Specific means and standard errors are included in the text.

Mean Analysis of means revealed main effects for both group ($p < 0.0001$) and state ($p = 0.0072$). MEDITATORS (-0.480 ± 0.0596) were found to have lower SpO_2 levels overall, compared to *controls* (-0.060 ± 0.0588). Both groups exhibited lower SpO_2 levels in the ascending baseline state (-0.612 ± 0.1535) compared to the descending second absorption (0.093 ± 0.1498). No group-by-state interaction was found.

Slope Analysis of slopes revealed a main group effect ($p = 0.018$) where a more negative slope overall was found for MEDITATORS (-0.002 ± 6.94e-04) compared to *controls* (4.404e-05 ± 6.835e-04). No main state effects or group-by-state interactions were found.

Temperature

Finger temperature A larger overall mean temperature increase was found for MEDITATORS, compared to *controls*, and significant mean temperature changes in particular states were found for combined groups (Figure 4.14). Additionally, significant slopes were revealed in certain states for both groups combined, as well as MEDITATORS alone.

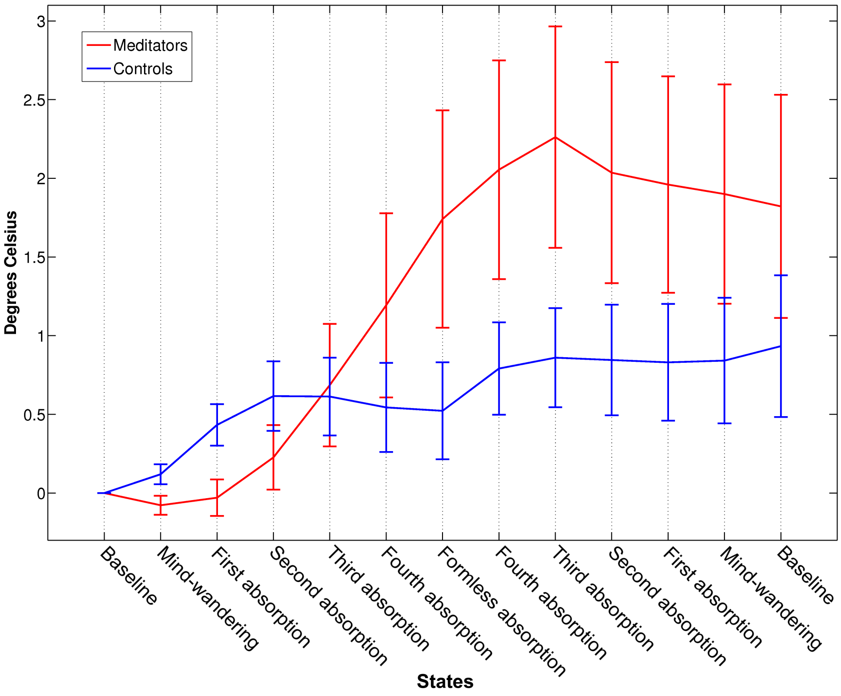

Figure 4.14: **Finger temperature** changes in degrees Celsius (°C) relative to baseline for MEDITATORS (red) and *controls* (blue) plotted over all states.

Mean A significant main group effect (p = 0.0006) revealed an overall higher temperature increase in MEDITATORS (1.21 °C ± 0.12), compared to *controls* (0.61 °C ± 0.12). There was a highly significant main effect ($p < 0.0001$) for state with higher temperatures in the ascending third absorption (1.56 °C ± 0.31) compared to the descending baseline. No group-by-state interaction was found.

Slope Analysis on slopes indicated a significant main state effect (p = 0.0013) which revealed a significantly more positive slope in the ascending third absorption, compared to the descending baseline. This finding was further defined by a group-by-state interaction (p = 0.0011), revealing more positive slopes for MEDITATORS in the descending third absorption (0.003 °C ± 0.0008) and descending fourth absorption (0.003 °C ± 0.0008) when compared to the descending baseline (-0.0011 °C ± 0.0008). All states combined revealed no main group effect for slope.

Toe temperature The descending baseline was found to be negligibly more negative than most other states, however, no significant mean temperature changes were found (data not shown).

