Chapter 2

Review of the Literature

Before reviewing the extant literature, a brief explanation will be made of certain technologies and measurements in order to provide more clarity to the summary of evidence.

2.1 Aspects of electroencephalography

2.1.1 Continuous EEG

The electroencephalograph (EEG), developed by Richard Caton over 130 years ago (Caton 1875), quickly evolved into a tool for clinical diagnosis (Berger 1925) and has been used as early as the 1950s to study brain activity during the practice of meditation (Das & Gastaut 1955).

EEG is a measure of electrical activity from the brain via the detection of electrical signals by electrodes typically attached to the scalp. This activity originates from neurons via a range of cellular and synaptic processes (Kandel et al. 2000) and is "considered to reflect the extracellular current flow associated with summated [excitatory and inhibitory] post-synaptic potentials in synchronously activated, vertically orientated pyramidal cells" of the upper layers of the cerebral cortex (Barlow 1993). By using EEG, the activation and inhibition of these cell groups can be measured (Rowan & Tolunsky 2003). The variation in signals recorded depends on the particular behaviour of the subject and what is occurring in the brain (consciously or unconsciously) at the time. Certain cell populations in particular brain structures are responsible for producing rhythmic cortical patterns, or waveforms, which can often be distinguished by their differences in frequency and amplitude (Niedermeyer & Lopes da Silva 1999) (§2.1.2). The mechanisms of EEG rhythmicity are currently understood as 1) a cortical-thalamic interaction, where the activity of thalamic pacemaker cells in the thalamus stimulates rhythmic cortical activation, and 2) an intrinsic capacity for rhythmicity in large neuronal networks in the cortex, which include cortico-cortical interactions (Rowan & Tolunsky 2003).

Standard EEG electrode positions were utilised in this project, viz., the International 10-20 electrode reference system (Figure 2.1) and a 120-electrode EEG montage based on the same reference system (Figure 2.2).

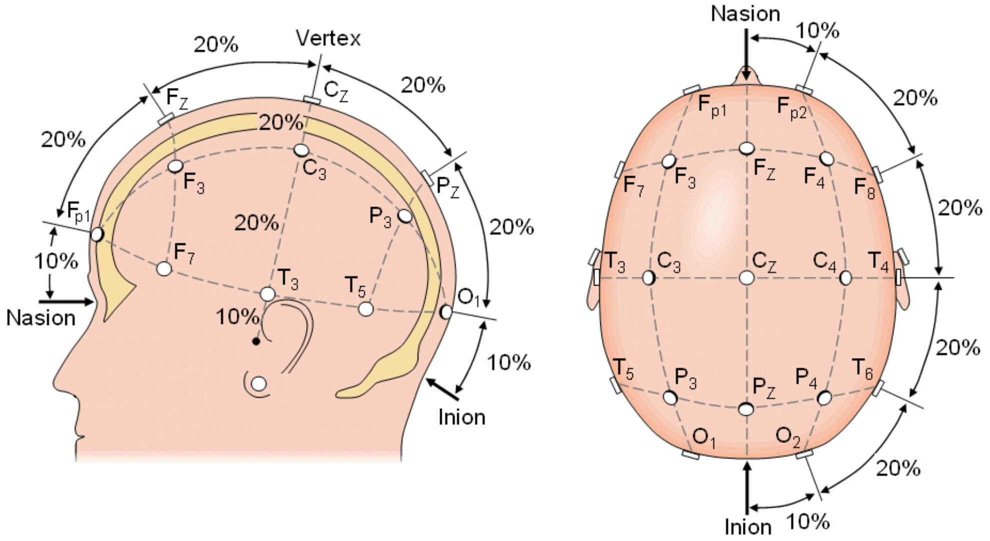


Figure 2.1: **International 10-20 electrode reference system** presented laterally (left) and dorsally (right). Percentages represent standard distances between electrodes as calculated in the International 10-20 reference system. Replicated from Malmivuo & Plonsey (1995).

2.1.2 EEG frequencies

Although the EEG is a fundamentally crude measure of the temporal activity generated by approximately 2 x 10^{10} (20 billion) neocortical neurons connected by around 0.15 quadrillion synapses (about a trillion synapses per cubic centimeter of cortex) (Drachman 2005), research has established accurate correlations between

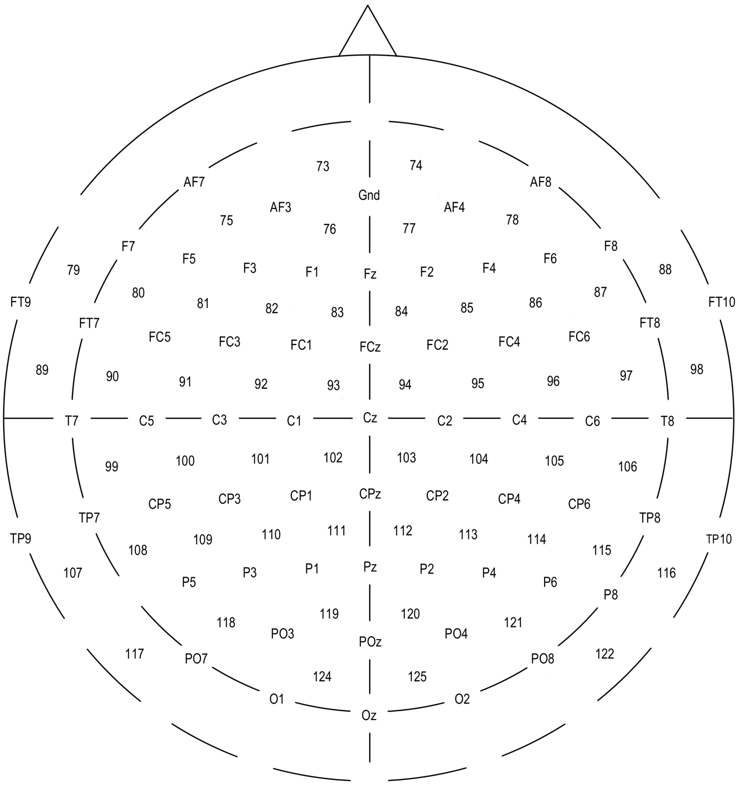
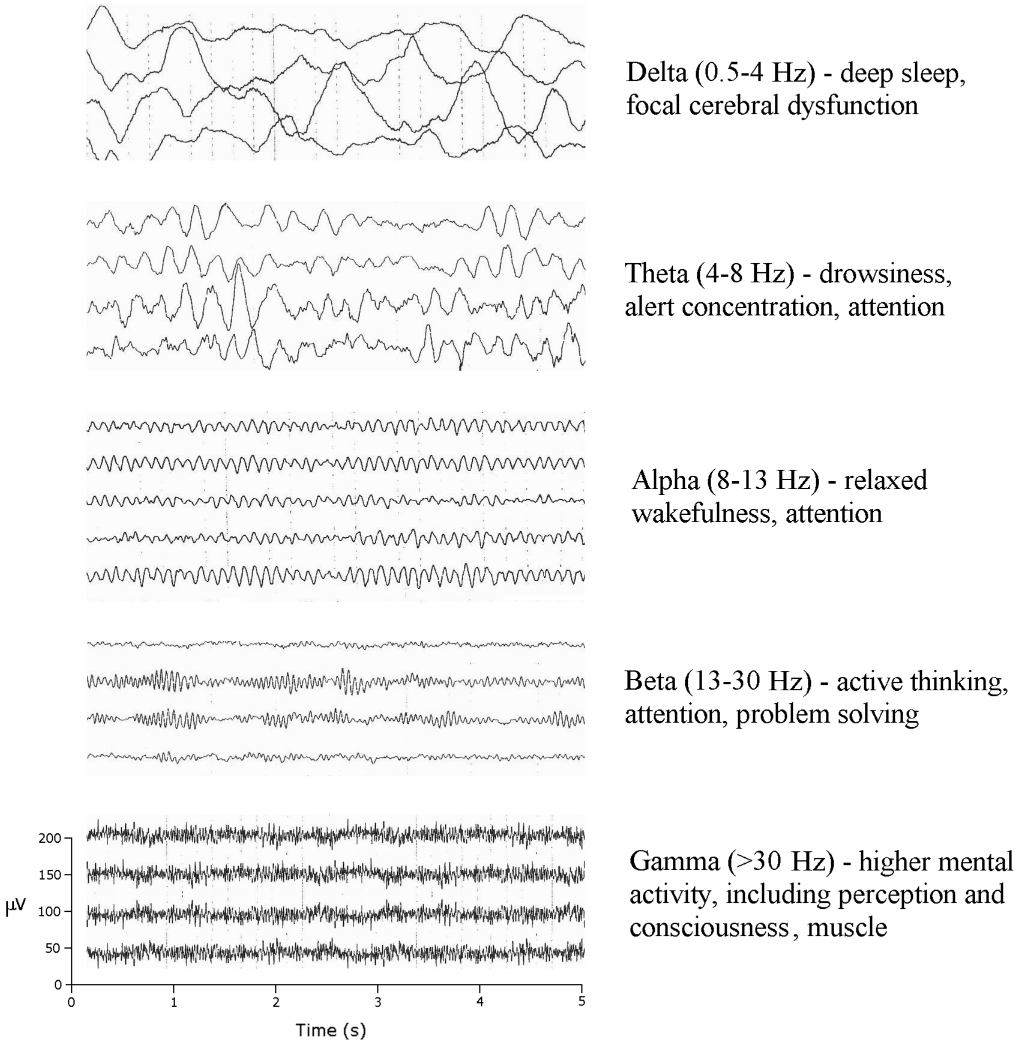


Figure 2.2: **120-electrode EEG montage based on the 10-20 reference system.** Letters on the montage refer to the following: Gnd - ground, AF - anterio-frontal, F - frontal, FC - fronto-central, FT - fronto-temporal, C - central, CP - centro-parietal, TP - temporo-parietal, P - parietal, PO - parieto-occipital, O - occipital. Odd numbers which accompany these letters are on the left hemisphere and even numbers are on the right. Adapted from http://www.easycap.de/easycap/e/electrodes/11_M15.htm.

EEG rhythms and changes in states of consciousness (alert wakefulness, sleep and sleep phases, epileptic seizures, comas) (Fell et al. 2005; Ferri et al. 2001; Jovanov 1998) (Figure 2.3).



Delta (0.5-4 Hz) - deep sleep, focal cerebral dysfunction

Theta (4-8 Hz) - drowsiness, alert concentration, attention

Alpha (8-13 Hz) - relaxed wakefulness, attention

Beta (13-30 Hz) - active thinking, attention, problem solving

Gamma (>30 Hz) - higher mental activity, including perception and consciousness, muscle

Figure 2.3: **Examples and descriptions of classic EEG frequency bands.** Delta, theta, alpha, beta and gamma EEG frequencies have been correlated to different mental states and cognitive function.

Recorded EEG can be transformed into the frequency domain using a fast Fourier transform in order to effectively view and analyse amplitude changes of frequencies in an EEG spectrum (Figure 2.4).

