Chapter 6

Sensory Processing

6.1 Introduction

As discussed in the previous chapter, meditators report changes in sensory, perceptual and cognitive abilities during, and as a result of, the practice of meditation (Austin 1998; Rahula 1959). Hitherto, investigations into the effects of meditation on sensory processing have not measured the brain's response to continuous repetitive stimuli, that is, cortical activity referred to as a steady-state response (SSR, or a steady-state evoked potential, SSEP).[1] A sensory stimulus presented continuously at a specific frequency, 40 Hz for example, drives the cortical response into what is called a "steady state", consisting of oscillations in the same narrow frequency band as the stimulus (Noss 1996).

An auditory evoked steady-state response (AESSR or ASSR) is a well-studied example of oscillatory stimulus-locked neuronal activity induced by auditory stimuli. In the study by Ross et al. (2004) using magnetoencephalography, a significant attentional effect on 40 Hz ASSR amplitudes was revealed. The effect of focused attention was investigated by recording SSRs during attended conditions and unattended conditions. The attended condition involved differentiating between two amplitude-modulated (AM) signals (500 Hz tone with 30 or 40 Hz amplitude modulation) while the unattended condition involved watching a

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[1] To avoid confusion with standard evoked potentials, the term *steady-state response* is used throughout this chapter.

slideshow with an AM signal playing. The authors found that focused attention during the attended conditions resulted in more sustained responses and augmented ASSR amplitudes compared to non-attended conditions (Ross et al. 2004).

Given that concentrative meditation involves training one's attention to remain single-pointedly focused on an object for significant periods of time, it is worth investigating whether SSR amplitudes are augmented by concentrative meditation. The processing of sensory stimuli would correspond to the first and second aggregates in the Buddhist model of consciousness (Table 1.1).

Studies examining levels of meditation proficiency report changes in brain activity (Brefczynski-Lewis et al. 2007; Carter et al. 2005) and cortical structure (Lazar et al. 2005; Pagnoni & Cekic 2007) which support claims by contemplative traditions of strengthening attention through mental training. These attentional improvements are suggested to occur, in part, through the effective management and allocation of limited brain resources (Lutz et al. 2008). With this in mind, individuals with no meditation experience were compared to experienced meditators performing the same experiment. To assess the effects of meditation on steady-state responses, stimuli from different modalities (viz. auditory, visual and somatosensory) were delivered during three attention conditions in which subjects were instructed to mind-wander, attend to their breath or attend to the stimulus.

6.2 Hypotheses

Considering the findings reported above, MEDITATORS and *controls* were hypothesised to demonstrate increased SSR amplitudes during the attend-to-stimulus condition. Both groups were also hypothesised to show decreased SSR amplitudes during the attend-to-breath condition and even further reductions in SSRs during the attend-to-thoughts condition. Considering the attention training involved in concentrative meditation, MEDITATORS were hypothesised to exhibit larger SSR amplitudes than *controls* during the attend-to-stimulus condition and smaller SSR amplitudes than *controls* during the attend-to-breath condition. These hypotheses reflect the greater attentional strength predicted by MEDITATORS, such that MEDITATORS would demonstrate greater concentration on the stimulus during the attend-to-stimulus condition and greater concentration on the breath during the attend-to-breath condition. Again, these changes are hypothesised to reflect MEDITATORS' ability to modify brain resource allocation and effectively control cognitive processes involved in concentration.

6.3 Methods

6.3.1 Subjects

Out of the twenty-six subjects recruited for the project, four subjects' data were contaminated by electrical interference and one subject was unable to complete the experiment. These five MEDITATOR subjects were therefore excluded from the sensory processing experiment. The *controls* paired to these subjects also had to be excluded to ensure that only pair-matched subjects were included in analyses. Therefore, eight MEDITATORS (♀ 3, ♂ 5, age range 30–62 years, $\bar{x}$=46.6 years) with 4–30 years meditation experience ($\bar{x}$=18.5 years) from the Lifeflow Meditation Centre in Adelaide, South Australia participated in the sensory processing experiment (Table 3.1) and all MEDITATORS were pair-matched to non-meditator *controls* for age (± 6 years), gender, handedness and education level (§2.7.2.2).