Ear temperature Negligible changes in slope (more negative) were found in certain states compared to the descending baseline, however, no differences between groups were found. MEDITATORS were slightly warmer overall compared to *controls*, but no mean temperature differences were found between states (data not shown).

Ambient air temperature Analysis of air temperature revealed no differences between groups during the experiment and very minor significant decreases in mean temperature in seven states (maximum change from baseline was 0.32 °C) for combined groups (data not shown).

Electrodermal activity

Overall, MEDITATORS were found to have lower electrodermal activity, compared to *controls* (Figure 4.15). Electrodermal activity in MEDITATORS during meditation also decreased more rapidly than *controls*.

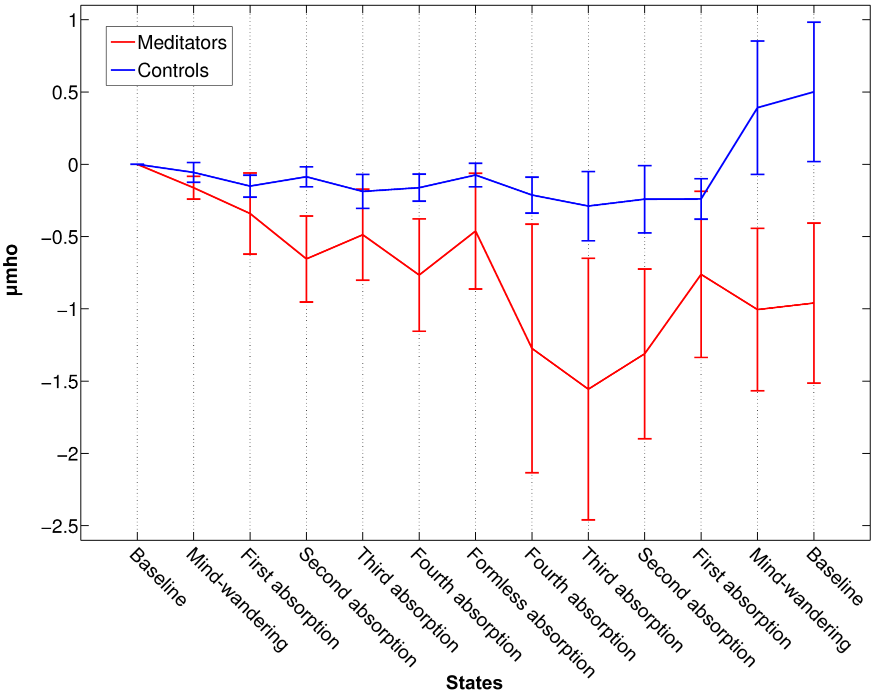

Figure 4.15: **Electrodermal activity** changes in micromho (µmho) relative to baseline in MEDITATORS (red) and *controls* (blue) plotted over all states.

Mean A significant main group effect ($p < 0.0001$) revealed lower electrodermal activity overall in MEDITATORS (-0.75 µmho ± 0.1105) compared to *controls* (-0.062 µmho ± 0.1088). No main state effects or group-by-state interactions were found.

Slope ANOVA on slopes revealed a main group effect ($p = 0.0003$) where a significantly more negative slope overall was found for MEDITATORS (0.006 µmho ± 0.0009) compared to *controls* (0.002 µmho ± 0.0009).

4.5 Discussion

4.5.1 EEG

In discussing EEG changes, each frequency band will be prefaced by a brief summary. Posterior changes will be dealt with first, followed by central/frontal changes. Generally, MEDITATORS will be reported first, followed by *controls*.

Due to the number of tests performed, six electrodes (or $\frac{1}{20}$) were expected to occur by chance alone in individual states.

Delta

Decreases in delta in distributed electrodes were found in MEDITATORS during meditation, particularly the first, second, third and fourth absorptions (Figure 4.5) while minimal increases in delta power were found in *controls* during meditation.

The number of significant electrodes (including a number of electrodes with significant p-values less than 0.01) exceeded the amount expected by chance. The majority of significant electrodes occurred in the left frontal region and the direction of change in delta power in MEDITATORS was consistent with predictions regarding an alert mental state during meditation.

