The human default consciousness and its disruption: insights from an EEG study of Buddhist jhāna meditation

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While the brain's "default mode network" (DMN) and the "neural correlates of consciousness" are familiar topics in neuroscience research, this paper focuses instead on the underlying human default consciousness, of which we consider the DMN to be the outer expression. Task-based studies of the DMN by their nature recruit one part of the cortical network to study another, and are therefore both limited and compromised as to what information they can reveal about consciousness itself. The only situations to give a glimpse of consciousness as a whole, or its absence, are severely disrupted states such as anaesthesia, coma, deep non-rapid eye movement (nREM) sleep, or some extreme pathological states, all of which are essentially involuntary, and generally regarded as "unconscious". An exception to involuntary disruption can be found in Buddhist jhāna meditation, whose implicit aim is to intentionally withdraw attention from the everyday default consciousness to an inward-directed state of stillness, referred to as jhāna consciousness, as a basis from which to develop insight. In this context the human default consciousness is regarded as a sensory consciousness, where information about, and our experience of, the outer world is evaluated against personal and organic needs and forms the basis of our ongoing self-experience. This paper is a preliminary report on the first detailed EEG study of this form of meditation, with findings radically different to EEG studies of more familiar and less focused forms of meditation. A high proportion of subjects display "spindle" activity in their EEG, superficially similar to spindles seen in the approach to nREM sleep, while more-experienced subjects display high voltage slow-wave EEG activity reminiscent, but significantly different, to the slow waves of deep nREM sleep, or even high-voltage delta coma. Some others show brief posterior spike-wave bursts, again similar, but with significant differences, to absence epilepsy. Some subjects also develop the ability to consciously evoke clonic seizure-like activity at will, under full control. We suggest that the intensity and remarkable nature of these observations reflects a profound disruption of the human DCs when the personal element is progressively withdrawn.

Keywords: EEG, meditation, jhāna, consciousness, epilepsy, slow-waves, spike-waves

Abstract 342 words
Main text 11917 words
14 Figures
4 Tables

1 Supplementary Table

1. INTRODUCTION

1.1. A DEFAULT SENSORY CONSCIOUSNESS (DCs)

We consider the DCs to be a sensory consciousness, irrespective of whether we are responding to direct sensory input, or accessing memory or processing ideas, or indeed dreaming, all of which are experienced within a sensory framework. This consciousness is represented at the cortical and biological level as an ongoing dynamic functional organisation intrinsic to our lives as human beings interacting with others and the world. This sensory consciousness is the *de facto* subject of the many "content" studies of the neural correlates of consciousness (NCC) (Koch *et al*., 2016; Boly *et al*., 2017), and the related default mode network (DMN) (Raichle, 2015a,b), where researchers examine which parts of the cortical networks are stimulated or suppressed by a subject undergoing tasks or external stimuli.

The subjective component is ever-present in the DCs, and is likely the dominant factor in the dynamic neuronal balance between inputs from the outer world and from our body, with their resonances to past experiences held in memory, then weighed as to their value to the "I" or "self", in the light of current needs or actions. This understanding of consciousness is implicit in psychoanalysis, from the early work of Freud (1895) in his *Project for a Scientific Psychology*, to the long-established clinical experience of psychotherapists and psychoanalysts of the constant ongoing resonance between current experience and stored memories, particularly memories of reciprocal roles that contain information on the emotional impact of events (pain-pleasure; liking-disliking) for the self (e.g. Ryle and Kerr, 2002; and Matte Blanco's, 1980, description of the *Unconscious as Infinite Sets*).

Whilst content studies of the NCC can reveal different features of the DCs, state-based approaches compare it, for example, to states of sleep, anaesthesia, coma, epilepsy and some pathological states, mostly regarded as unconscious. If it is indeed possible, as we aim to demonstrate, for a person to intentionally and progressively withdraw their personal involvement from the DCs, even partially, while remaining fully conscious, a new window is opened into exploring the NCC (Hohwy, 2009), and the nature of consciousness itself.

1.2. JHĀNA MEDITATION

Given the rather remarkable observations to be described, certainly atypical compared to previous EEG studies of meditation, it is appropriate to give a context and overview of some of the key features of Buddhist jhāna meditation.