6.3.2 Steady-state response

Steady-state responses (SSRs) have been most effectively demonstrated in the auditory and somatosensory modalities with the use of a sinusoidally amplitude-modulated (SAM) waveform stimulus (Figure 6.1). When used to elicit auditory steady-state responses (ASSRs) or somatosensory steady-state responses (SSSRs), a carrier frequency (for example, 150 Hz) modulated by a lower message frequency (for example, 27 Hz) produces the largest steady-state oscillations in the brain, which match the message frequency (27 Hz) (Noss 1996).

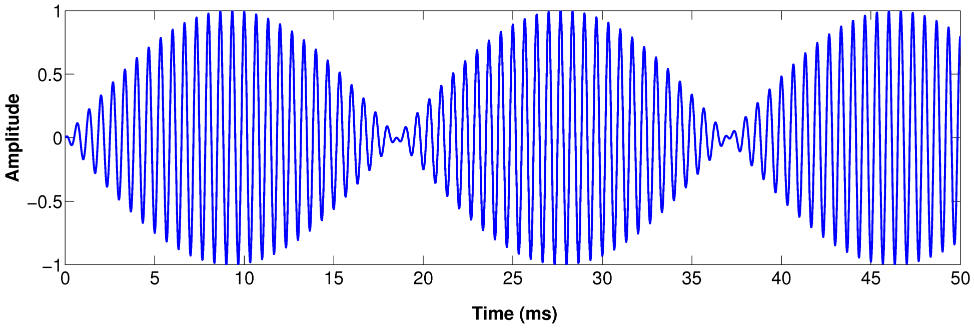

Figure 6.1: **Example of a sinusoidally amplitude-modulated (SAM) waveform** (sinusoidal, 100% modulation depth), using a message frequency (f_m) of 27 Hz and a carrier frequency (f_c) of 1500 Hz. The equation to represent this SAM waveform is: $[1 + \sin(2\pi + f_m t)] \times \sin(2\pi\ f_c t)$.

In the case of visual steady-state responses (VSSRs), a pulsed light source (for example a strobe light amplitude modulated with a square wave message) set approximately 30 cm from the subject's eyes is generally used (Niedermeyer & Lopes da Silva 2004; Nunez & Srinivasan 2006).

Studies have established that the efficacy of carrier and message frequencies used to elicit SSRs is dependent upon the sensory modality investigated. Below are examples of stimulus configurations which have been effectively implemented in the investigation of targeted sensory modalities and therefore adopted here.

Auditory (ASSR)

In a study which used sinusoidally amplitude-modulated (SAM) auditory stimuli with carrier frequencies of 500 and 1000 Hz and varying message frequencies, tones with a carrier frequency of 500 Hz and a message frequency of 40 Hz produced a maximal steady-state response amplitude with a mean response latency of 37.5 ms (Umegaki 1993).

In a preliminary study, maximal responses were found bilaterally in peripheral tempo-parietal electrodes (auditory cortex) using an auditory stimulus with a carrier frequency of 1500 Hz and a message frequency of 40 Hz, compared to carrier frequencies of 500 and 1000 Hz. As other message frequencies (37 and 43 Hz) produced comparable responses to 40 Hz and there is a great deal of literature on the 40 Hz auditory response, a 40 Hz message frequency modulating a 1500 Hz carrier frequency was utilised in this experiment.

Visual (VSSR)

A study by Pastor et al. (2003) demonstrated that the amplitude of the visual steady-state response (VSSR) is maximum at 15 Hz in occipital regions in humans and decreases at higher stimulation frequencies (25 and 40 Hz).