Significant electrodes in *controls* numbered even fewer than those found in MEDITATORS and consequently little can be deduced from the results, except to note that the direction of change in delta power was consistent with predictions of controls becoming drowsy during meditation. This possible drowsiness may reflect the potential difficulty for *controls* to engage or remain engaged in meditation (Dunn et al. 1999).

Theta

The most striking EEG result was found in the theta band (Figure 4.6) in MEDITATORS during meditation. The map of combined states shows centrally and posteriorly distributed theta activity with a central locus of statistical significance less than 0.01. No changes in theta power were found in *controls*.

On examination of individual states, theta power significantly increased fronto-centrally in the second absorption and continued to increase during the remaining three absorptions. The most likely explanation for the lack of significant power increase in MEDITATORS in the first absorption is the non-significant increase in *controls* in the first absorption (Figure 4.16). Statistical analyses determined if the difference in means between groups at a particular state (for example the second absorption) were significantly different from the difference in means between groups at baseline. Without the increase in *controls*, it is possible that significance theta power increases would have been found in MEDITATORS in the first absorption as well. Although theta increases in MEDITATORS were only very small, they were nevertheless significant.

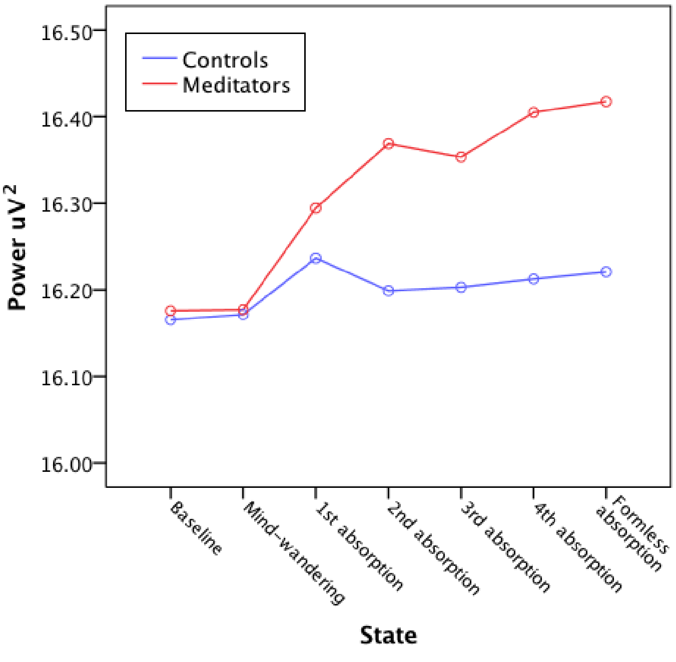

Figure 4.16: **Theta increases** in MEDITATORS (red) and *controls* (blue) during baseline and meditative states at electrode Fz.

Activity in the prefrontal cortex (PFC), particularly the right hemisphere, and the cingulate gyrus has been implicated in initiating willful acts and tasks requiring sustained attention (Coull 1998; Newberg & Iversen 2003; Pardo et al. 1991; Posner & Petersen 1990; Vogt et al. 1992). These findings are consistent with studies on volitional types of meditation which necessitate an intent to clear one's mind of thoughts and involve intense concentration for long durations of time (Lazar et al. 2000; Newberg et al. 2001). Changes in attentional processing (Carter et al. 2005; Brefczynski-Lewis et al. 2007) and brain structures (Pagnoni & Cekic 2007; Lazar et al. 2005) also support Buddhist claims that voluntarily orientating and sustaining attention is strengthened with practise, such that less effort is required in virtuosos (Lutz et al. 2008). Additionally, frontal theta oscillatory activity has been suggested to correlate with the suppression of evaluating and interpreting processes of prefrontal brain structures (Baijal & Srinivasan 2009). This theory reflects subjective reports of minimised or inhibited distraction from internal thoughts and external stimulation as well as single-pointed concentration during meditation. The increases in fronto-central theta activity found here during meditative states supports phenomenological reports obtained from MEDITATORS post-experiment of single-pointed concentration and diminished thought activity (Table 4.1).