Buddhist meditation, whether Southeast Asian, Tibetan, Japanese or Chinese, comprises two strands, Samatha (Wallace, 1999) and Vipassanā (Cousins, 1994-96); the former often translated as tranquillity or serenity, and the latter as insight or wisdom. Mindfulness, though well-known as a form of practice in its own right, and accepted as useful in the treatment of recurrent depression, is just one of the basic factors underpinning both samatha and vipassanā. Jhāna meditation falls within the Samatha division. Etymologically, jhāna is most often translated as "absorption", but has a secondary root, *jhapeti*, meaning to burn up, which is a reflection that it is a highly active, and far from passive, state (Cousins, 1973; Gunaratana, 1980). While there have been many EEG studies of meditation (e.g., Thomas and Cohen, 2014; Cahn and Polich, 2006), there have been no in-depth studies of jhāna meditation, and there exist very few centres that teach its practice. The background to this requires some explanation. In South and Southeast Asia during the 1950s, Buddhist meditation practices underwent a "Reform", where age-old samatha practices were criticised as unscientific, and repressed in favour of a heavily politically-promoted form of meditation known as Burmese vipassanā, which claimed that jhāna was not necessary as a prerequisite for insight and realisation of Buddhist meditational goals (Crosby, 2013). As a result, jhāna meditation was relegated to an almost esoteric role, sidelined in favour of vipassanā. Many also believed it was not possible to develop and practice jhāna in a lay context, outside monastic and forest meditation traditions.

Recently, however, an interest in jhāna has revived, with two main traditions emerging in the West. The first, and best known, comes via monastic practitioners, and in this form the breath is not controlled.

Hagerty *et al.* (2013) describe an EEG study of a single Western practitioner of this form, but with results very different to those described in this paper. In the second form, the length of breath *is* controlled in the approach to jhāna, specifically because the "normal" length is regarded as an integral component of the DCs, withdrawal from which is the primary aim of jhāna. This form of meditation was introduced to the UK in the 1960s by a former Thai-Cambodian Buddhist monk (The Samatha Trust, UK regd Charity 1973), and is closely related to the *Yogāvacara*, a formerly widespread and ancient, mainly oral, tradition of meditation, practiced by both monks and lay people across South and Southeast Asia, currently the subject of research by ethnologists based on palm-leaf manuscripts discovered in Cambodia and Thailand (Bizot, 1994; Crosby, 2000). In some monasteries this practice was regarded as a means to develop mastery of jhāna, but was also considered particularly suitable for lay meditators leading normal household lives, as are the subjects of this study. Using lengths of breath longer or shorter than "normal", marks a protected space where jhāna can be safely developed, and safely left to return to the normal DCs and everyday life without conflict. "Safely", refers to the containment of highly energised states that are frequently developed in the approach to jhāna; in this respect, and in the precise ways in which the breath is controlled, there are similarities to Tibetan Buddhist yoga (Minvaleev, 2014).

Wallace (1999), referring to the Samatha tradition, and implicitly the practice of jhāna, comments that "The mind and consciousness itself are the primary subjects of introspective investigation within the Buddhist tradition". Indeed, the techniques employed are remarkably relevant to current neuroscience, once the different terminologies are understood. To develop jhāna, the meditator's first task is to overcome the "hindrances", usually listed as: sense-desire, ill-will, sloth and torpor, restlessness and worry, and doubt (Cousins, 1973; Gunaratana, 1980). These represent, in our terms, key features of the human DCs: a constant evaluation of sensory input against past experience and future needs and expectations, based on value to the "I" or "self", which implies liking or disliking, pleasure versus pain, habits of attachment, as well as available energy, restlessness and doubt. In practice, a meditator does not think about or dwell on the hindrances during meditation, but simply begins by turning attention to the breath; each time the mind wanders, distractions in the form of thoughts or feelings are acknowledged and attention patiently, again and again, brought back to the breath. The Buddhist jhāna tradition describes eight jhānas: four rūpa (form) jhānas, and four arūpa (formless) jhānas; of which this paper deals mainly with the former.