Preliminary studies demonstrated that an effective stimulus frequency (via a strobe light) for inducing a robust steady-state response in the occipital region was 16 Hz. A 16 Hz frequency, rather than 15 Hz, enabled the visual steady-state response to be generated well outside of the naturally occurring high-amplitude alpha frequency range (8–13 Hz). Preliminary studies required strobe placement 10 cm from closed eyes to elicit sufficient steady-state responses.

Somatosensory (SSSR)

A SAM electrical alternating-current with a carrier frequency of 150 Hz modulated by a message frequency of 25.6 Hz was found to produce the most significant SSR across three subjects, compared to message frequencies of 7.4, 14.7 and 41.2 Hz (Noss et al. 1996). By using SAM electrical stimuli, the authors recorded reliable responses from scalp electrodes overlying the contralateral somatosensory cortex in only a few seconds.

In order to avoid potential subharmonics of 50 Hz DC electrical artefact (which occurs at 60 Hz in the US), a 27 Hz message frequency was chosen for this experiment. During a preliminary study of three people, a message frequency of 27 Hz appeared to produce a more robust response than 25.6 Hz during a preliminary study. Preliminary studies also revealed that a carrier frequency of 1500 Hz produced a significantly enhanced response, relative to 150, 500 and 1000 Hz. The SSR was primarily found frontally (around F3) and parietally (P1 and CP1) contralateral to the site of stimulation (right wrist in this example). Accordingly, an electrical stimulus with a carrier frequency of 1500 Hz and a message frequency of 27 Hz was utilised here.

6.3.3 Experimental protocol

Stimuli from three modalities (viz. auditory, visual and somatosensory) were presented in a fixed order across three attention conditions (Figure 6.2). During the mind-wandering condition, subjects were instructed to let the mind wander without remaining on one thing and when a stimulus was presented, continue to mind-wander. In the attend-to-breath condition, subjects were instructed to meditate on the breath as deeply as possible and when a stimulus was presented, maintain the breath as the object of focus. In the attend-to-stimulus condition, subjects were also instructed to meditate on the breath as deeply as possible and when a stimulus was presented, adopt the stimulus as the object of focus. During each two minute condition, a one minute stimulus-free baseline preceded each one minute stimulus administration condition. Although the three stimulus modalities (viz. auditory, visual and somatosensory) were presented in the same order *within* each subject across all three conditions, the order in which the stimulus modalities were repeated *across* subjects was counterbalanced. In addition, the order in which the conditions of mind-wandering, attend-to-breath and attend-to-stimulus were presented was also counterbalanced across subjects.

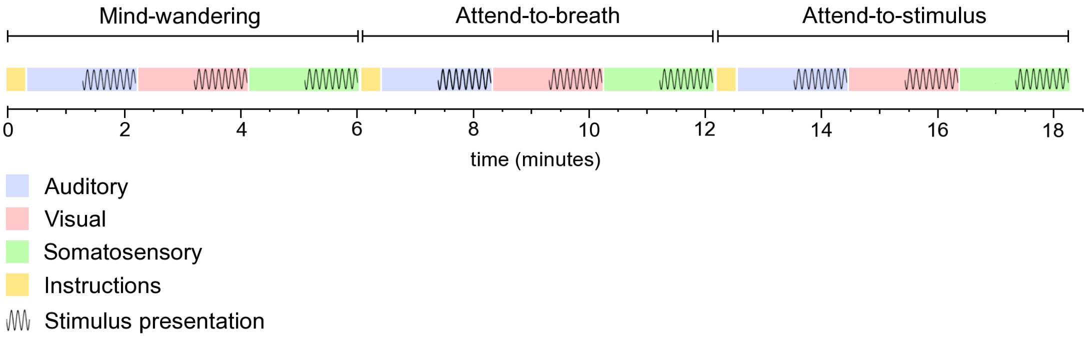

Figure 6.2: **Sensory processing experimental protocol.** Three stimuli of different modalities (viz. auditory, visual and somatosensory) were presented during three attention conditions: 1) attend-to-thoughts; 2) attend-to-breath; and 3) attend-to-stimulus. A one-minute stimulus-free baseline preceded each stimulus presentation. Stimulus modalities and attention conditions were counterbalanced across all subjects.