Interestingly, theta power increases were fronto-centrally distributed during the second absorption. This finding may reflect the positive affect and occasional feelings of bliss MEDITATORS report experiencing during this state (§1.3.5) which would support findings of increased theta activity correlating with feelings of peace or blissfulness and low thought content (Aftanas & Golocheikine 2001). These changes also correlate with subjective experiences of “feelings of joy and happiness”, “pleasant emotion” and “bliss” during the second absorption.

Widespread posterior changes in theta power during the formless absorption where subjects experience a feeling of expansion into space might reflect activation of occipital and possibly temporal cortices, regions implicated in spatial awareness (Clavagnier et al. 2004; Karnath et al. 2001).

In light of the relationship between theta occurring in anterior regions of the brain and attentional processing (Basar-Eroglu et al. 1992; Deiber et al. 2007), frontal theta is now considered a necessary contingent for meditation (Baijal & Srinivasan 2009). Our results support evidence for theta power increases during meditation (Aftanas & Golocheikine 2001; Kasamatsu & Hirai 1966; Kasamatsu et al. 1957), specifically in frontal midline theta power (Aftanas & Golocheikine 2002; Baijal & Srinivasan 2009; Holzel et al. 2007; Kubota et al. 2001). In particular, our findings demonstrate interesting parallels with a recent study of concentrative meditation (Baijal & Srinivasan 2009). The authors reported increased frontal theta power during a middle-block of meditation data (designated "deep meditation") compared to the initial block ("entering meditation") and the end block ("exiting meditation"). Although Baijal and Srinivasan's stage designations appeared to be arbitrarily derived from reports of phenomenological differences within the Sahaj Samadhi meditation technique (regrettably omitted from the article), the similarity in findings is intriguing. Indeed, the largest increases in theta power found by Baijal and Srinivasan were not in left and right frontal regions, but in left and right fronto-central regions (FC5, FC3, FC1, FCz, FC2, FC4 and FC6), which correspond closely to changes found in our experiment. Although only small increases, these changes in theta represent significant implications for mental behaviour.

Our findings of increased central/frontal theta EEG power, taken with previous reports, strongly suggest concentrative meditation to be a theta state.

Alpha

No change in alpha activity was found in either group during meditation.

The lack of change in alpha power fails to corroborate the substantial literature stating that meditation leads to an increase in alpha rhythms, which initially slow and extend to anterior channels (Anand et al. 1961; Banquet 1972; Corby et al. 1978; Elson et al. 1977; Hirai 1974; Kasamatsu & Hirai 1966; Kasamatsu et al. 1957 [see also the review by Cahn & Polich 2006]).

Beta

MEDITATORS were found to have decreased beta2 power during meditation while *controls* were found to have increases in both beta1 and beta2 power during mind-wandering.

MEDITATORS were found to decrease in beta2 power occipitally (six electrodes below 0.01 significance), concomitant with the onset of meditation (first absorption), supporting the hypothesis that MEDITATORS would be more physically relaxed during meditation, as beta2 frequencies at circumferential electrodes are indicative of muscle activity.

MEDITATORS were also found to have centralised decreases in beta2 activity during the first, third, fourth and formless absorptions. Based on the discussion earlier regarding central and peripheral high frequency activity (§2.1.2), these central decreases are interpreted as brain activity. Central/frontal decreases were most significant in the first absorption (seven electrodes below 0.01 significance), but also occurred substantially in the fourth and formless absorptions. The third absorption also revealed a consistent topography of a small number of electrodes. Although a fraction of right frontal beta2 power reductions in the first absorption might have been due to reduced muscle activation, the majority of central/frontal decreases are considered to be evidence for the unbinding of neuronal assemblies involved in the evaluation and interpretation of the environment (discussed further in §4.5.1.1 below). Interpreting increases in beta2 power as EEG is appropriate in light of central electrodes up to 50 Hz being uncontaminated by EMG (Whitham et al. 2007).