2.1.2.1 Delta (0.5–4 Hz)

Since its description in 1936, delta activity (0.5–4 Hz) has been reliably used to diagnose localised brain disease (Kandel et al. 2000). Generally not present

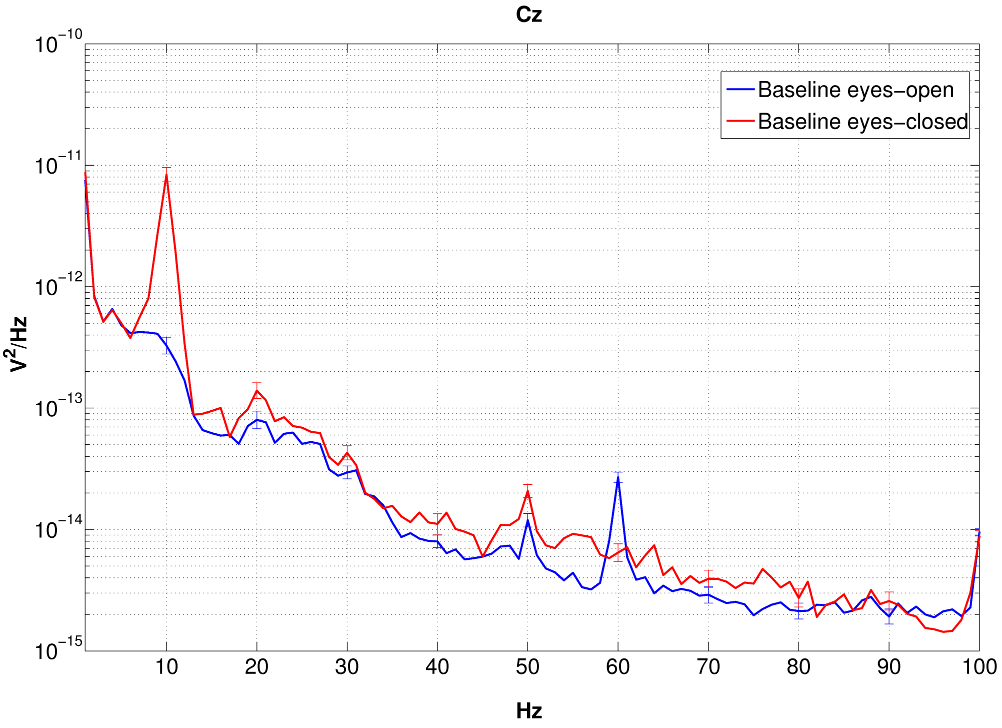


Figure 2.4: **Frequency spectra of normal EEG.** Shown here are EEG spectra from eyes-open (blue) and eyes-closed (red) conditions with log-power plotted against frequencies. Typical peaks can be seen in the delta band (0.5–4 Hz) as well as the normal significant augmentation of alpha band power (8–13 Hz) during the eyes-closed condition. Peaks at 50 Hz reflect artefact from mains DC electrical activity and the peak at 60 Hz during the eyes-open condition is a steady-state response induced by a computer monitor's refresh rate. Error bars represent the standard error of the mean.

during wakefulness, delta features during drowsiness and as an important component of sleep; its proportion, amplitude and frequency reflecting different stages of sleep (Niedermeyer & Lopes da Silva 1999). Delta occurs both diffusely in the brain (over both hemispheres) and as rhythms in the frontal region (Rowan & Tolunsky 2003). It has been proposed that delta activity results from both sequences of excitatory and inhibitory processes and intrinsic properties of cortical neurons (Barlow 1993).

2.1.2.2 Theta (4–8 Hz)

Theta denotes the frequency range between 4–8 Hz and is generally only present in small amounts in a normal waking adult. The importance of rhythmic theta has been demonstrated in infancy and childhood as well as in drowsiness and sleep (Niedermeyer & Lopes da Silva 1999). Theta is generally symmetrically distributed and is often detected in the frontal region during mental tasks (Austin 1999), reflecting the activation of attentional networks.

2.1.2.3 Alpha (8–13 Hz)

Alpha rhythms between 8–13 Hz occur during wakefulness and are accentuated by mental effort and attention (Niedermeyer & Lopes da Silva 1999). In the normal human adult EEG, rhythmic alpha activity is the principle background feature and is seen most readily posteriorly and with eyes closed (Rowan & Tolunsky 2003). However, alpha activity displays regional differences depending on what is happening, e.g., mental tasks, motor tasks, eyes closed, eyes open, etc. (Austin 1999). Although originally attributed to cortico-cortical and cortico-thalamic circuits, recent research on the topographic distribution, coherence and propagation of alpha activity has suggested that it is primarily cortical in origin (Barlow 1993).

2.1.2.4 Beta (13–25 Hz)

The beta frequency ranges from 13 to 25 Hz, although some authors include frequencies up to 30 Hz (Niedermeyer & Lopes da Silva 1999). In addition to alpha, beta is also present as background activity and is found in most normal adults

(Rowan & Tolunksy 2003). It usually increases during states of attentiveness but drops off over maintained periods of vigilance (Austin 1999). For higher frequency resolution and functional differentiation, beta can also be divided into two bands: beta1 (13–20 Hz) and beta2 (20–25 Hz) which has been done for analysis in this project.

2.1.2.5 Gamma (> 25 Hz)

Gamma activity is generally defined as frequencies oscillating above 25 Hz, and over the last fifteen years has received increasing interest (Niedermeyer & Lopes da Silva 1999). Higher-level brain function, such as perception and consciousness, has been correlated with high frequency oscillations (above 30 Hz) generated collectively by the neocortex, the thalamic and reticular nuclei, the inferior olivary and the pyramidal cells (Llinás & Paré 1991; Gray & Singer 1989; Singer & Gray 1995). Studies reporting instrinsic oscillations of 40 Hz in multiple cortical visual columns in cats and other non-human animals have indicated that these high frequency rhythms are depressed during anaesthesia and sleep (Fell et al. 2005; Ferri et al. 2001).

Electromyography (EMG or muscle electrical activity) affecting brain rhythms is normally characterised as high frequency activity originating from muscles in and surrounding the face, jaw, neck, tongue or by swallowing, coughing, yawning, etc. As a consequence, distinguishing between brain gamma and muscle gamma can be problematic (Rowan & Tolunsky 2003) and requires sophisticated signal processing techniques like Indepedent Component Analysis (ICA) or Principal Component Analysis (PCA).

In a study by Whitham et al. (2007) comparing scalp EEG recordings in the absence and presence of complete neuromuscular blockade, 6– to 100–fold differences in the power of frequencies above 25 Hz during paralysis were found (or as the authors state, “84% of the power in the EEG signal is derived from electrical activity which is abolished by paralysis, i.e., EMG”). For this reason, any high-frequency activity should probably be regarded as EMG. Figures 2.5 and

2.6 show EEG frequency spectra demonstrating diminished EEG power during a paralysis condition reflecting the removal of contributions by muscle activation (EMG).

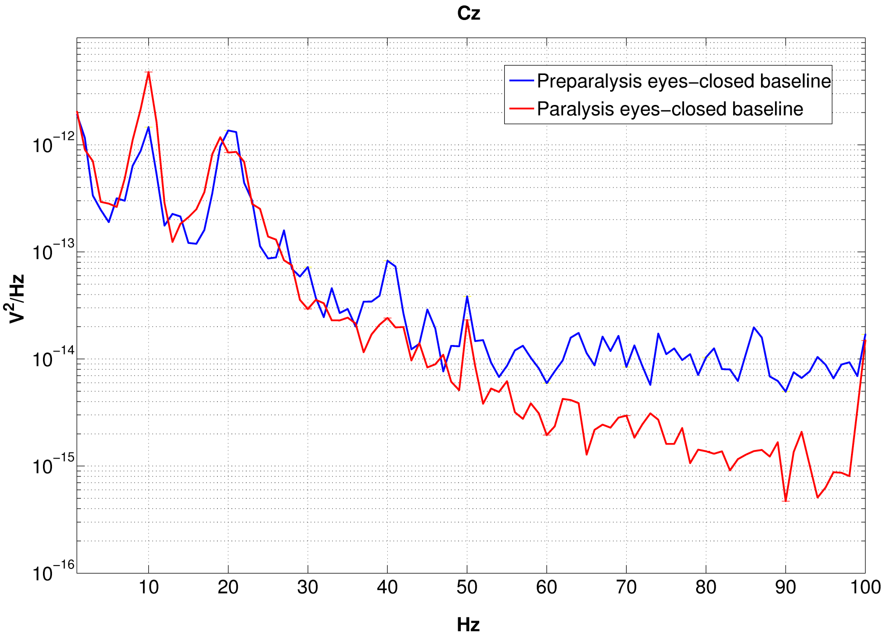


Figure 2.5: **EEG frequency spectra** of a pre-paralysis eyes-closed baseline (blue) and paralysis eyes-closed baseline (red) at electrode Cz. Diminished EEG power above 50 Hz during the paralysis condition reflects the removal of contributions by muscle activation (EMG).

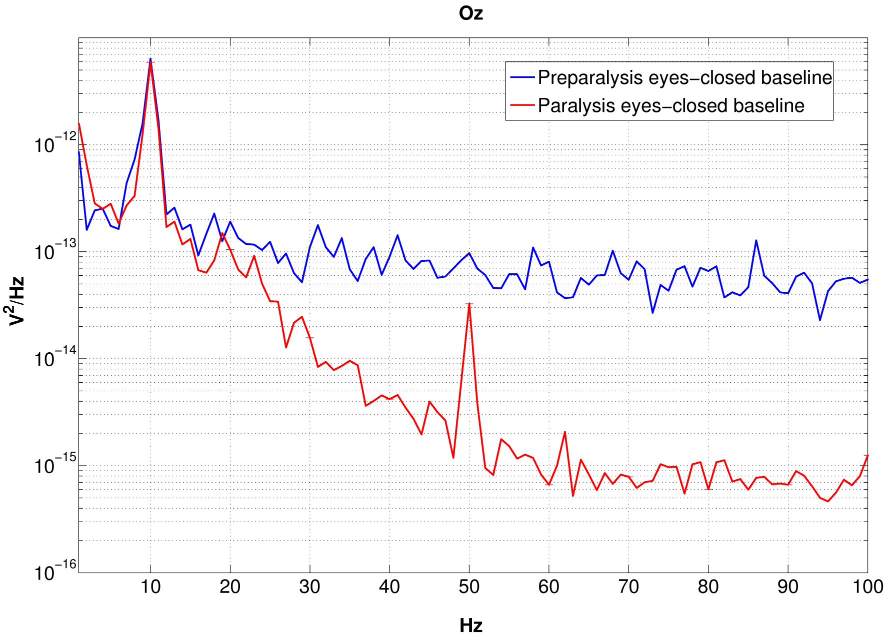


Figure 2.6: **EEG frequency spectra** of a pre-paralysis eyes-closed baseline (blue) and paralysis eyes-closed baseline (red) at electrode Oz. Diminished EEG power above 20 Hz during the paralysis condition reflects the removal of contributions by muscle activation (EMG).

High frequency oscillations The unification of diverse sensory inputs into a cohesive perception is hypothesised to require the rapid communication between discrete neuronal sub-populations, commonly referred to as *cognitive binding*, the mechanism of which, has been proposed as *temporal coherence* (Singer & Gray 1995). A theory of *whole-brain-work* described by Erol Basar "assumes that functions of the brain, especially those in cognitive processing, are based on EEG and field potentials, shortly, the oscillatory activity" (Basar 2006). Such coherence occurs via 40 Hz rhythmic oscillators of the thalamic nuclei which interact with cortical structures and is seen as a necessity for the emergence of consciousness. Different states of consciousness can occur via an reorganisation of these oscillators, such as an uncoupling of cortical rhythms or "cognitive unbinding" (Tononi 2004). These temporal correlations and oscillatory couplings occur at different organisational levels, from the cellular to the global (Niedermeyer & Lopes da Silva 1999).