The following modality-specific stimuli were presented during each attention condition.

Auditory

Tones with a sinusoidally amplitude-modulated (SAM) frequency of 40 Hz and a carrier frequency of 1500 Hz were presented binaurally via pneumatic headphones through earplugs at a comfortably high volume.

Visual

A strobe light flickering at 16 Hz was presented approximately 10 cm from subjects' closed eyes via a custom-made strobe (Flinders Biomedical Engineering, Flinders Medical Centre, Bedford Park, Australia) operated programmatically via Presentation computer software (Neurobehavioral Systems, California, USA).

Somatosensory

An electrical stimulus with a carrier frequency of 1500 Hz and a amplitude-modulated frequency of 27 Hz was presented using a custom-made somatosensory stimulator (Flinders Biomedical Engineering, Flinders Medical Centre, Bedford Park, Australia). Two 3M red dot electrodes were positioned on the non-dominant wrist over the median nerve. One electrode was placed in the centre of the wrist above the radiocarpal and ulnocarpal joints and the other electrode was positioned on the arm, approximately 2–3 cm proximal of the first electrode. Although electrical stimulation elicits a weaker signal than a vibratory stimulus (Noss et al. 1996), the former method was employed here due to the ease at which the stimulator could be integrated into and operated using Presentation computer software (Neurobehavioral Systems, California, USA). In addition, surface electrodes could be quickly and reliably attached, reducing setup time and operator error. The intensity of the stimulus was determined individually before the experiment at a maximal level that was comfortably tolerable.

6.3.3.1 EEG analysis

Although 120 channels were used to record EEG, only a small number of electrodes which consistently recorded the largest steady-state responses (SSRs) in preliminary studies were selected for analysis (Figure 6.3).