Striking increases in beta2 power occurred occipitally in *controls* during mind-wandering (4 electrodes below 0.01 significance). A trivial number of occipital electrodes also increased in beta1 power in controls during mind-wandering. This was similar for beta2 power during meditative states, however, beta2 changes showed a consistent topography across states, suggesting these significant results were more than random chance occurrences. Occipital changes in beta2 activity were expected to be evidence for EMG contributions from cervical muscles supporting the head, reflecting findings that high frequency power is most evident in lateral and posterior leads, consistent with a localisation close to cranial and cervical muscles (Whitham et al. 2007). The occipital increases in beta2 (and minimally beta1) in *controls* during mind-wandering reflect this muscle topography and are also compatible with the reported effects of thinking on EMG (Whitham et al. 2008).

In *controls*, beta1 and beta2 power was also found to increase frontally during mind-wandering. Only the beta1 frequency range can be confidently considered sufficiently free from muscle at circumferential electrodes and interpreted as EEG. However, changes in beta1 and beta2 power did not show expected concomitant increases in gamma power or increase during meditative states (as did gamma), and consequently, beta power changes were interpreted as EEG reflecting increased thought activation during mind-wandering.

Gamma

Decreases in gamma1 and gamma2 were found occipitally in MEDITATORS in the first absorption, as well as centrally and fronto-centrally during meditation, while increases in gamma1 and gamma2 power were found occipitally in *controls* during meditation.

Occipital changes in gamma activity in both *controls* and MEDITATORS resemble topographic distributions of beta2 power changes, supporting the view that high frequency activity in posterior leads is contributed to by cervical muscles (Whitham et al. 2007). The marked reductions of gamma1 and gamma2 power at posterior channels in MEDITATORS during the first absorption (and the second, third and fourth absorptions for gamma2 only) demonstrate a greater ability to physically relax during meditative states of enhanced internalised attention and diminished mental wandering. Decreased gamma2 power occipitally in the first four meditative states is consonant with the finding that high gamma frequencies (above 45 Hz) are most affected by EMG. Alternately, elevated (and possibly increasing) levels of cervical muscle tension in *controls* (marked by elevated occipital gamma1 and gamma2) suggests an inability to relax, potentially exacerbated by frustration associated with unsuccessful attempts to meditate.

The distribution of central and fronto-central beta2 increases in MEDITATORS during meditation was congruous with that of reduced gamma1 and gamma2. The most dramatic decreases in high frequency activity (up to nine electrodes below 0.01 significance and three electrodes below 0.001 significance) occur in gamma1 (25–48 Hz) and are seen in all meditative states. Gamma2 only appreciably decreases in the first absorption with a negligible number of electrodes distributed comparably in deeper states. Bearing in mind the frequencies largely unaffected by EMG centrally, these central and fronto-central decreases in gamma1 (as with beta2) power can be interpreted as a reduction of higher cognitive activity. The fact that the most significant power decreases (less than 0.001) in beta2, gamma1, and to a lesser extent gamma2, occur in the first absorption when focus becomes single-pointed and thinking is greatly diminished, supports this theory. During meditation, practitioners report a reduced awareness of one's surroundings, diminished bodily boundaries and spatial orientation, and complete union between object and mind (§1.3.5), experiences which appear compatible with the inhibition of brain function involved in segregating, differentiating and analysing the environment and one's experience (Baijal & Srinivasan 2009). Changes in spectral gamma power have recently been found in an EEG study on the conscious and nonconscious processing of briefly flashed words (Gaillard et al. 2009). The authors report large increases in gamma power and sustained frontal voltage changes during conscious word processing and suggest that these changes may be causally related to higher-level cognitive processing. Additionally, the suggestion that frontal theta may correlate with the suppression of frontal higher brain functioning (Baijal & Srinivasan 2009) is substantiated by findings of increased frontal theta in MEDITATORS during meditation.