2.1.3 Evoked and event-related potentials

An evoked potential (EP) is the direct time-locked response of the brain to (often repeated) short external stimuli such as light flashes, tones, finger pressure or mild electric shocks. From this triggered electrical activity, an EP waveform can be obtained by time averaging up to several thousand scalp responses (single-stimulus waveforms) (Nunez & Srinivasan 2006). Brainstem potentials reflect initial sensory processing within the first 10 ms of the onset of a stimulus, while middle latency potentials reflect initial cortical processing occuring between 10 and 50 ms (Luck 2005). Longer latency potentials are referred to as P1, N1, P2 and N2[1] components (Figure 2.7) which reflect primary cortical activation and can be influenced by attention (Picton & Hillyard 1974).

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[1] The letters here indicate whether the deflection is positive-going (P) or negative-going (N) and the numbers indicate the order in which the component peaks occur.

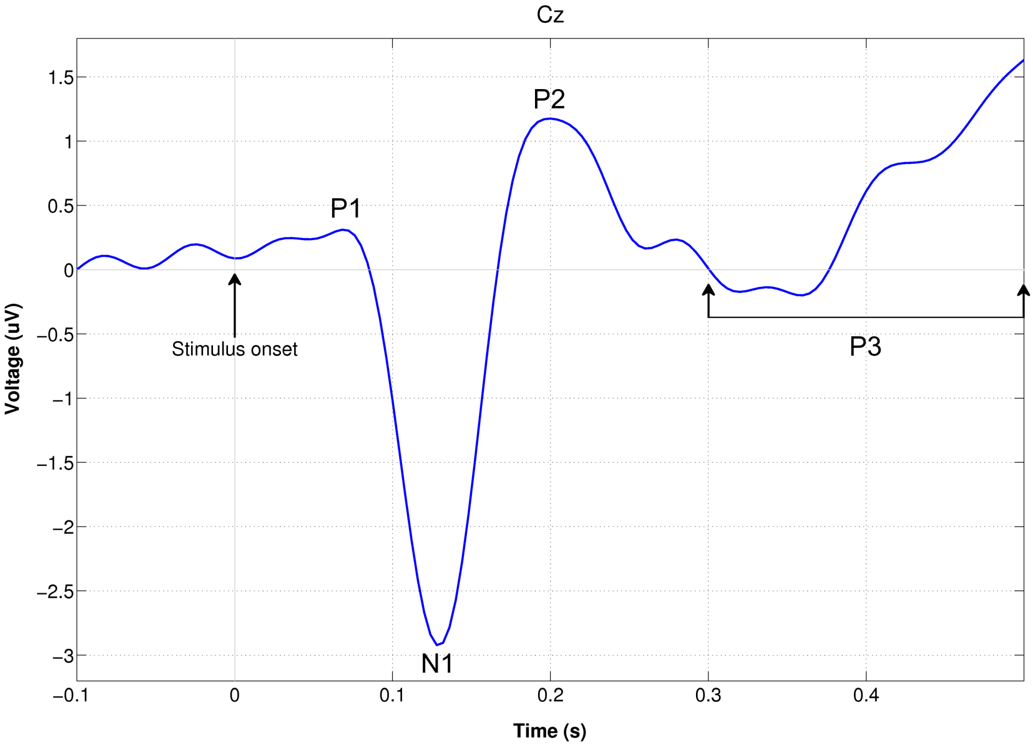

Figure 2.7: **Event-related potential example.** This ERP example shows the P1, N1, P2 and P3 components. P3 in this thesis is the mean voltage measure from 300–500 ms. Positive is plotted upward.

An event-related potential (ERP) (Figure 2.7) is recorded in the same way as an EP but depends additionally on state-dependent brain processing of the stimulus (Nunez & Srinivasan 2006). This activity is generally recorded at longer latencies from the stimulus due to multiple feedback interactions required for conscious mentation, such as target recognition in an oddball paradigm (Nunez & Srinivasan 2006). This activity is expressed in what is called the P3 or P300 component, which is the third positive-going deflection occurring over midline electrodes around 300–500 ms (Figure 2.7). A distinction has also been made between two subcomponents of the P3: the P3a and the P3b, which in the past has been related to attention and memory processing, respectively (Polich 2003, 2007). However, a three-stimulus (target, non-target and distractor) paradigm is required to differentiate the P3a from the P3b, compared to an oddball paradigm which elicits the P300 only (Polich 2007).

EPs are considered the sensory subset (commonly visual, auditory and somatosensory) of event-related potentials (ERPs, see below) and are often below the noise level and require signal averaging to improve the signal-to-noise ratio

(Malmivuo & Plonsey 1995). Both EPs and ERPs are defined in the time domain and consist of characteristic peaks, of which “the amplitude and latency from the stimulus or covariance (in the case of multiple electrode sites)” may be studied in connection with a cognitive task (ERPs) or with no task (EPs) (Nunez & Srinivasan 2006).

Review of the literature

2.2 Neuroelectrical studies in meditation

As mentioned previously (§1.1.1), evidence from experiments lacking suitable control groups are difficult to interpret. With the exception of specific studies of interest (for example, gamma findings or remarkable temperature changes), this review will only consider those studies that include appropriate control groups, i.e., non-meditators in a comparable treatment to meditators.

2.2.1 Continuous EEG

Zen in the Art of Electroencephalography[2] One of the earliest studies on EEG and meditative correlates was performed in Japan on practitioners of Zen meditation using only four electrodes, each positioned along the midline over a different region of the brain - frontal, central, parietal and occipital (Kasamatsu & Hirai 1966). One study found reduced EEG power during meditation which was correlated to subjective reports of decreased mental activity (less discursive thought). Also reported were 1) the appearance of alpha, 2) increases in alpha amplitude, 3) decreases in alpha frequency and 4) the appearance of rhythmical theta trains which were defined as four “stages” of EEG changes. Kasamatsu and Hirai (1966) were the first to describe a relationship between EEG changes and the training durations of the practitioners (that is, meditation experience) which has since been reported elsewhere, not only in other studies on Zen meditation

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[2] With apologies to Eugen Herrigel and his 1948 book *Zen in the Art of Archery,* and Robert M. Pirsig and his well-known *Zen and the Art of Motorcycle Maintenance* (1974).

(Murata et al. 1994), but also other meditative techniques using EEG (Carter et al. 2005; Lutz et al. 2004) and fMRI (Brefczynski-Lewis et al. 2007).

A study by Hardt (1994) revealed how EEG amplitude (from 8 electrode sites: O1, O2, T3, T4, F3, F4, C3 and C4) and coherence (4 channel pairs) corresponded to proficiency in Zen meditation (as rated by a Zen master). Beginners demonstrated low-amplitude alpha EEG and low coherence (both at O1 and O2) whereas intermediates displayed increasing alpha EEG amplitudes, with anterior spreading and frequency slowing. Developing coherence was also found in intermediate meditators which spread anteriorly. Advanced Zen meditators demonstrated high-amplitude alpha EEG (100 µV) which slowed in frequency (down to theta) and spread anteriorly to frontal sites. Alpha coherence was also found during meditation of advanced practitioners in the following electrode pairs: F3:O1, F3:T3, F4:T4, F3:F4.

The changes in EEG activity during meditation reported by Kasamatsu and Hirai (1966) have since been replicated, such that the following findings are commonly described:

- Increases in alpha amplitude, predominantly in the occipital region (Anand et al. 1961; Banquet 1973; Corby et al. 1978; Delmonte 1984; Hardt 1994; Kasamatsu & Hirai 1966; Murata et al. 1994);
- Slowing of alpha activity, often spreading anteriorly, with distribution predominantly in the parietal or central regions (Banquet 1973; Davidson 1976; Lehrer et al. 1980; Kasamatsu & Hirai 1966; Murata et al. 1994);
- Appearance of theta activity, often frontally and following the increase in alpha (Aftanas & Golocheikine 2001; Corby et al. 1978; Murata et al. 1994). This activity can often occur as strong bursts of frontally dominant rhythms (Banquet 1973; Fenwick 1977; Kasamatsu & Hirai 1966; West 1980);
- Bursts of high frequency beta during deep meditation (Banquet 1973; Fenwick et al. 1977; Kasamatsu & Hirai 1966).

Aftanas and Golocheikine (2001; 2002; 2003) reported increases in theta and alpha power (fronto-central) and increased theta coherence in EEG studies comparing novice and expert Sahaja yoga practitioners. Other studies have also found differences in alpha and theta power in response to meditative training (Corby 1978; Travis 1991; Travis et al. 2000). Evidence of meditation trait effects has also been reported recently in an fMRI study (Brefczynski-Lewis et al. 2007).

Delta

Slow-wave delta activity is representative of drowsy and sleep states (Niedermeyer & Lopes da Silva 1999) and has been reported in meditators in a handful of studies, particularly during the practise of TM meditation. Pagano et al. (1976) found five experienced practitioners of TM spent 19, 23 and 17 percent of meditation sessions in sleep stages 1, 2 and 3/4, respectively. When using conventional designations of sleep stages, that is, stage 1 as drowsiness and stage 2, 3 and 4 as sleep, TM subjects were considered asleep for 40 percent of their meditation time. In fact, when analysing the time spent in sleep stages 2, 3 and 4, Pagano et al. reported no difference between the subjects' meditation and nap sessions. Another two studies have also reported sleep activity in TM meditators. Younger et al. (1975) found that advanced TM meditators spent 41 percent of their meditation in sleep stages 1 and 2, and Banquet (1973) reported large amplitude sleep stage 4 delta waves during TM meditation, although did not discuss sleep in his analysis.

Tebecis (1976) comments that the "physiological effects of TM are far more variable than previously publicised" and that "EEG changes during TM were rarely as pronounced or consistent as previous reports suggest" (Tebecis 1975). Tebecis reported considerable variation in EEG between subjects practising TM, with some subjects displaying no EEG changes at all compared to a non-meditative condition. Overall, no consistent significant differences were found between meditation and non-meditation (Tebecis 1975). Also reported were increases in slow, large-amplitude, "rolling" eye movements during TM meditation, as well as during non-meditation, and it was concluded that the "main changes in eye movements during TM are similar to those during passive hypnosis" (Tebecis 1976).

In a comparison between concentration meditation, mindfulness meditation and relaxation, Dunn et al. (1999) found higher mean amplitude of delta activity (anteriorly and centrally) during a relaxation condition compared to concentration and mindfulness meditation. This result probably indicates that subjects had more trouble maintaining an alert state during the relaxation condition compared to the meditation conditions, although this was not discussed by the authors. When compared to concentration, mindfulness resulted in greater delta activity in specific global sites (electrodes F7, F8, P3, P4, Pz, T5 and O1). These findings may be suggestive of the levels of arousal or alertness required for these mental conditions. In other words, an OBAMA requires a very vigilant mental state to monitor for deviations in attention as well as levels of drowsiness and hyperarousal. While a NOBAMA does not require the degree of focus necessary for single-pointed concentration, it still requires vigilance of thought processes. Therefore it might be expected that both meditation techniques would demonstrate greater levels of arousal than someone who is simply relaxing.

Theta

Increased theta activity generated by the attentional networks of the anterior frontal lobes reflect the activation of the medial prefrontal cortex and anterior cingulate cortex (Aftanas & Golocheikine 2003). These changes are thought to be indicative of the recruitment of theta oscillating networks in memory and focused attention.

After recording EEG from meditators during a meditative state of positive emotion or bliss, Aftanas and Golocheikine (2001) reported increased long-distant theta connectivity between the prefrontal (especially lateralised to the left frontal region) and posterior association cortex regions, indicated by increased EEG coherence changes between these two regions. Such coherence changes are generally considered as an indicator of information flow along local and/or distant cortico-cortical projections.