1.2.1. Attention

The jhānas are described by their characterising factors; 5 factors for the first rūpa jhāna, 3 for the second, and 2 for the third and fourth jhānas, as listed below with the Pali terms:

First rūpa jhāna factors

- Applied attention, or initial thought (= *vitakka*)
- Sustained attention or thought (= *vicāra*)
- Energised interest, or "joy" (= *pīti*)
- Happiness, contentment or bliss (= *sukha*)
- One-pointedness of mind (= *ekaggatācitta*)

Second rūpa jhāna factors

- Energised interest, or "joy" (= *pīti*)
- Happiness, contentment or bliss (= *sukha*)
- One-pointedness of mind (= *ekaggatācitta*)

Third rūpa jhāna factors

- Happiness, contentment or bliss (= *sukha*)
- One-pointedness of mind (= *ekaggatācitta*)

Fourth rūpa jhāna factors

- One-pointedness of mind (= *ekaggatācitta*)
- Equanimity(= *upekkha*)

The dominant factors of the first rūpa jhāna are two aspects of attention: *vitakka*, or applied attention, the repeated placing of attention on the meditation object, in this case the breath, as a mental act; and *vicāra*, sustained attention, which develops as the meditator becomes more skilled at noticing and resisting distraction. In the second, third and fourth jhānas these two factors are dropped, as attentional processes stabilise. Working with attention is therefore the dominant activity in developing the first jhāna, and a meditator is required to develop attention to a high level, often over years of practice. Typically the practitioner starts by mentally counting during in and out breaths, to aid noticing when attention wanders. Distractions are acknowledged as minimally as possible, before returning to the count. Maintaining a different length of breath also enhances mindfulness, and in this tradition four lengths are used, two longer than "normal", and two shorter. As distraction eases, counting is dropped and the meditator follows the breath, from its touch at the nose tip, to the sensations through the nose to the throat, to the chest, the diaphragm, and then back on the out breath; continually noting and managing distractions as before. Finally the meditator rests attention at one point, usually the nose tip, and at this stage attention is progressively transferred to an internal mental object, referred to in the jhāna texts as the *nimitta* (Wallace, 1999; Cousins, 1973) or "sign", which is the meditator's growing sense of his/her own consciousness. We are tempted to say the "qualia" of that consciousness, provided qualia is not interpreted in sensory terms as too-crudely "this" or "that".

Allowing for terminology, we expect these two factors of attention to have their counterparts in the executive attention networks of the brain. However, attention cannot be separated from the broader processes of perception (Hohwy 2012), which requires us to consider the personal component. Here the subjective experience of the meditator is a clue as to what we might expect. At first the meditator's attention, as in the DCs, is strongly sensorily-determined by the habit of wanting to mentally "commentate" or "name", or "recognise", or discriminate in some way, to orient experience within the familiar sensory structure of the DCs. Since the subjectivity in these perceptual processes is heavily "Eye/I"-driven, we may expect disruption not only to the executive attention networks, but also to the ventral and dorsal perceptual streams (Milner, 2017; Cloutman, 2012), as the meditator resists the pull back towards DCs processes in developing the first rūpa jhāna.

1.2.2. Attachment

When applied attention, *vitakka*, and sustained attention *vicāra*, become effortless and steady through experience in the first rūpa jhāna, the further development of the second, third and fourth rūpa jhānas is more concerned with feeling, and the underlying subject-object nature of consciousness rather than the cognitive processes of attention. In fact, even to develop the first rūpa jhāna, a meditator is already working with resisting attachment to liking and disliking, which in Buddhist terms are the roots of craving and the source of suffering. Here there is a correspondence to Freud's "pleasure principle", and the twin pulls of craving and aversion, as well as the importance of understanding attachment disorders in psychiatry and psychotherapy. Since liking and disliking, and associated emotions, are dominant features of our habitual DCs, linking perception to action choices, it may be no surprise to find rather dramatic changes in brain activity when the personal element is withdrawn from the DCs.