4.5.1.1 High frequency EEG

The functional connectivity of the thalamocortical and corticocortical systems has been of particular interest to researchers of consciousness due to their "ability to integrate the activities of functionally diverse cognitive modules" (Lee et al. 2009). Information integration theory suggests that consciousness corresponds to the capacity of a system to integrate information, a process often referred to as "binding". This capacity for information integration has been shown in models to increase in systems maintaining consciousness, for example, thalamocortical processes, and decrease in those that do not, for example, cerebellar processes and sleep (Tononi 2004). Consequently, the "unbinding" of neural processes has been suggested as essential to unconscious states (Mashour 2004). While meditation does not represent an unconscious state, the concept of the cognitive unbinding paradigm in anaesthesia might be functionally useful in understanding meditation. Our findings of central/frontal decreases in high frequency EEG power during meditation are of particular interest, given the associations between gamma EEG activity and higher cognitive function (Mashour 2006), and also findings of reduced mean information integration capacity during anaesthesia as quantified in the 30–50 Hz EEG gamma band (Lee et al. 2009). Our operational framework for distinct meditative states suggests a reduction in higher brain functioning and information integration which we propose is correlated to diminished gamma EEG power and unbinding of cognitive modules. This proposal also fits with the model of perception mentioned earlier, such that deeper states of meditation are associated with diminished mental and perceptual elaborations. It appears from the results that central and fronto-central reductions in high frequency oscillations (beta2, gamma1 and gamma2) are potentially involved in the deactivation or unbinding of neuronal assemblies involved in higher brain functioning and occur most notably between 25 and 48 Hz.

A way to further differentiate EEG and EMG would be to examine coherence measures of high frequency activity. The temporal synchrony of neurons offers the most promising mechanism for "binding" together different stimulus features of an object, such as colour, texture, distance, spatial position and smell, by the temporal coherence of activated neurons oscillating at gamma frequencies. Although other solutions to the "binding problem" have been proposed (for a thoughtful discussion, see Buzsáki 2006), "the temporal binding mechanism by gamma-oscillation-assisted temporal synchrony" (Buzsáki 2006) has the support of abundant evidence and coherent models. Therefore, during meditative states of “contentless awareness” (Wallace 2007), a decrease in coherent long-distance neural synchrony might be found, along with decreased gamma-band activity (Raffone & Srinivasan 2009). Tests for synchrony were not done due to the lack of access to sophisticated analysis algorithms.

4.5.2 Autonomic function

Heart rate

No group differences or state changes in heart rate timing measures were found. This lack of change might be due to a floor effect. In other words, heart rate may have been low when the experiment began and therefore any changes during the experiment might not have been large enough to reach significance. Heart rate is one of the more inconsistent measures reported in literature, with decreases (Goleman & Schwartz 1976; Solberg et al. 2004), increases (Corby et al. 1978; Elson et al. 1977; Lehrer et al. 1980) and no changes (Holmes et al. 1983; Morse et al. 1977; Orme-Johnson 1973) found during meditation. It may be necessary to increase subjects’ heart rates before they undertake experimental conditions to assess the efficacy of meditation on restoring a physiological baseline.

Blood pressure

No group differences or state changes were found in measures of blood pressure. Although a considerable number of uncontrolled experiments and case studies report decreases in blood pressure in normal and hypertensive patients during meditation, no changes have been found in controlled studies (Holmes et al. 1983; Morse et al. 1977; Solberg et al. 2004).

Respiration

MEDITATORS had a lower respiratory rate overall, compared to *controls,* suggesting that meditation is effective at reducing sympathetic tone. In addition, a difference between groups in the respiratory frequency during baseline was found, suggesting a long-term effect of meditation on reducing sympathetic tone. This finding supports the idea that decreases in respiration rate are concomitant with relaxation (when levels of carbon dioxide are lower) and MEDITATORS are more relaxed during meditation due to decreased thought activity and muscle activation.

Blood oxygen saturation

MEDITATORS were found to have lower peripheral blood oxygen saturation overall, compared to *controls.*

During ordinary periods of rest, a general level of arousal and readiness is still expected to exist, reflected by a degree of sympathetic tone. This low level of arousal still requires a certain level of oxygen to facilitate metabolism, however, meditation may allow for a lower set point of sympathetic tone and for oxygen requirement by inducing a calm and reposeful psychological and physical condition (Wallace 2006).