Surprisingly, Dunn et al. (1999) reported more mean theta amplitude during relaxation when compared to both concentration and mindfulness. This result conflicts with recent studies demonstrating increased theta power (frontal midline) during a concentrative form of meditation (Aftanas & Golocheikine 2001, 2003). The discrepancy may be accounted for by method of meditation and level of experience (Dunn et al.'s 16 week course of both concentration and mindfulness vs. Sahaja Yoga practitioners with 0.5-7 years practise). Dunn et al. (1999) also found greater frontal theta during mindfulness compared to concentration.

A study on Ananda Marga Yoga revealed relatively constant "non-descending alpha-theta"[3] in meditators during meditation and increased levels after meditation compared to non-meditators (Elson et al. 1977). Ananda Marga Yoga meditation is similar to TM in that practitioners mentally repeat a meaningful word (mantra) which eventuates in "mental withdrawal and concentration" (Elson et al. 1977). It is also reported that practitioners of Ananda Yoga usually begin by focusing on the breath in order to achieve this withdrawal from external orientation and then move to the mantra meditation (Cahn & Polich 2006).

Frontal midline theta Frontal midline (Fm) theta, recorded from central anterio-frontal (AFz, Fz and FCz) electrodes, is often distinguished from general theta activity. Fm theta has been found to appear during concentrative performance of mental tasks or meditative concentration in normal subjects, representing focused attentional processing (Aftanas & Golocheikine 2001). This activity has also been correlated to changes in autonomic activity during "attention demanding meditation" (Kubota et al. 2001). Kubota et al. (2001) found this distinct theta activity (frontal midline) to reflect mental concentration and a non-anxious meditative state and suggested the attentional network in anterior frontal lobes including anterior cingulate cortex as the generator of this activity.

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[3] The authors' (Elson et al. 1977) term here refers to the transitional stage between wake and sleep, also called stage 1 sleep, characterised in their study by $> 50\%$ alpha or predominant theta on slow-wave background which *does not* lead to stage 2 sleep within five minutes or less, as opposed to "descending alpha-theta" which *does* lead to sleep within five minutes or less. They also define "full arousal" as low-voltage random fast-beta EEG and "unambiguous sleep" as stage 2 sleep, characterised by spindles and K-complexes.

Frontal theta band activity was also negatively correlated with sympathetic activation suggesting “a close relationship between cardiac autonomic function and activity of medial frontal neural circuitry” (Kubota et al. 2001).

A high-resolution EEG and MEG study by Asada et al. (1999) suggests the Fm theta activity is generated by the attentional networks of the medial prefrontal cortex and the anterior cingulate cortex (ACC) which are activated during mental tasks.

Theta bursts Reports of short theta bursts (up to 100 μV) have occurred during TM meditation (Banquet 1973; Banquet & Sailhan 1974). In a study of 78 TM meditators, Herbert and Lehmann (1977) found theta bursts with a minimum amplitude of 100 μV over one second long in 26% of meditators. The maximal amplitude of the theta bursts was 135 μV and lasted about 1.8 seconds. The authors also found ten percent of practitioners demonstrating drowsiness EEG patterns, one of which displayed theta bursts. No changes in heart rate, phasic skin resistance or muscle activity were associated with such theta bursts. However, ten subjects exhibited theta bursts during pre-sleep relaxation periods (six of whom had the same bursts in stage 1 sleep) (Herbert & Lehmann 1977).

Alpha

A change in alpha activity, whether in amplitude or frequency, has been one of the most commonly reported changes during meditation.

The general consensus on alpha appears to be as follows:

- Increases in alpha amplitude, predominantly in the occipital region (Anand et al. 1961; Banquet 1973; Corby et al. 1978; Delmonte 1984; Hardt 1994; Kasamatsu & Hirai 1966; Murata et al. 1994);

- Slowing of alpha frequency, often spreading anteriorly, with distribution predominantly in the parietal or central regions (Banquet 1973; Davidson 1976; Lehrer 1980; Kasamatsu & Hirai 1966; Murata et al. 1994); and

- Persistence of alpha activity after meditation, even with eyes open (West 1980).

Dunn et al. (1999) found higher amplitude alpha posteriorly during concentration compared to the relaxation condition, however the mindfulness condition produced more mean alpha amplitude centrally and posteriorly than either concentration or relaxation.

Changes in alpha activity over the course of Zen meditation were revealed by Murata et al. (1994) in novice and experienced Zen meditators in the following order: 1) alpha appeared predominantly in parietal and occipital regions; 2) the frequency of alpha decreased; and 3) slow wave alpha appeared predominantly in the frontal region. It is interesting to note that these Soto Zen subjects meditated with their eyes open, a fact that did not prevent the increase of alpha activity after the onset of meditation.

Alpha-blocking and habituation Alpha-blocking (also referred to as alpha suppression) is a phenomenon which occurs when a subject's continuous alpha activity is disrupted by an external stimulus (normally an auditory click or tone, but it can be visual or somatosensory) and changes from regular 8–13 Hz rhythms to low-voltage fast frequencies (Anand et al. 1961). Generally, when presented with auditory clicks or tones, a healthy resting subject will exhibit alpha-blocking for a second or two before their alpha activity returns to baseline. This phenomenon can continue for up to 25 times (Becker & Shapiro 1981) before one's alpha activity is no longer disturbed by the stimuli, hence becoming *habituated.*

Anand et al. (1961) found no alpha blocking in meditators practising Raj Yoga during the exposure to external stimuli, that is, photic (strong light), auditory (loud banging noise), thermal (touching with hot glass tube) and vibration (tuning fork). In addition, during the non-meditation condition, the same subjects demonstrated blocked alpha activity which changed to low voltage fast activity. Surprisingly, in the same experiment, two Raj Yoga meditators also did not exhibit alpha suppression during the submersion of their hands in 4°C cold water (during which they subjectively felt no discomfort or pain). During Raj Yoga, attention is withdrawn from the external environment and focused inward (on a mantra) (Becker & Shapiro 1981) to a such degree that during a highly concentrative state of meditation called *samādhi,* practitioners claim they are oblivious to external and internal environmental stimuli. Practising Raj Yoga is also said to induce a "state of ecstasy" (Anand et al. 1961).

Kasamatsu and Hirai (1966) found that Zen monks exposed to auditory click stimuli did not habituate. However, in a study comparing the responses to click stimuli in five groups (Zen, TM and Raj Yoga meditators and "attending" and "ignoring" groups), all groups exhibited initial alpha suppression and similar skin conductance responses (see §2.3.4) and all groups habituated at similar rates (Becker & Shapiro 1981). These results were interpreted as aspects of a generalised orientating response, rather than an attentional component, as no differences in their two orientating response measures (viz. alpha suppression and skin conductance level) were found between groups who were instructed to attend to the stimuli and groups who were instructed to ignore them. It is very likely that the differences in results for Zen meditators may be attributed to the level of experience of the subjects meditating. Kasamatsu and Hirai (1966) studied 48 meditators with between 1 and 20+ years experience (16 of whom had over 20 years experience), compared to 10 Zen subjects in Becker and Shapiro's (1981) study who averaged 7.5 years experience (Raj Yoga and TM subjects had averages of five and seven years meditation experience, respectively). This possibility is further substantiated by other studies finding a positive correlation between the subjects' proficiency in Zen training and the degree of EEG changes reported during Zen meditation (Hardt 1994; Kasamatsu & Hirai 1966), a finding not replicated in Becker and Shapiro's study.

These results are directly related to the technique of meditation practised and what mental processes are involved. For example, in the study on yogis exposed to sub-noxious stimuli (Anand et al. 1961), the level of concentration was likely to have been so intense that all external events were precluded. The Raj Yoga technique does not employ the faculty of meta-awareness that enables one to be conscious of external environmental occurrences. On the other hand, Zen meditators who develop a mindful, open awareness are able to hear each tone distinctly as if each tone was presented for the first time.

Beta

Similar to changes in alpha, Dunn et al. (1999) found higher amplitudes in the lower beta frequency band (13–25 Hz) in a comparison between concentration meditation and relaxation, and higher amplitudes of beta during the mindfulness meditation compared to concentration and relaxation. However, in the higher beta frequency band (26–32 Hz), results were more variable, with relaxation producing greater amplitudes than both meditations frontally and centrally, and both meditations producing greater amplitudes posteriorly. In comparing concentration and mindfulness, concentration produced more beta at electrodes Fp2, O1, and O2 and mindfulness produced more beta at sites Fp1, F3, F4, T4, and T5. These variable results may be explained by possible contamination from muscle activity, which is readily generated by the neck and face in frequencies above 20 Hz (Whitham et al. 2007).

Gamma

Only a handful of studies have identified gamma activity during the practice of meditation. Even though most of these studies did not employ suitable control groups (viz. non-meditators), they will be discussed here due to the limited number of reports and their frequent citations.

In a case study of an experienced meditator, low resolution brain electromagnetic tomography (LORETA) was used to investigate four meditation techniques - visualisation, internal mantra recitation, self-dissolution and self-reconstruction (Lehmann et al. 2001). During the experiment, the aforementioned meditative practices were repeated, however, no resting conditions were included. During visualisation gamma power increased in the right posterior occipital regions and during verbalisation (mantra recitation), gamma power increased in left centro-temporal regions. During self-dissolution, increased gamma activity was found in the right superior frontal gyrus, an area linked with experiences of agency and self-awareness (Cahn & Polich 2006). In light of the paralysis study mentioned above (Whitham et al. 2007), it is difficult to determine what these changes might mean. For example, internal verbalisation could feasibly activate muscle groups involved in speech (especially around the jaw) which may significantly contribute to EMG recorded from scalp electrodes.

In a study by Aftanas and Golocheikine (2005) investigating trait effects, long-term Sahaja Yoga meditators demonstrated a lack of frontal gamma power increases, compared to controls, when viewing emotionally aversive movie clips. The authors' interpretation of gamma changes during meditation as being due to less reactivity and greater emotional stability is probably accurate, but perhaps not for the right reasons. The lack of gamma in meditators is likely due to a more relaxed state and therefore less muscle activation during a stressful event. There is some discrepancy in the literature between reports on Sahaja Yoga, possibly due to its recent establishment (less than 40 years ago). Studies on this meditation technique claim it involves mental states of internalised attention and emotionally positive experience of bliss (Aftanas & Golocheikine 2001, 2002, 2003). However, a review by Cahn and Polich (2006) described Sahaja Yoga as emphasising the observance of thoughts instead of becoming caught up in them. This description indicated that the technique involves more mindfulness than concentration. Although it is likely that Sahaja Yoga incorporates a combination of concentration and mindfulness, it has not been thoroughly described by either those researching the technique or those reviewing the research. Sahaja Yoga seems to primarily involve focus on the breath and the alleged energy channels in the body in order to experience states of thoughtless awareness and spontaneous insight.

A recent and now commonly-cited study by Lutz et al. (2004) investigated long-term Buddhist practitioners and the relationship of high-amplitude gamma oscillations and phase-synchrony to *compassion* meditation. The authors found large increases in 40 Hz gamma power during meditation, compared to resting.

They also found different synchrony patterns between expert and novice meditators, implying changes in both state and trait effects in the gamma band (Cahn & Polich 2006). These high frequency findings require serious re-evaluation in light of the recent study which demonstrated a significant (6– to 100–fold) difference in the power of EEG frequencies above 25 Hz between a paralysed and unparalysed conscious state (Whitham et al. 2007). This discovery makes obvious that much of the EEG activity above 25 Hz recorded from the scalp is of EMG origin. In light of the striking similarities between topographic maps showing scalp distribution of gamma activity (25–42 Hz) during meditation (Figure 2.8) (Lutz et al. 2004) and an eyes-closed baseline preceding paralysis (Whitham et al. 2008), the reason for Lutz and colleagues' increases in high frequency activity becomes reasonably obvious.