Subjectively, the movement from the first to the second rūpa jhāna is characterised by a growing sense of peace and contentment, at the increasing freedom from dependence on DCs processes, as well as a growing "energised interest". These are the two factors *sukha* and *pīti*, respectively, listed above for the second rūpa jhāna, together with the third factor one-pointedness of mind (*ekaggatācitta*) which underpins all four jhānas. The factor *pīti* plays a very important role in the Yogāvacara, which lists 5 levels of intensity ranging from fine bodily vibration or prickling of the hairs on the head and body, to, at its most intense, bodily shaking and even jumping in the air (*The Yogāvachara's Manual*). Some meditators develop the ability to deliberately enhance this energisation, producing effects reminiscent of epilepsy, but under full control. The EEG observations of high energy states described in this paper, are, we believe, the counterparts of this energisation. In developing the second rūpa jhāna, *pīti* represents the growing involvement of the body and its subtle bodily energies, into a state of mind-body integration referred to as *samādhi*, a term frequently used interchangeably with "concentration" or jhāna.

1.2.3. Subject-Object

Whilst the task of the first rūpa jhāna is to develop a degree of mastery of attention, the task of the second rūpa jhāna is to master *pīti*; not to suppress it, but to tranquilise (pali, *passaddhi*) any bodily disturbance into an increasingly still mental state "held" by attention to the *nimitta*. For some meditators the *nimitta* is experienced visually as light, for others as touching something intangible with the mind, or by others as listening to silence (Buddhaghosa, *Visuddhimagga*); these differing experiences reflecting the traces of a meditator's habitual preference for one or other sense modality in their DCs. Once tranquilised and incorporated, the factor *pīti* is dropped in the third rūpa jhāna, revealing an experience described in 5th-century texts as "completely conscious" (Upatissa, *Vimuttimagga*), or "full awareness like that of a man on a razor's edge" (Buddhaghosa, *Visuddhimagga*). Interestingly, avoiding the words conscious or aware, subjects of this study prefer, "vivid presence" for their subjective experience.

Practice of the second, third and fourth rūpa jhānas is also regarded as an exploration and refinement of the subject-object relationship (*nāma-rūpa*, or name and form in Buddhist terms), which progressively becomes less cognitively and sensorily-determined, and less dependent on liking or disliking; such that in the fourth rūpa jhāna even dependence on the "reward" of pleasure or satisfaction ends, replaced by deep stillness and finely poised balance and equanimity. The nature of the subject-object experience is of considerable interest to neuroscience, and will be taken up later in this paper.

The development of the jhāna factors is not a straightforward cognitive process, as in task-based EEG studies. Meditators cannot simply "think" themselves into jhāna. While the primary motivation approaching the practice is to withdraw from the habitual DCs ("*secluded from sense desire*…", Cousins, 1973), it is the *nimitta* acting as an "attractor" that allows the meditator to eventually settle into jhāna. It could be said that the *nimitta* plays a similar role to the feedback sign given to a subject undergoing neurofeedback (Sitaram R. *et al*., 2017), and that samatha meditation is a naturalistic form of neurofeedback, predating modern forms of neurofeedback by over two millenia (Dennison, 2012). Since the development of jhāna is not a cognitively controlled process, we may not be surprised to find variations in the EEG responses of different meditators, whose brains may enrol neural networks in subtly different ways, to produce similar subjective experiences.

2. METHODS AND MATERIALS

2.1. EQUIPMENT

Recordings were made using 24-bit Mitsar DC amplifiers, either the 31-channel Mitsar 202, or the 21-channel wireless SmartBCI amplifier (Mitsar Medical, St Petersberg). The former has a sampling rate of 500/sec and upper frequency limit of 150 Hz, and was used with Easycaps and sintered Ag/AgCl electrodes. The 21-channel system has a sampling rate of 250/sec and upper frequency limit 70 Hz, and was used with MCScaps and sintered Ag/AgCl electrodes. In using DC amplifiers it is critical to find the best cap and gel combination to minimise drift and maintain stable low impedances at the electrode-skin interface. Having tested many combinations, we agree with Tallgren *et al*. (2005) that saline-based gels in combination with sintered Ag/AgCl electrodes are essential with DC amplifiers. After testing most commercial gels, we favour a combined conductive and mildly abrasive gel to obtain impedances as close to or less than 5KΩ as possible, with caps that allow good visual access to the electrode-skin interface for application of gel.