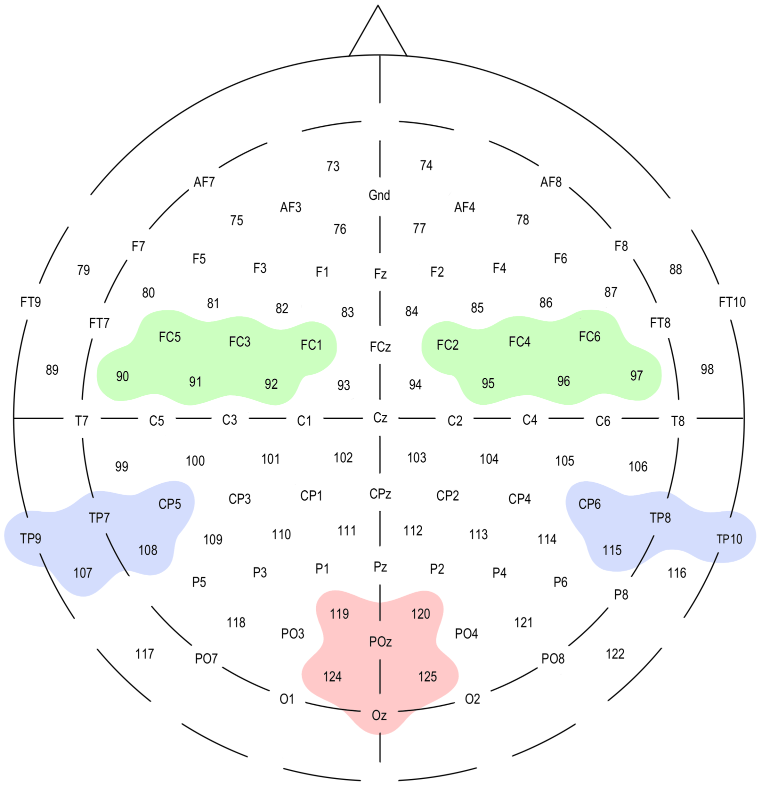

Figure 6.3: **Electrode selection for steady-state responses.** 120-channel EEG montage showing electrodes selected for SSR analysis which during preliminary studies consistently recorded the largest SSR amplitudes within auditory (blue), visual (orange) and somatosensory (green) modalities. Adapted from http://www.easycap.de/easycap/e/electrodes/11_M15.htm.

SSRs have also been successfully recorded from these brain regions in other studies (Noss et al. 1996; Pastor et al. 2003; Ross et al. 2004). For auditory SSRs, selected electrodes were FC5, FC3, FC1, 90, 91, 92 (left hemisphere), FC2, FC4, FC6, 95, 96 and 97 (right hemisphere). For visual SSRs, selected electrodes were 119, POz, 124, Oz (left hemisphere), 120, POz, 125 and Oz (right hemisphere). For somatosensory SSRs, selected electrodes were TP9, TP7, CP5, 107, 108 (left hemisphere), CP6, TP8, TP10 and 115 (right hemisphere).[2] Average EEG power

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[2] Electrode 116 was utilised for autonomic measures.

was calculated for all electrodes within each modality and each hemisphere. General linear model repeated measures ANOVAs were performed on SSR data with group, hemisphere, modality and attention condition as factors.

6.4 Results

Steady state responses were successfully evoked in varying degrees in all subjects and for all stimulus modalities (Figures 6.4, 6.5 and 6.6). Although robust steady-state responses were evoked in all subjects in response to all stimulus modalities, no significant effects were found for mind-wandering, attend-to-breath or attend-to-stimulus conditions.

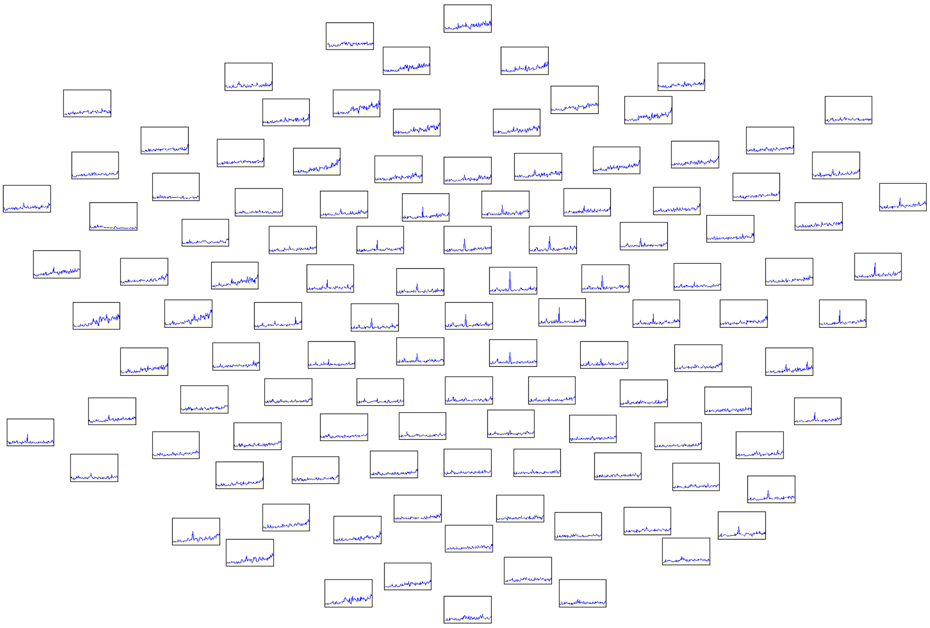

Figure 6.4: **EEG montage for auditory steady-state response**s. This EEG montage represents one of the better examples showing an auditory steady-state response evoked at 40 Hz centrally and in electrodes over the auditory cortex. Horizontal axis is 0–90 Hz.