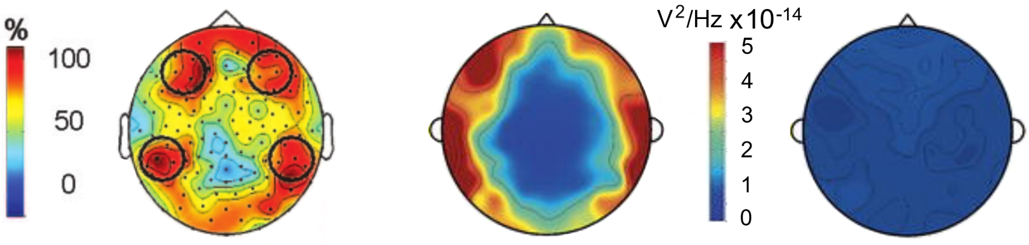

Figure 2.8: **EEG topographic maps.** The map on the left shows scalp distribution of gamma EEG activity during meditation, expressed as a percentage of meditators that had an increase of gamma activity (Lutz et al. 2004). The centre map shows a pre-paralysis baseline for gamma activity between 30 and 100 Hz, and the map on the right shows post-paralysis baseline (Whitham et al. 2008).

The compassion meditation studied was described as an "unrestricted readiness and availability to help living beings" (Lutz et al. 2004). Meditators practising compassion are instructed to begin by cultivating a sense of empathy and "readiness to help" for those individuals whom are emotionally closest, such as family and friends. By beginning with people for whom the meditator already feels these sentiments, it becomes less challenging to then extend these existing feelings toward those who are unfamiliar and with whom the practitioner has emotional difficulties with. This feeling of readiness, or preparedness, conceivably triggers specific muscle activation as an expression of the subject's intention to actively help another being, contributing to high-frequency activity in the form of EMG. The salience of this possibility is supported by the finding that even fictive finger movements generate activity in ipsilateral muscles (Whitham et al. 2007). One might sensibly deduce that if this particular fictive activation of EMG is “related to the expression of preparedness for primitive states of fight or flight” (Whitham et al. 2007), then this activation is also likely to manifest in the event of a disadvantaged or distressed conspecific, which evolutionarily speaking would be of primary concern to a community. Lastly, Lutz et al.’s observation that the gamma activity was high in amplitude supports the influence of EMG in their EEG recordings as EMG is ordinarily high in amplitude compared to brain gamma, which is low in amplitude and requires signal processing to extract. Although muscle activation as a cause for the gamma increases was carefully considered by Lutz and his colleagues, the degree to which EMG can contaminate EEG may have been underestimated. Due to the frequency to which this research finds itself cited, the significance of high frequency brain oscillations during meditation requires thoughtful reappraisal.

2.2.1.1 Hemispheric laterality

In 1979, Jon Kabat-Zinn began teaching Mindfulness-Based Stress Reduction (MBSR), a technique involving a combination of Vipassana-derived mindfulness meditation and Hatha Yoga.[4] The technique is designed to help patients cope with stress, pain and illness by using moment-to-moment awareness (mindfulness) and has become very popular in mainstream medicine and society. In a study on MBSR, Davidson et al. (2003) found increased left-sided activation using fMRI (prefrontal and central locations), previously associated with reductions in anxiety and negative affect, and increases in positive affect. These asymmetries were found to be a function of meditation proficiency, suggesting the plasticity of this area in response to meditation training. Left-sided activation in response to positive affect induction along with other evidence leads to Davidson et al.’s (2003) suggestion that “left-side anterior activation is associated with adaptive

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[4] Hatha Yoga involves moral disciplines, physical exercises (relaxation, postures and breath control) and meditation.

responding to negative and/or stressful events."

In two studies, Aftanas and Golocheikine (2001, 2003) found greater EEG theta power in the left prefrontal cortex which correlated to internalised focus and positive states of emotion. Theta coherence was also found to be most pronounced in the left frontal cortex.

Another hemispheric laterality study by Bennet and Trinder (1977) found no asymmetry of alpha activity in either TM meditation or relaxation, exercises which the authors suggested required neither analytical nor spacial processing.

2.2.1.2 EEG coherence

Recent studies on meditation have investigated EEG coherence, spectral power and EEG frequency bands. The investigation of specific narrow frequency bands has revealed that theta and alpha oscillations reflect the "activity of multifunctional neuronal networks, differentially associated with orientating, attention, memory, affective and cognitive processing" (Aftanas & Golocheikine 2001).

In a study which recorded high-resolution EEG from subjects practising Sahaja Yoga meditation (Aftanas & Golocheikine 2001), spectral power and coherence estimates were analysed in individually defined narrow EEG frequency bands, which were then "used to identify and characterise brain regions involved in meditative states." Subjective scores of positive emotional experience positively correlated with theta power and increased anterior frontal and midline theta synchronisation, whereas "thought appearance rates" negatively correlated with theta power. The study revealed differences in theta coherence between short-term meditators (STM) and long-term meditators (LTM), with LTM demonstrating "increased synchronisation between prefrontal and posterior association cortex with distinct 'center of gravity' in the left prefrontal region" (Aftanas & Golocheikine 2001). Theta power increases in long-term meditators included both general theta and Fm theta processes, reflecting oscillating networks involved in attention, memory and positive emotional experience mechanisms. The lack of Fm theta power increases in STM was suggested to have been a result of hyper-arousal, anxiety and frustration in respect to their meditation proficiency (Inanaga 1998).

2.2.1.3 Non-linear dimensional complexity (DCx)

In 1949, Donald Hebb proposed a theory of how neuronal assemblies work as functional processing units and how large numbers of cell assemblies synchronously oscillate at different frequencies. Hebb's neural model considers: 1) a diffuse cell group capable of acting briefly as a single structure (Nunez & Srinvasan 2006); 2) the number of cell assemblies activated as an indicator of complexity of neuronal computations in the working brain; and 3) how the non-linear geometrical measure of dimensional complexity (DCx) can be applied to understanding the brain's overall complexity. "The dimension calculated from EEG time series has been shown to be a monotonically increasing function of the number of independent neural processes" (Aftanas & Golocheikine 2002). Therefore, this dimensional value at different times and during different tasks can be representative of the number of neural assemblies active simultaneously in the brain.

In a reanalysis of a prior study, Aftanas and Golocheikine (2002) found increases in EEG DCx over midline anterio-frontal (AFz and Fz) and centro-frontal (FCz and Cz) regions during meditation. These DCx estimates were also found to be negatively correlated to computed linear measures of power in theta-2 (6–8 Hz) and alpha-1 (8–10 Hz) and positively with beta-3 (22–30 Hz) bands. As DCx represents the number of synchronously oscillating cell assemblies, decreases in dimensional complexity may reflect the deactivation of "irrelevant networks for the maintenance of focused internalised attention and inhibition of inappropriate [distracting] information" (Aftanas & Golocheikine 2002).

2.2.2 Evoked potentials and event-related potentials

Studies examining changes in sensory evoked potential (EP) and cognitive event-related potential (ERP) recordings have found that different meditation practices influence sensory processing (Barwood et al. 1978; Liu et al. 1990; McEvoy et al.

1980; Panjwani et al. 2000; Slagter et al. 2007; Srinivasan & Baijal 2007; Telles et al. 1994; Zhang et al. 1993) and attentional resource allocation (Banquet & Lesèvre 1980; Cahn & Polich 2008; Cranson et al. 1990; Goddard 1989, 1992; Lutz et al. 2008).

Banquet and Lesèvre (1980) found larger P2 amplitudes in meditators before and after meditation, relative to controls in a visual go/no-go task. Meditators were also more accurate and faster to respond before and after meditation compared to controls. Additionally, P3 amplitude increased in meditators after meditation and decreased in controls after rest. These findings were suggested to indicate that meditation affects sensory processing and attentional resource allocation.

Slagter et al. (2007) recently investigated the effect of meditation on the brain's ability to process two temporally close meaningful items using an attention-blink task and scalp recorded brain potentials. They found that three months of intensive mental training (meditation) resulted in "a smaller attentional blink and reduced brain-resource allocation to the first target, as reflected by a smaller T1[target 1]-elicited P3b", relative to controls. There was also an important positive correlation between the decrease in the P3b and the reduction in attentional blink. The changes in brain potentials were significant over the dorsal posterior electrode sites (around Pz). The authors suggest that the "ability to accurately identify T2 [target 2] depends on the efficient deployment of resources to T1" and that the changes demonstrate an "increased control over the distribution of limited brain resources." The Vipassana practice studied in the experiment is supposed to reduce mental activity in the brain, allowing the meditator to remain focused on the present moment. For further discussion, see §4 and Cahn and Polich (2006).

2.3 Autonomic measures

In the same fashion as the review of neuroelectric studies, this subsection does not consider case studies or experiments where meditators acted as their own control, that is, the study did not include a non-meditator control group. Table 2.1 lists a number of controlled studies on the effects of meditation on autonomic function. Included in the table is information about the type of meditation, population size, meditation experience, experimental design, measurements and findings.

2.3.1 Heart rate

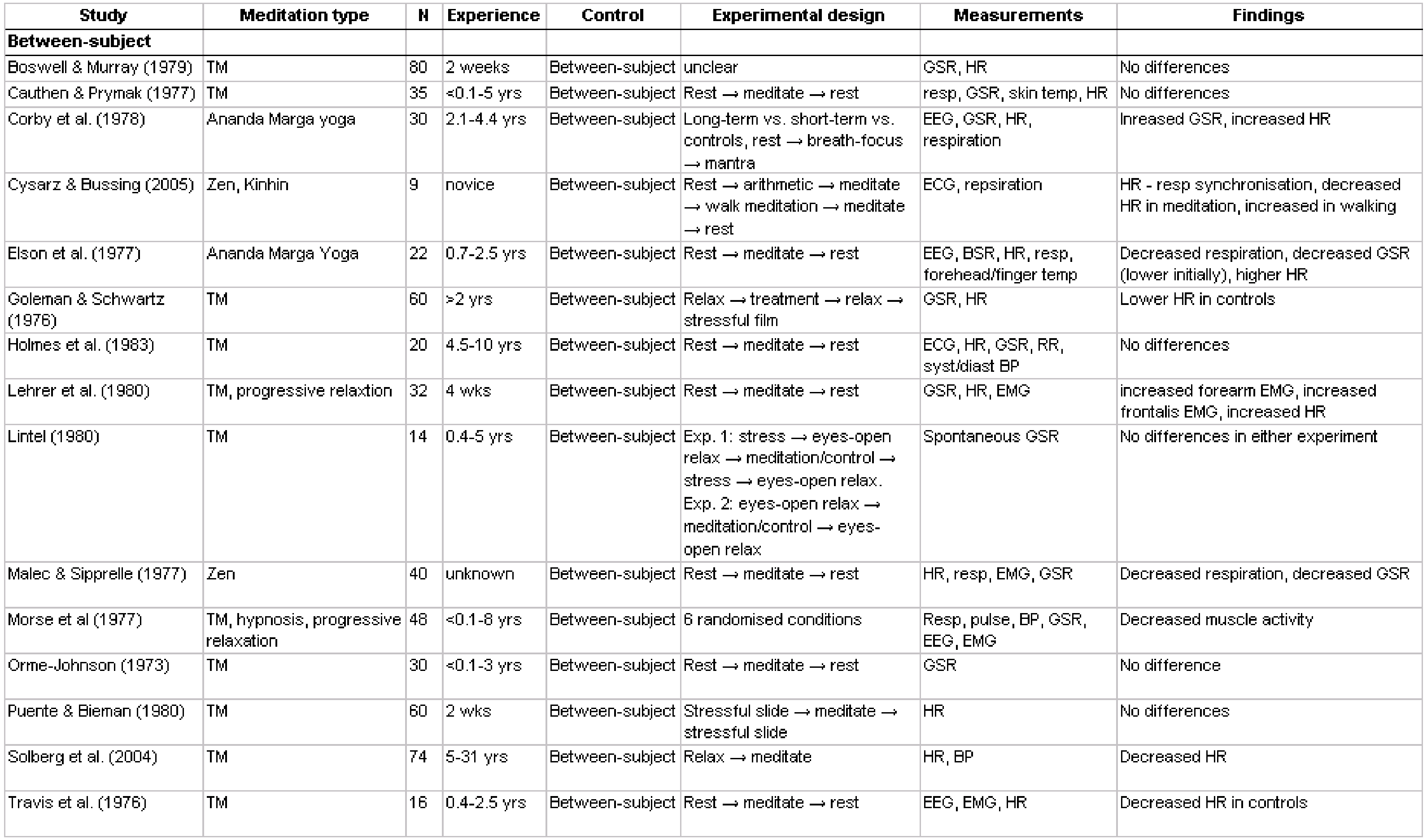
While some studies have found decreases in heart rate (Cauthen & Prymak 1977; Elson et al. 1977), others have reported increases or no change (Anand et al. 1961; Bahrke & Morgan 1978, Morse et al. 1977). A study by Holmes et al. (1983) found that although meditation was associated with reduced arousal (as measured by heart rate, skin resistance, respiration rate, systolic blood pressure and diastolic blood pressure), this reduction was not significantly greater than the reduction in resting non-meditators. Cauthen and Prymak (1977) compared three groups of TM meditators with varying experience (average seven days [novice], fourteen months [medium] and five years [experienced]) to a relaxation group and found decreases in heart rate during meditation. However, they also found decreases in heart rate after relaxation. Skin temperature increases were only found in the relaxation group and novice meditators which does not support other evidence that TM elicits a *relaxation response* that is dose sensitive.