Electrodes were placed according to the international 10-20 system, and a monopolar linked-ears reference used. Software analysis was carried out with WinEEG, implementing the Infomax algorithm as used in EEGLAB (Delorme and Makeig, 2004) to compute independent components (ICs). Cortical sources were identified for ICs using eLoreta (Pascual-Marqui, 2002, 2007).

2.2. SUBJECTS AND RECORDING PROTOCOL

This is a within-group study of the effects of jhāna meditation on brain activity; the control group is, in effect, the wealth of other EEG studies of meditation and the NCC. A pilot study in 2010-12 with a non-DC amplifier found unexpectedly strong delta and SW EEG activity, which led to the acquisition of DC

amplifiers, and recordings resuming in August 2014. Since then, 29 experienced meditators from a total pool of around 400 in the UK, Ireland and the US have been recorded, some also re-recorded after 1-3 year intervals, including with both of the different amplifiers at different times to test consistency. Years' of experience of Samatha meditation range from 4–40+ years, with most individuals maintaining a daily practise of 30-60 mins, with more intensive 7-10 days "retreats" every 1–3 years. Twenty-four of the subjects are of graduate or postgraduate-levels of education, and more than half hold, or have held, senior professional roles in health-care or education, providing an excellent pool for subjective reports. Jhāna practice in detail has been taught and explored only during the last 10 years, so that out of the group of 29, experience of jhāna varies between 2-10 years. Because of variability and demands of different lifestyles and occupations, skill in jhāna does not necessarily correlate with years of practice. Four of the 29 subjects have also spent temporary periods of from 1-10 months as ordained Buddhist monks in Thailand.

Subjects practice seated on the ground, usually on a cushion, with the body erect and composed, still but not rigid, without resting on any supports. EEG recordings begin with a few mins eyes-open and then eyes-closed, before moving into meditation, with a duration of 40-50 mins. The meditation technique is progressive, moving through stages of increasingly internalised attention, prompted by cues from the person managing the recording. The observer/researcher notes events such as shifts in posture, a cough, external noise, or anything likely to cause an artefact. For some meditators this protocol is quicker than their everyday practice, with corresponding disadvantages, but is adopted for consistency. Given that the recordings sometimes show features superficially similar to deep sleep, it is important to stress that subjects are fully conscious throughout. There are no signs of loss of muscle tone or sleepiness in posture; subjects respond immediately to verbal cues; and at the end show no signs of sleep inertia or disorientation. On the contrary, meditators describe feeling more alert and present during and after practice. The protocol at the end of a recording is that subjects describe their recollection of the practice, in as much detail as possible, while the researcher monitors the recording in parallel.

2.3. ARTEFACTS OR CORTICAL?

With atypical EEG phenomena, the question of what is artefact and what is cortical is an important question, with the risk of discarding important cortical activity if some unusual feature is too quickly labelled as "artefact". Accordingly, the experimental design and protocol aims, as far as possible, to prevent artefacts arising in the first place. In the early pilot study, there were concerns over movement and eye artefacts. The former are caused mainly by movement of electrode connector wires if a subject moves during recording, and for the 31-electrode system the most effective solution has been to gather the electrode wires into an "umbilical cord" sheathed in earthed carbon-fibre material between the headcap and the amplifier. The 21-channel wireless system is already resilient to movement artifacts, due to the short connections to the wireless amplifier mounted directly on the headcap. Combined with a subject group experienced in meditation and used to holding still postures for long periods, as well as the observer/researcher noting posture changes or signs of muscle tension, there have been very few segments needing to be excluded. The only situation where movement remains a problem is in recording the deliberate arousal of clonic seizure-like states, where the task of separating movement artefact from cortical activity is a work in progress, to be dealt with in a future paper.

For eye artifacts, visual inspection and experience can recognise the more typical types, and we have chosen not to use automated software-removal algorithms to avoid confusion with atypical frontal delta and SW activity seen in this form of meditation. Visual inspection confirms that the bulk of the frontal activity is quite different to typical eye-blink artefacts, or lateral eye tracking; for example, if it does occur it is far slower than eye blinks, and is not just at frontal EEG sites. In addition, the SWs once developed have a recognisable rhythmicity, and can reach high and sustained intensity levels well above anything typical of artefacts. Nevertheless, sometimes meditators are prone to eye-flutter due to over-concentration, and since we sometimes also observe spike-wave activity, this flutter may be related to eyelid myoclonia (Joshi and Patrick, 2007) seen in absence epilepsy. For a meditator, eyelid flutter, if it does occur, usually settles down during a recording, but we have found that soft cotton-wool pads held

gently in place on the eyelid by lightweight spectacles effectively damps down the physical effects of such activity.