Temperature

MEDITATORS were found to have higher finger skin temperatures during meditation, compared to *controls.*

As increased skin temperature is a result of reduced sympathetic tone, and therefore considered one reliable marker of relaxation (Blessing 1997), an overall elevated skin temperature during meditation demonstrates a greater ability in meditators to mentally relax. A negligible increase in ear temperature correlated with finger temperature, however, this small change is of dubious physiological relevance and points to the hand being a better site for revealing sympathetic tone. A lack of significant group difference in ambient air temperatures during the experiment supports the fact that the overall higher temperatures in MEDITATORS were due to the practice of meditation and not atmospheric variations. The most significant change in temperature was found in the finger suggesting this region as a more effectual indicator of emotional responses. The reason for this marked blood flow to the hands only may suggest an evolutionary purpose. Activation of the sympathetic vasomotor fibres occurs during stressful situations and results in the constriction of cutaneous blood vessels. The restriction of blood to deep body areas would be an advantagous adaptation in our ancestors, as conflicts over resources and mates could potentially result in damage to the body, especially to those parts which are primarily involved in assault and defense (viz. the arms).

It can only be imputed from these results that the effects of meditation on finger and ear temperature are conditional upon the *act of meditating,* rather than being correlated with any particular state of meditation. Although the latter possibility exists, the experimental strategy did not allow for such hypotheses to be tested. An increase in finger temperature was seen in MEDITATORS coincident to the engagement of meditation, that is, from the descending first absorption onward and then exhibited stability or a non-significant trend to decrease after the ascending third absorption. It is possible there exists certain lag in the temperature changes such that each meditative state precipitates a change in temperature which occurs after some delay and the trend to decrease in temperature after the ascending third absorption is the change associated with the lighter absorptions,[7] but again, this could not be tested. *Controls* exhibited a non-significant trend to increase in temperature over the states, possibly reflecting ordinary relaxation.

Electrodermal level

The finding that MEDITATORS exhibited lower electrodermal levels than *controls* during meditation supports the hypothesis regarding psychological relaxation such that lower electrodermal activity reflects less skin moisture and therefore less sympathetic tone, that is, a more restful state. The effects of state and trait anxiety on increased skin sweating and hence higher electrodermal levels have been thoroughly established (Boucsein 1992). Decreases in electrodermal activity also inversely followed the changes in finger temperature (Figures 4.14 and 4.15) confirming the association between warm skin temperatures and dry skin

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[7] It could reasonably be assumed that once the increases in temperature have occurred, a reversal may take longer to achieve whilst continuing to meditate, even though the ascending states are progressively lighter.

during a relaxed state (Blessing 1997).

4.5.3 Summary

The hypothesis that MEDITATORS would demonstrate enhanced attentional processing (viz. intense concentration and distraction inhibition) during meditation was supported by findings of increased theta EEG activity fronto-centrally in MEDITATORS during states of meditation.

The indication that increased theta activity was associated with the suppression of thought activity and evaluating processes was supported by central decreases in high frequency EEG activity (viz. beta2, gamma1 and gamma2). The reduction in high frequencies is a potential reflection of the deactivation or the unbinding of higher cognitive structures.

Hypotheses regarding arousal were not supported as no changes in delta activity were seen in either group. However, MEDITATORS demonstrated decreased muscle activation during meditation (revealed as posterior EMG) while *controls* exhibited increased EMG activity posteriorly which suggests increased tension and possibly anxiety.

Hypotheses of relaxed and calm physical and mental states in MEDITATORS during meditation were demonstrated by reductions in EMG. The hypotheses were also supported by findings of overall decreased blood oxygen saturation, electrodermal activity and respiratory rate, as well as increased finger temperatures. These autonomic changes suggest that MEDITATORS had reduced sympathetic tone during meditation. Combined with findings of muscle deactivation, these autonomic changes imply that MEDITATORS were both physically and emotionally relaxed during meditation. Additionally, MEDITATORS were found to have lower resting respiratory rates suggesting the long-term ability of meditation to change sympathetic tone.

Overall, meditation is demonstrated to be a mentally and physiologically calm state of focused concentration.