2.3.2 Respiration

Similar inconsistent results have been reported for respiration, for example: decreases (Elson et al. 1977; Malec & Siprelle 1977) or no change (Cauthen & Prymak 1977; Cysarz & Büssing 2005; Holmes et al. 1983). See §4.2.2 for further discussion.

2.3.3 Temperature

Thermoregulation is an important ability in humans to maintain a precise temperature homeostasis (homeothermia), even over a wide range of ambient temperatures. Heat is mainly produced by muscle contractions and the skin plays



Study	Meditation type	N	Experience	Control	Experimental design	Measurements	Findings
Between-subject							
Boswell & Murray (1979)	TM	80	2 weeks	Between-subject	unclear	GSR, HR	No differences
Cauthen & Prymak (1977)	TM	35	<0.1-5 yrs	Between-subject	Rest → meditate → rest	resp, GSR, skin temp, HR	No differences
Corby et al. (1978)	Ananda Marga yoga	30	2.1-4.4 yrs	Between-subject	Long-term vs. short-term vs. controls, rest → breath-focus → mantra	EEG, GSR, HR, respiration	Inreased GSR, increased HR
Cysarz & Bussing (2005)	Zen, Kinhin	9	novice	Between-subject	Rest → arithmetic → meditate → walk meditation → meditate → rest	ECG, repsiration	HR - resp synchronisation, decreased HR in meditation, increased in walking
Elson et al. (1977)	Ananda Marga Yoga	22	0.7-2.5 yrs	Between-subject	Rest → meditate → rest	EEG, BSR, HR, resp, forehead/finger temp	Decreased respiration, decreased GSR (lower initially), higher HR
Goleman & Schwartz (1976)	TM	60	>2 yrs	Between-subject	Relax → treatment → relax → stressful film	GSR, HR	Lower HR in controls
Holmes et al. (1983)	TM	20	4.5-10 yrs	Between-subject	Rest → meditate → rest	ECG, HR, GSR, RR, syst/diast BP	No differences
Lehrer et al. (1980)	TM, progressive relaxtion	32	4 wks	Between-subject	Rest → meditate → rest	GSR, HR, EMG	increased forearm EMG, increased frontalis EMG, increased HR
Lintel (1980)	TM	14	0.4-5 yrs	Between-subject	Exp. 1: stress → eyes-open relax → meditation/control → stress → eyes-open relax. Exp. 2: eyes-open relax → meditation/control → eyes-open relax	Spontaneous GSR	No differences in either experiment
Malec & Sipprelle (1977)	Zen	40	unknown	Between-subject	Rest → meditate → rest	HR, resp, EMG, GSR	Decreased respiration, decreased GSR
Morse et al (1977)	TM, hypnosis, progressive relaxation	48	<0.1-8 yrs	Between-subject	6 randomised conditions	Resp, pulse, BP, GSR, EEG, EMG	Decreased muscle activity
Orme-Johnson (1973)	TM	30	<0.1-3 yrs	Between-subject	Rest → meditate → rest	GSR	No difference
Puente & Bieman (1980)	TM	60	2 wks	Between-subject	Stressful slide → meditate → stressful slide	HR	No differences
Solberg et al. (2004)	TM	74	5-31 yrs	Between-subject	Relax → meditate	HR, BP	Decreased HR
Travis et al. (1976)	TM	16	0.4-2.5 yrs	Between-subject	Rest → meditate → rest	EEG, EMG, HR	Decreased HR in controls

Table 2.1: **Controlled studies on autonomic activity.** This table includes information about the type of meditation, population size, meditation experience, experimental design, measurements and findings.

an important role in the maintenance of the core body temperature. The mechanisms by which the skin reacts to varying internal temperature changes and climate are primarily vasoconstriction and vasodilation[5] (Blessing 1997), which are vasomotor adjustments controlled by the autonomic nervous system (ANS) and driven by the preoptic region of the anterior hypothalamus. Activation of the sympathetic vasomotor fibres causes cutaneous blood vessels to strongly constrict, resulting in a restriction of blood to deep body areas. By bypassing the skin, which is separated from deeper organs by a layer of insulating, subcutaneous (fatty) tissue, heat loss from the extremities is dramatically reduced. Conversely, the inhibition of vasomotor fibres allows blood vessels in the skin to dilate and thus facilitating heat loss via radiation, conduction and convection. Accordingly, there is a positive relationship between an increase in cutaneous blood flow and an increase in skin temperature (Schönbaum & Lomax 1990). These thermoregulatory responses are also influenced by arousal states such as alerting and stress responses (Blessing 1997), sleep (Lack & Gradisar 2002) and sexual and emotional arousal.

The most significant study on meditation and temperature was undertaken by Benson et al. (1982) on three Tibetan Buddhist monks practising a technique called g Tum-mo Yoga. The meditation involves the visualisation and manipulation of energy called *"prāna"* (Sanskrit, literally "wind"), alleged to flow in channels throughout the body. Extensive temperature measures (navel and lumbar region, left calf, left fifth toe, finger, nipple, forehead and rectum) were taken during pre-meditation resting, meditation and post-meditation recovery periods. During meditation, subjects 1, 2 and 3 had finger temperature increases of 5.9°C, 7.2°C and 3.15°C, respectively, and toe temperature increases of 7.0°C, 4.0°C and 8.3°C, respectively. Other temperature measurements revealed increases of up to 1.9°C (navel, lumbar and nipple) during meditation. Resting heart rates of all monks were within normal limits and during the *g Tum-mo* meditation did not change significantly. The mechanism for these changes was interpreted as vasodi-

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[5] Perspiration is also an important way of attempting to lose excess heat, via the evaporation of sweat from the skin's surface.

lation, although no direct peripheral blood flow measures were made. Another study by Heller et al. (1987) recorded skin temperature (forehead, chest, forearm, hand and thigh) increases between 2 and 4°C and a body core temperature (via the rectum) decrease of 0.4°C from a single subject during yoga meditation.

2.3.4 Electrodermal activity

Also referred to in the literature as skin conductance response (SCR), psychogalvanic reflex (PGR), galvanic skin response (GSR), skin potential response (SPR), skin resistance (SR) and skin conductance (SC), the term now used in the literature to collectively denote this list of measures is electrodermal activity (viz. electrodermal response, EDR or electrodermal level, EDL) (Boucsein 1992).[6] EDR reflects a transient change in certain electrical properties of the skin, associated with the sweat gland activity and is elicited by any stimulus that evokes an arousal or orienting response. Electrodermal level (EDL) on the other hand represents a measure of the tonic background levels adjusted naturally under a range of emotional situations (Malmivuo & Plonsey 1995). Anxiety-induced perspiration leads to low skin resistance (increased conductance or electrodermal levels) and is generally thought to be a reliable indicator of stress (Boucsein 1992). As with cutaneous vasoconstriction and vasodilation, perspiration can also be driven by thermosensitive neurons in the preoptic region of the anterior hypothalamus.

While some studies have reported increases in EDR and EDL (Bagchi & Wegner 1957; Corby et al. 1978; Elson et al. 1977), others have reported decreases (Jevning et al. 1992) or no change (Cauthen & Prymak 1977). Lintel (1980) found no differences between TM meditators and non-meditators in the measurement of galvanic skin response during a treatment condition of meditation or rest/eyes-closed and in response to an electrical shock representing a stress condition. Another study investigating stress responses (Orme-Johnson 1973) measured GSR from subjects exposed to noxious loud tones. The author found

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[6] The aforementioned classic terms imply the historic methods of measurement. For example, GSR and SPR measure voltage produced at the skin surface via a bioamplifier, whereas SR and SC use an excitation voltage from a specific coupler and measure resistance expressing the output in Ohms or Siemens (the reciprocal of Ohms), respectively.

TM meditators habituated faster to the tones relative to non-meditating controls. Meditators also demonstrated less spontaneous GSR indicating greater stability in response to stress.

2.4 Cognitive measures

There are many differences in the cognitive processes between concentration meditation and mindfulness meditation and some neurophysiological studies have been able to demonstrate these differences in terms of attention and perception. For example, meditations which lay more toward the *concentration* end of the "meditation spectrum", such as Nidra Yoga, may be prone to be resistant to alpha-blocking. It is feasible that when practising these *concentrated* techniques, the process of becoming intensely focused and absorbed in an object inhibits the mind's awareness of any other stimuli. The brain is very efficient at allowing in information of interest whilst simultaneously screening out the multitudes of irrelevant stimuli (Simons & Chabris 1999). Toward the other end of the spectrum, practices such as Zen and Vipassana, which are *mindfulness* based, are resistant to alpha-blocking *habituation*, that is, each time the meditator hears a stimulus their alpha activity is blocked and this alpha-blocking continues to occur each time a stimulus is presented for the duration of the experiment. There is anecdotal evidence that during this event, meditators are in a state of "open-awareness" and "mindfulness" where each sound is heard as if for the first time. These two ideas of inhibiting awareness of other stimuli and expanding one's awareness, relate to the two faculties of *focus* and *meta-awareness*, respectively. During meditation, the qualities of focus and meta-awareness are employed in order to successfully keep one's mind with the object. However, beginners are often found to lack one or the other until both are refined and balanced. An example is a student without much meta-awareness during meditation, who begins by following the teacher's guiding voice, but soon finds themselves lost in deep meditation until they are brought out by the teacher's call, or they eventually come out by themselves. Often the students have no recollection of the teacher's voice for the entire session (apart from the beginning) or awareness of the passage of time. In such cases, it is expected that during meditation, the strength of stimuli required to draw meditators out of meditation is proportional to the depth of meditation one is in, that is, that someone in a deeper state of meditation will require a stronger stimulus to gain their attention, compared to a lighter state.[7] Although attention and perception are explicitly linked and influence each other in many ways, the following headings and sections will indicate the manner in which the appropriate research was undertaken (by measuring attentional capacities or perceptual changes) and not which cognitive function it has the most bearing upon.