On the remaining few occasions where there is doubt about artefacts, those sections have been excluded. All sections analysed and described in this paper are uninterrupted sections to avoid problems of interpolation. The fact that recognisable themes and patterns of cortical sources are found in recordings carried out over several years, with two different amplifiers, with some subjects re-recorded after intervals of 1-3 years, adds to our confidence that we are dealing with patterns of cortical activity inexplicable by artefacts or flawed methodology.

3. RESULTS

Supplementary Table 1 gives an overview of EEG recordings of 29 subjects during 2014-17, mostly during 10-day intensive meditation retreats. Two recordings (subjects 4 and 22) were excluded due to impedance problems at one or more electrodes, leaving 27 subjects. Five of these were also re-recorded after intervals of 1-3 years, giving 34 independent recordings. From visual inspection we identify three broad themes:

1. Spindles: 16 subjects show extensive spindle activity, and another 4 less well-defined spindle activity.
2. Slow waves: 23 subjects show SW activity (<1 Hz), of which 6 (9 independent recordings 2014-17) show particularly strong (200-600 μV, p-p), consistent and well-defined SW activity, frequently "travelling" (Massimini, *et al*., 2004), and dominating the EEG. Three other subjects show equally strong, but quite different, isolated SWs recurring every 10-30 secs. The remainder are of variable strength and form.
3. Instability in the form of discrete bursts of spike-waves (S-Ws) for 7 subjects.

The presence of persistent and strong SWs, and spindles, invites comparison to nREM sleep, anaesthesia and coma, while the occurrence of S-Ws is reminiscent of absence epilepsy. In this section each of these themes is taken in turn, with its own discussion, with the findings considered as a whole in the final Summary and Conclusions.

3.1. SPINDLES

To examine spindling separate from SWs as well as higher frequency beta and gamma activity, a 5.3-15 Hz bandpass was used, and three examples are shown in Figure 1. Some subjects show extensive global spindles (e.g. middle panel), others less extensive, but all the subjects we have recorded show involvement of occipital areas.

While the origin of spindles is generally accepted as thalamic (Souza *et al*., 2016), modes of propagation within thalamo-cortical networks are not well-understood. To explore cortical sources that underlie meditation-related spindles, 15 subjects showing the clearest examples of spindling were chosen for independent component (IC) analysis using WinEEG. Subject 1 was recorded in 2014 and 2016, giving 16 independent samples. ICs were computed for 60-sec samples from each subject, with bandwidth 5.3-15 Hz, and 4-sec epochs with 50% overlap Hanning windows. Sources were computed for the strongest ICs that in total accounted for at least 50% of the signals' variance of each sample, with total variance normalised to 50%, using the reverse solution of eLoreta (Pascual-Marqui, 2007). Figure 2 is an example for subject 14, 2016. In this case, the two strongest sources (ICs 1, 2) are limbic, Brodmann 31 the cingulate gyrus, and B30 the parahippocampal gyrus. The other two sources are temporal (IC3) at B7 precunius, and occipital (IC4) at Brodmann 19 the fusiform gyrus.