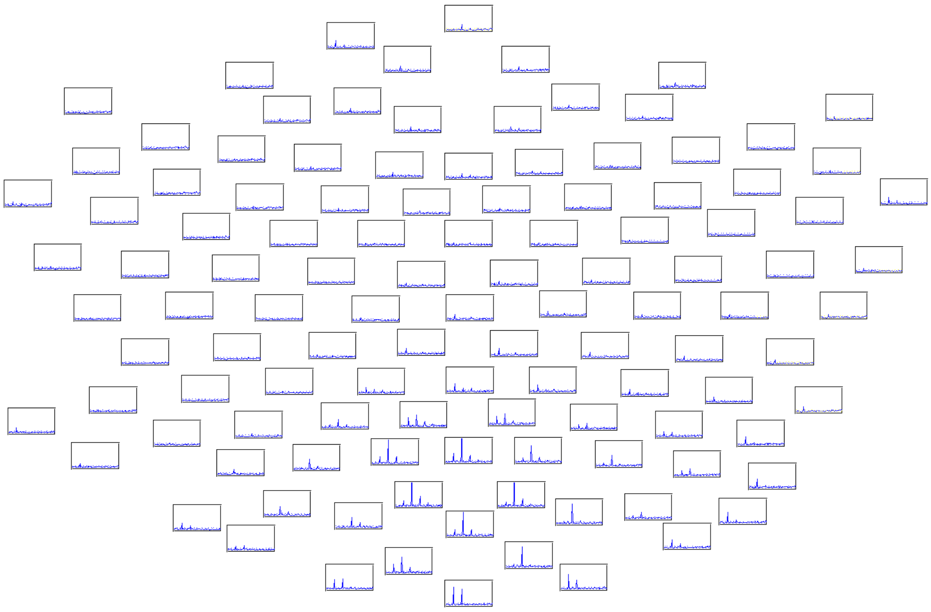

Figure 6.5: **EEG montage for visual steady-state responses**. This EEG montage represents one of the better examples showing a visual steady-state response evoked at 16 Hz in posterior electrodes over the occipital cortex. Harmonics at 32 Hz and even 48 Hz can also be seen. Horizontal axis is 0–90 Hz.