2.4.1 Perception

In the 1860s, Hermann Helmholtz[8] measured electrical nerve conduction signals for the first time. When he found nerve conduction to be about 90 m/sec and a subject's conscious response to a consciously perceived stimulus was even slower, he deduced the brain was processing a great deal of information unconsciously. The inference was that "much of what goes on in the brain is not represented in consciousness, and that the perception of objects depends on 'unconscious inferences' made by the brain, based on thinking and reasoning without awareness" (Kandell 2000). This idea is now very much accepted, with evidence notably established in neuroimaging studies on emotion, where dramatic responses have been recorded in the brain (particularly the amygdala) in response to unconsciously-viewed fearful stimuli (Carlsson et al. 2004; Ohman & Soares 1993, 1994).

One method that has been used to investigate the ways in which meditation affects the brain is by exposing meditators to external stimuli such as *auditory* clicks or tones and *visual* light flashes.

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[7] This may also prove to be the case with relevant sounds, for example, in the case of calling a person's first name. The sound level at which one may respond to such relevant stimuli (for example, a personal name or familiar voice), may be lower than the level at which they respond to other, non-relevant sounds. This would be something worth investigating in future meditation research.

[8] Hermann Helmholtz (1821-1894) was a German physicist and physician turned neuroscientist who discovered and wrote on the principle of conversion of energy and invented the ophthalmoscope and the Helmholtz resonator (Kandel et al. 2000).

2.4.1.1 Auditory processes

See §2.2.1 on alpha blocking and habituation.

2.4.1.2 Visual processes

Visual sensitivity A study by Brown et al. (1984b) on the practice of Buddhist (Burmese) mindfulness meditation found that subjects who practised intensively for three months were able to "detect light flashes of shorter duration and to discriminate between two light flashes separated by a shortened interval" when compared to results before their intensive practise and other meditators who did not practise as intensively for three months (but were comparable in background and meditation experience). The Buddhist mindfulness technique used in the study begins with the subjects' *focus* on an object, commonly a sensation in the body such as the movement of breath at the nostrils or abdomen, and then progresses to the development of *meta-awareness* of other objects such as "emotions, thoughts, images, memories, perceptions, and the hedonic tone of each moment of experience" (Brown et al. 1984b). As explained in §1.2, the aim of this *mindfulness* is to become and remain aware of each type of these events from the beginning to the end, while objectively observing the *processes* by which these events enter awareness in a nonjudgmental, interpretive manner. Indeed, Brown et al. (1984b) explain that the "extension of awareness to a variety of events constitutes mindfulness." Interestingly, phenomenological reports by meditators after three months of intensive practise indicated an enhanced awareness to some of what the authors referred to as pre-attentive processes involved in visual detection, such as arousal, confidence, anxiety and thought occurrence. The results from this study lend support to meditation as a "self-control strategy" (Shapiro & Giber 1978) which allows insight into and eventual control over "reactivity and perceptual biases which underlie reactivity" (e.g., Brown et al. 1984a; Carter et al. 2005; Cysarz & Büssing 2005), considered in Buddhist philosophy as the basis of emotional suffering.

Although not a longitudinal study of the first subject groups (Brown et al.

1984b), a follow-up study revealed that when compared to non-meditators, meditators demonstrated an ability to detect light flashes of shorter duration, suggesting that this effect was the result of long-term changes in the meditators' perception (Brown et al. 1984a). However, a lack of differences in the ability of meditators and non-meditators to discriminate between successive light flashes was interpreted as a "plateau" of perceptual improvement in the subjects (who were allegedly more experienced than the first study), suggested by the authors as nearing the physical limit of their improvements for detection.

Two types of changes in perception have been described in classical texts on meditation: temporary and permanent (Nyanamoli 1976). The first type of changes occur during meditation but "may cease if meditation practice is discontinued, permitting old perceptual habit patterns to be re-established" (Brown et al. 1984b). The second, permanent type of changes also occur during meditation, but persist even in the absence of further practise. The above two types also relate to acute and chronic changes, the former representing short-term changes which occur relatively soon after beginning practise, and the latter representing changes that, as stated above, persist for a long time after the meditator discontinues practise. A more traditional view of acute and chronic effects describe the changes occurring according to the type, that is, acute changes happen quickly after beginning practise, whereas chronic changes, although potentially the same as the acute changes, take much longer to appear in an individual. There are numerous reports of EEG and physiological changes which are positively correlated with degrees of meditative proficiency (Carter et al. 2005; Brown et al. 1984a, 1984b), however, other studies do not support this evidence (Cauthen & Prymak 1977).

A study using a Rorschach test as a perceptual test (rather than a personality test) found that advanced meditators capable of attaining deeper, more concentrated states of meditation "were less reactive to percepts and were more aware of the automatic perceptual processes ordinarily outside of consciousness" compared to less accomplished meditators (Brown et al. 1984b).

Perceptual rivalry One recent study on binocular rivalry revealed results which have significant implications for understanding perceptual rivalry, attentional mechanisms and consciousness. Through perceptual measures of binocular rivalry, involving head-mounted display goggles, 23 Tibetan monks with 5 to 54 years experience, were studied before, during and after "one-point" meditation[9] (Carter et al. 2005). The authors found "extreme increases in perceptual dominance durations," reported by 50% of monks *after* one-point meditation, in other words, one image was stabilised for long a duration. In addition, a prolongation and stabilisation of the display *during* one-point meditation, results which "contrast sharply with the reported observations of over 1000 meditation-naïve individuals tested previously." The prolongation of rivalry "results from intense attentional focus and the practised ability to stabilise the mind during one-point meditation" (Carter et al. 2005). When the above visual function was measured during compassion[10] meditation, no significant differences were found. In another part of the study, one meditator with over 25 years experience was able to voluntarily maintain the disappearance of the target dots for 723 seconds during a test on motion-induced blindness prior to meditation. This demonstrates how meditators "can measurably alter the normal fluctuations in conscious states induced by binocular rivalry and motion-induced blindness" (Carter et al. 2005).

2.4.2 Attention

Meditation offers us a form of attentional training that is beginning to yield strong evidence in many areas of research. The interpretation of attention in meditation research primarily centres around the distinction between whether a meditation practice primarily involves *concentration* or *mindfulness*. Although awareness (and sometimes meta-awareness) is discussed in research (Brefczynski-Lewis et al. 2007; Lutz et al. 2007), it is not granted the prominent role in meditation that

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[9] This concentrative meditation, also called "one-pointed" or "single-pointed", involves maintaining one's focus on a single object while reducing and inhibiting the distracting influences of other internal and external events (Carter et al. 2005).

[10] The authors define compassion meditation as "a non-referential contemplation of suffering within the world, combined with the emanation of loving kindness" (Carter et al. 2005).

attention is. As mentioned in §1.1, a meditation practice is generally classified according to these two styles, however when a technique (such as Zen or the one studied in this project) involves a combination of the two in varying degrees, an extra level of interpretation of the data is often required, especially if measures are averaged across entire meditation periods. Such complications validate the increasing use of first-person data in order to further clarify and understand subjective experiences, especially in a field where there is such a wide variety of phenomenological and metaphysical reports.

There has been a great deal of research into the neural mechanisms of attention and how behaviourally relevant information is sorted out from the constant flood of events reaching the senses simultaneously. There are now considered to be different types of attention which involve different regions (Johnson & Zatorre 2006). For example, in regard to within-modality attention (one sensory modality, such as audition), one can *selectively* attend to a binaural (both ears) or monoaural (one ear) sound (unimodal selective attention), or *divide* attention between sensory loci, that is, right ear vs. left ear (unimodal divided attention). In terms of multimodal or bimodal attention, one can attend to one sense (visual) while ignoring another sense (auditory) (bimodal selective attention) (Johnson & Zatorre 2005) or attend simultaneously to two senses, such as auditory visual (bimodal divided attention) (Degerman et al. 2007). By extending the duration in which a subject participates in these scenarios, sustained attention can be investigated by measuring changes in performance over time.

A recent fMRI study by Brefczynski-Lewis et al. (2007) found surprising levels of distributed brain activation in meditators practising concentrative meditation. Activation in a network of brain regions involved in sustained attention and other cognitive processes in meditators vs controls included fronto-parietal regions, cerebellar, temporal, parahippocampal and posterior occipital cortex. They also found activation in anterior insula, a region related to self-monitoring or meta-awareness, “a form of metacognition” (Brefczynski-Lewis et al. 2007) that monitors the quality of meditation and allows the meditator to make necessary cognitive adjustments in the event of inappropriate mental states such as hyper-arousal (including distractibility) and drowsiness. Activation in the anterior cingulate may be associated with internal state monitoring, whereas the prevention of habitual discursive and emotional reactions contrary to meditation may have been mediated by the activation in prefrontal regions, basal ganglia and subthalamic nuclei. The study also revealed greater activation in the attention regions mentioned above in meditators who were more experienced (more practise hours). The authors conclude that "meditation may result in a less cognitively active (quieter) mental state, such that other tasks performed in its wake may become less effortful (decreased resources allocated without any compromise in performance), perhaps resulting from fewer cognitive processes competing for resources" (Brefczynski-Lewis et al. 2007).

In a study looking at the effects of meditation on the attentional subsystems of alerting, orientating and conflict monitoring, Jha et al. (2007) found that after practising concentration meditation for one month, practitioners demonstrated improvements in exogenous alerting-related stimuli detection, relative to two other groups. Subject groups consisted of 1) meditation naïve individuals who participated in an eight week course emphasising concentrative meditation skills, 2) experienced concentration meditation practitioners who participated in a one month intensive retreat and 3) meditation-naïve individuals who received no meditation training. Functioning of these attentional subsystems was indexed by performance on the Attention Network Test (Adólfsdóttir et al. 2008). Individuals learning MBSR revealed significantly improved orientating after the eight week course, relative to the other two groups, suggesting that the concentrative training can improve the "ability to endogenously orient attention." The improvement of the exogenous stimuli detection in concentration practitioners revealed the "development and emergence of receptive attention skills." The authors concluded that meditation training may "improve attention-related behavioural responses by enhancing functioning of specific subcomponents of attention" (Jha et al. 2007).

Rutschman (2004) demonstrated that meditation leads to “increased attentional flexibility and sustainment”, relative to relaxation, during a study in which both groups performed a divided-attention task. The increase in sustained attention was found in meditators demonstrating less decline in their performance across trials. The improvements in attentional flexibility were demonstrated by quicker reaction times in task performance in meditators after the meditation condition. In addition to these improved reaction times constituting attentional flexibility, the author commented that meditators displayed more readiness than non-meditators to shift their attention to another stimulus while engaged in the main task.

2.5 Psychological phenomena

2.5.1 Expectation

A study undertaken by Malec and Sipprelle (1977) was performed on non-meditators in order to investigate the expectational effects on meditation, that is, whether the way an individual thinks meditation will affect them actually does so. Forty meditation-naïve subjects were divided into four groups, one of which was a control group. The other three groups watched instructional videos of Zen meditation showing three different outcomes; a relaxation outcome, no particular outcome and an arousal outcome. Of the four physiological measurements taken (heart rate, respiration rate, EMG and GSR), only muscle tension and respiration rate exhibited decreases in the three meditation groups after meditation (compared to controls), although changes in respiration proved nothing but the subjects’ ability to follow instructions since “the very act of counting breaths was expected to slow respiration” (Malec & Sipprelle 1977). In any case, these changes did not differ significantly between meditation groups, demonstrating a lack of expectational effect on the outcome of meditation practice.

2.6 Neurophenomenology

A great deal of research papers gloss over the principles of the meditative technique studied as if these are assumed to be subsidiary to the more quantitative research. Many attempts to incorporate subjective studies are often done perfunctorily, without sufficient depth to warrant any respectable interpretations. Subjective reports of individual experience are essential to building bridges to neurophysiological data and when collected properly, can be used effectively in correlation analyses.

The research programme called *neurophenomenology* requires a "precise and rigorous method to collect first-person data" (Lutz & Thompson 2003) in an attempt to pursue an integrated and large-scale dynamical approach to the neuroscience of consciousness (Varela 1996). By exploring the mutual constraints between first-person data and neuroimaging data, this research strategy aims at the integration of these two types of description. The general approach of neurophenomenology in terms of a methodology are 1) "to obtain richer first-person data through disciplined phenomenological explorations of experience" and 2) "to use these original first-person data to uncover new third-person data about the physiological processes crucial for consciousness" (Lutz & Thompson 2003).

In 2002, Lutz et al. demonstrated that by gathering first-person data under certain methodological guidelines, such data can give insight into cognition when jointly analysed with quantitative measures of neural activity. Subjects were trained in an illusory depth perception task and performed the task until they developed their own phenomenological categories which involved their experience of the task and personal task strategies. This training allowed subjects to improve their perceptual discrimination and refine their verbal reports. Each trial was divided up into phenomenological clusters (PhC) based on subjects' descriptions of the degree of preparation felt and the quality of their perception. The PhC were called "steady readiness", "fragmented readiness" and "unreadiness". The authors found that the perception of 3D stereograms induced gamma over occipital and parietal electrodes, a response which was modulated by attention. Of particular importance to the study though was the finding that "frontal spectral emissions and long-distance synchronies peak into specific frequencies that vary with the degree of preparation" (Lutz et al. 2002). This gamma activity was time-locked signal averaged and can therefore be reliably interpreted as brain activity. Specifically, gamma band synchronisation in frontal electrodes was greater in subjects expecting the stimulus, whereas those who were unprepared had weaker gamma activity in occipito-parietal regions, interrupted by phase scattering (decreased synchrony). This suggests that evoked responses are modulated by the cognitive context in which the stimulation occurs. The frontal activation found during readiness suggests the "deployment of attention during the preparation strategy" and implies the involvement of the prefrontal cortex in the top-down modulation of attention. It was suggested by the authors that phase scattering may "be a necessary transition between two very distinct neural patterns, in particular during the adaptive response to a salient change in sensory flow" (Lutz et al. 2002). These findings also require close consideration in light of the recent study demonstrating that frequencies above 20 Hz are contaminated by EMG activity (Whitham et al. 2007).

Subjective reports can be biased and untrue (Hurlburt & Heavey 2001), making it difficult to accurately assess subjective experience. One way to use first-person data in conjunction with neuroimaging data is to repeat an identical experimental paradigm and find patterns which recur in subjects' reports (Lutz et al. 2002). Generally during an experiment, a subject's cognitive activity fluctuates by way of their attention level, spontaneous thought processes (inner speech) and mental strategies (e.g., preparation, vigilance, motivation) (Lutz & Thompson 2003). Therefore, for a complete description of the dynamics of a moment of consciousness, both the ongoing activity preceding an event such as the presentation of an image and any consecutive activity, needs to be characterised in terms of corresponding subjective discriminations and evoked neural activity (Lutz et al. 2002).

Meditation offers an excellent means for refining first-person data. The practice of insight meditation (a NOBAMA) is aimed at redirecting an individual's attention toward their own immediate mental processes and familiarising them with specific types of these processes (Brefczynski-Lewis et al. 2007). Even if insight work is not undertaken, a practitioner of concentration meditation (an OBAMA) will still become familiar with a variety of internal experiences like drowsiness, hyperarousal, emotional and discursive preoccupation. They will also become familiar with applying cognitive devices in order to counterbalance mental states contrary to meditation (discussed in §1.2). Another important aspect of meditation in regard to incorporating the neurophenomenology programme is the degree of training undertaken by each meditator. This training is essential for familiarising the individual with their cognitive content, an indispensable process when undertaking "disciplined phenomenological explorations of experience" (Lutz et al. 2002). Competency in meditation is established through the mastery of particular cognitive skills such as attentional stability and clarity, the inhibition of mental chatter and strategies such as motivation and vigilance. Beginners in meditation will find these processes fluctuating. The stabilisation of these cognitive aspects provides a "precise and rigorous method to collect first-person data" that can then be used more confidently in neurophysiological correlations. Meditation is also a technique which through professional training, can provide very replicable experiences and result in recurring patterns in subjects' verbal reports. During meditation training, students' verbal reports are assessed via a meditation expert and this feedback is a necessary interaction for further instruction.

The project described in this thesis investigates the neural activity during specific meditative states which are described above in §1.3.5. These meditative states involve specific changes in a practitioner's cognitive content (see Table 1.2). The two aspects of a subject's meditation performance we will use are *focus achieved* and *meta-awareness efficacy*. These are defined differently according to the different states of meditation, such that a range of achieved focus and meta-awareness is expected. By using the consistent and refined phenomenological data established in the explication, we can establish predictions about changes in neural activity during the states of meditation. We will also use subjective reports during and after meditative states (reports that are expected to fall within the respective meditation state ranges) to assist in interpreting changes in neural activity. The hypotheses in §§3.2, 4.2, 5.2 and 6.2 have incorporated these considerations.

2.7 Considerations of the investigation of distinct meditative states

2.7.1 Neurophenomenological considerations

Many early studies on meditation have been limited in their contributions to science due to a lack of statistical evidence, control conditions and populations, and experimental rigor (Lutz et al. 2008).

However, a larger and more difficult problem plaguing neuroscience-orientated research on meditation is an absence of clear operational definitions and detailed explications. This nescience has resulted in the failure to make distinctions between types of meditation practices along with attempts to classify and describe meditation as a mere relaxation technique (Benson 1983; Fischer 1971), leading to a wide range of results in the research, some of which are contradictory (for examples, see Austin 1999; Cahn & Polich 2006).

Much of this confusion stems from the language used (or lack thereof) to describe the meditation practices under investigation and insufficient information provided in regard to phenomenological experience. The variation among meditation techniques and the heterogeneity of meditative states is now being considered more carefully and comprehensively, such that meditation is now conceptualised 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).

It has been suggested that a reasonable way to approach an understanding of conscious experiences is to develop new definitions “that would allow the demonstration and analysis of the elements of subjective experience" (Kandel et al. 2000). By incorporating these phenomenological reports with neurophysiological data, we can not only expand the knowledge of neural correlates of subjective experience, but also redefine how we view and describe subjective experience. This methodological approach was championed by the late Francisco Varela (1996) under the title of *neurophenomenology* and has been written on extensively since (Lutz et al. 2002; Lutz & Thompson 2003; Varela & Shear 1999).

The suitability of Buddhist contemplative practice for scientific inquiry is facilitated by the claimed production of distinctive and reproducible states during meditation that are phenomenally reportable (Lutz et al. 2007). While efforts have been made to track temporal dynamics of brain activity during concentrative meditation by decomposing meditation data into initial, middle and end portions (Baijal & Srinivasan 2009), no studies have investigated phenomenologically distinct states of concentrative meditation as derived from traditional literature (see §1.3.5). Meditative practices from the Lifeflow Meditation Centre (Adelaide, South Australia) have been developed using meticulously and arduously translated Buddhist texts (themselves very detailed psychological and philosophical accounts of meditative practice) and were used in the body of work described in this thesis. The detailed descriptions and explanations of Lifeflow techniques are clear and comprehensible, intelligible from a neuroscientific perspective and amenable to science. This study utilised phenomenological descriptions during meditation to assist in the interpretation of neurophysiological data (Table 4.1).

In addition to recording brain activity, measurements of heart rate, respiration rate, peripheral skin temperature, electrodermal activity, blood pressure, peripheral blood oxygen saturation and muscle activity will be included. Past studies have incorporated all of the above measures at one time or another, however due to the existence of conflicting and ambiguous evidence (see Table 2.1 and Austin 1999), it is of direct relevance not only to this study but also the scientific literature that these measures collectively be included.

2.7.2 Lack of control protocols

When considering control groups and control conditions for meditation studies, a number of problems exist which complicate any comparisons between data sets. Obviously a lack of control groups, either meditators in a non-meditating condition (that is, resting), or more importantly, non-meditators in similar or identical conditions to meditators, leaves any recorded data and subsequent interpretations regarding the efficacy of meditation open to criticism. In other words, it is entirely possible that non-meditators, in comparable experimental conditions to meditators and undertaking a rest condition instead of meditation, might demonstrate similar neurophysiological results to those obtained from meditators during meditation (Holmes 1984). Without involving both groups, it is difficult to completely rule out this possibility. Although a valid and important criticism, it is one which is difficult to address experimentally. Several non-meditative tasks (for example, reading or listening to music) have been suggested as control conditions for meditation (Brefczynski-Lewis et al. 2007), however any cognitive activity too dissimilar from the meditative technique being investigated potentially involves inappropriate brain activation, and is therefore an ineffective comparison. The only reliable protocol involves treating control subjects as meditation-naïve potential meditators and providing identical meditation instructions to those meditators receive. Although certain non-meditators could potentially attain light states of meditation straight away, especially individuals with developed concentration (see §2.7.2.2 below), the majority of non-meditators would be unlikely to sustain their meditation with comparable stability and clarity or reach deeper meditative states.

Obviously the limits of an investigator's reach in terms of subject numbers and conditions they include in their experiment design, depend on available funding, time, effort and other practical constraints. As well as this, the designs and the conditions that are included constantly change in light of new observations. For example, blood lactate may no longer be measured during meditation due to a consistent lack of results (Cahn & Polich 2006) or the measurement of pupil dilation as an index of arousal may be included in future studies.

In order to minimise data interpretation errors and draw more accurate conclusions, the following control conditions were implemented in this study.

2.7.2.1 Baseline and mind-wandering conditions

These controls states are particularly pertinent to the meditation experiment, but are also relevant to the other experiments. In the meditation experiment, baseline and mind-wandering states were included before and after meditative states. The mind-wandering states differed from the baseline condition in the instruction to "let the mind wander without focusing on one thing" as opposed to "sit quietly with your eyes closed". Please refer to each experiment for more discussion about experimental protocols.

2.7.2.2 Control group

This method refers to comparisons between meditators and non-meditators during comparable treatment conditions. The most effective way to demonstrate the effects of a particular skill is to compare measures from an individual proficient in such a skill to someone unfamiliar with the skill. In this case, we will compare meditators to non-meditators given identical instructions to meditate. Although meditation can take hours to learn and many more to master, the instructions to meditate are not so unintelligible that meditation-naïve individuals would have trouble understanding them, although the efficacy of applying these instructions may be a different matter. Certain individuals who have not meditated previously, but have a particularly concentrative temperament, may demonstrate similiar changes to meditators in light meditative states (the first or second absorptions).

It would not be logical to compare groups in which subjects varied significantly, regardless of meditation experience (for example, five young left-handed males compared to fifteen elderly, right-handed females). Therefore, in order to produce accurate comparisons, meditators were pair-matched with non-meditators for gender, age (± 6 years), handedness and education level.