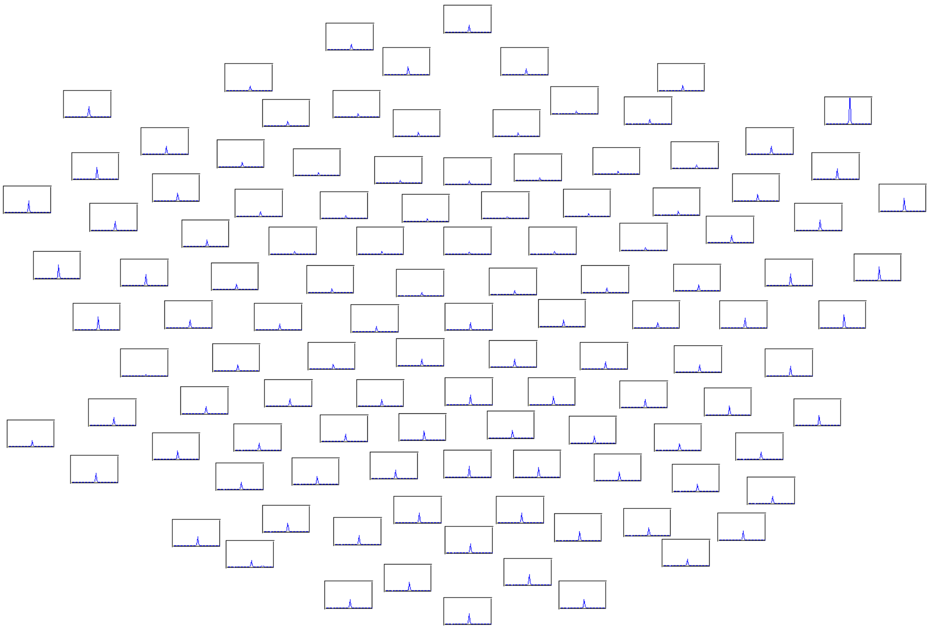

Figure 6.6: **EEG montage for somatosensory steady-state responses**. This EEG montage represents one of the better examples showing a somatosensory steady-state response widely evoked at 27 Hz in posterior electrodes including the somatosensory cortex. Horizontal axis is 0–50 Hz.

6.4.1 Auditory (ASSR)

No significant effects were revealed for group, hemisphere, modality or focus.

6.4.2 Visual (VSSR)

No significant effects were revealed for group, hemisphere, modality or focus.

6.4.3 Somatosensory (SSSR)

Due to an unidentifiable source of electrical contamination during the somatosensory condition, data from half of the subjects (eight) were corrupted. Therefore, the remaining unaffected subjects were included in analysis without being pair-matched. No significant effects were revealed for group, hemisphere, modality or focus.

6.5 Discussion

The experiment failed to find the modulation of steady-state response (SSR) amplitudes in any attention condition (viz. attend-to-thoughts, attend-to-breath or attend-to-stimulus).

In addition, findings of SSR amplitude augmentation in normal subjects during an attended condition compared to an unattended condition (Ross et al. 2004) were not corroborated in either group. Failure to confirm this study may be due to the instructions and tasks provided during the conditions. Ross et al. (2004) used an amplitude-modulated (AM) discrimination task during the attended condition which required specific attention to the stimuli presented and therefore may have induced more intense attention to the ASSR than in the experiment performed here. A different study (Linden et al. 1987) employed intensity and frequency discrimination tasks in the attended conditions and therefore did not require specific attention to the stimulus rhythm used to elicit the 40 Hz ASSR (Ross et al. 2004). No effects of attention of SSRs were subsequently found in this study. It appears that the modulation of SSRs requires a high degree of attention, evidently necessitated by an AM discrimination task (Ross et al. 2004). On that account, simply asking subjects to attend to the stimulus as the object of their meditation might not have resulted in level of the attention required to accentuate the SSR. Along with single-pointed attention, concentrative meditation involves abating thought activity, such that the second absorption and beyond involves no thinking whatsoever (§1.3.5). This fact makes even simple mental tasks such as target discrimination difficult to implement during meditative states.

The request to "meditate as deeply as possible" potentially caused confusion among both MEDITATORS and *controls*. Specific instructions for meditation were not given at any time during the sensory processing experiment, therefore, those *controls* undertaking this experiment before the meditation experiment would not have received instructions for all meditative states.[3] This lack of direction very likely provided uncertainty and possibly anxiety in *controls*. This problem did not apply to MEDITATORS however.

Electrodes selected for analysis were chosen as those sites which most consistently recorded the largest SSRs across subjects in preliminary studies. Electrode selection was also guided by evidence from other studies on SSRs (Noss et al. 1996; Pastor et al. 2003; Ross et al. 2004). Despite attempts to localise the SSR and maximise data quality, it is apparent that more sophisticated analysis techniques such as current dipole source localisation (viz. low resolution electromagnetic tomography or LORETA) might be required. Magnetoencephalography (MEG), as used by Ross et al. (2004), affords a better signal-to-noise ratio than EEG and therefore may provide more detailed information about the relationship between attention and the ASSR. In addition to this, future assessments of meditation (viz. focused attention) on SSR amplitudes require large group numbers to overcome variation in SSRs between subjects and EEG sites.

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[3] The only meditation instruction these subjects would have received by this point would have been for the second absorption in the attention experiment.