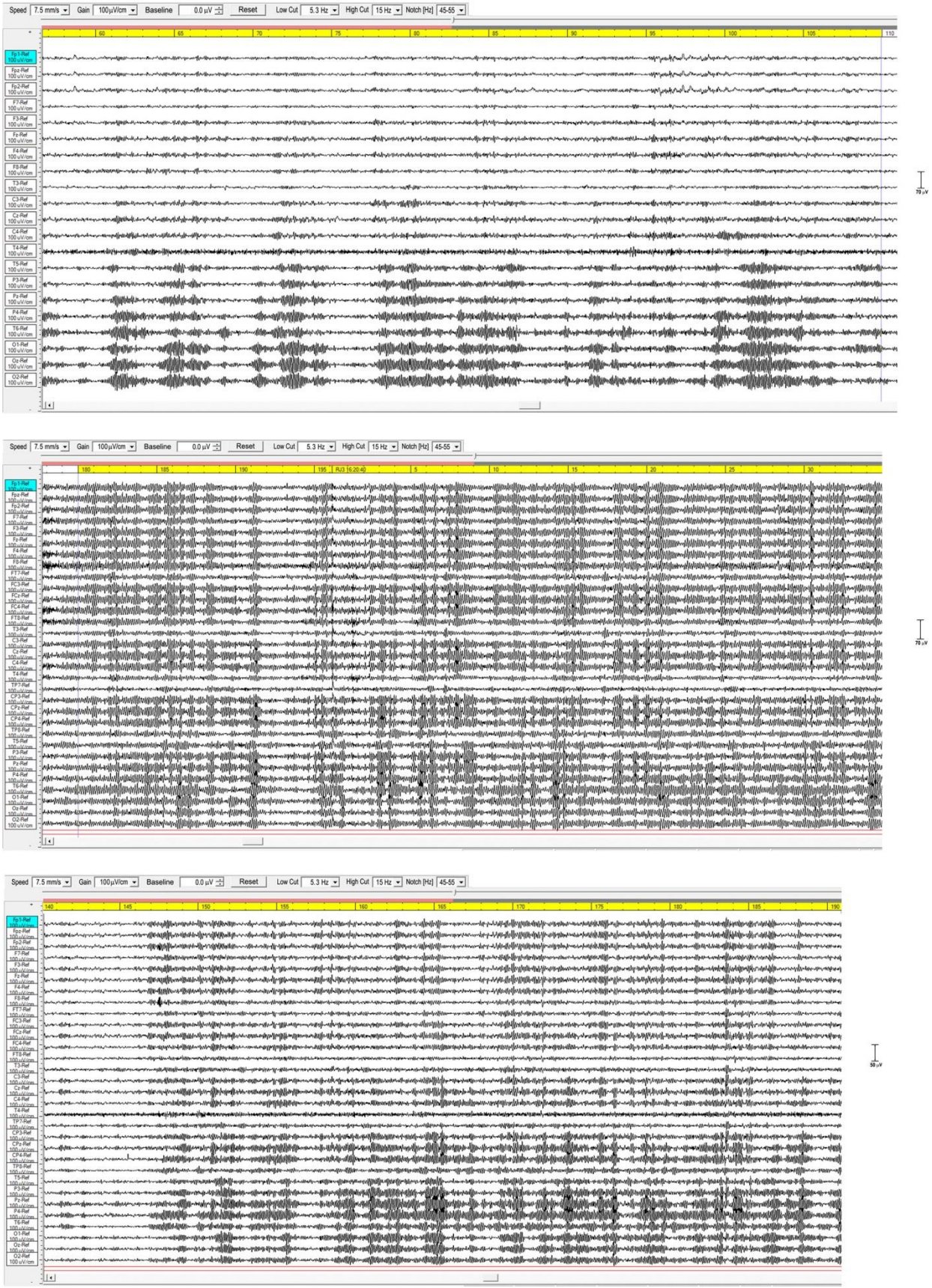

Figure 1 Three examples of spindling. The upper panel is from a recording of subject 16, 2016, the middle panel subject 1, 2014, and the lower panel subject 7, 2015. Bandpass 5.3-15 Hz.

The results for all 15 subjects are summarised in Table 1. The first column lists the dominant spindle spectral frequency for each subject, and the other columns the contributing sources by percentage, with corresponding Brodmann areas, and MNI (Montreal Neurological Institute) xyz coordinates. Subjects 9, 16 and 24 show dominant spindle frequencies of 10.01, 10.25 and 10.50 Hz, respectively, close to the

natural peak alpha frequencies of these subjects in their (non-meditating eyes-closed) resting state. The remaining subjects show spindle frequencies significantly lower than their natural alpha peak, in the case of subjects 1 and 6 well into the theta band at 7.51, 7.81 and 8.06 Hz. Subjects 2, 7 and 25 show double peaks below the alpha band, and in a number of cases there is evidence of weaker lower frequency sub-peaks in the spectra of the individual components.

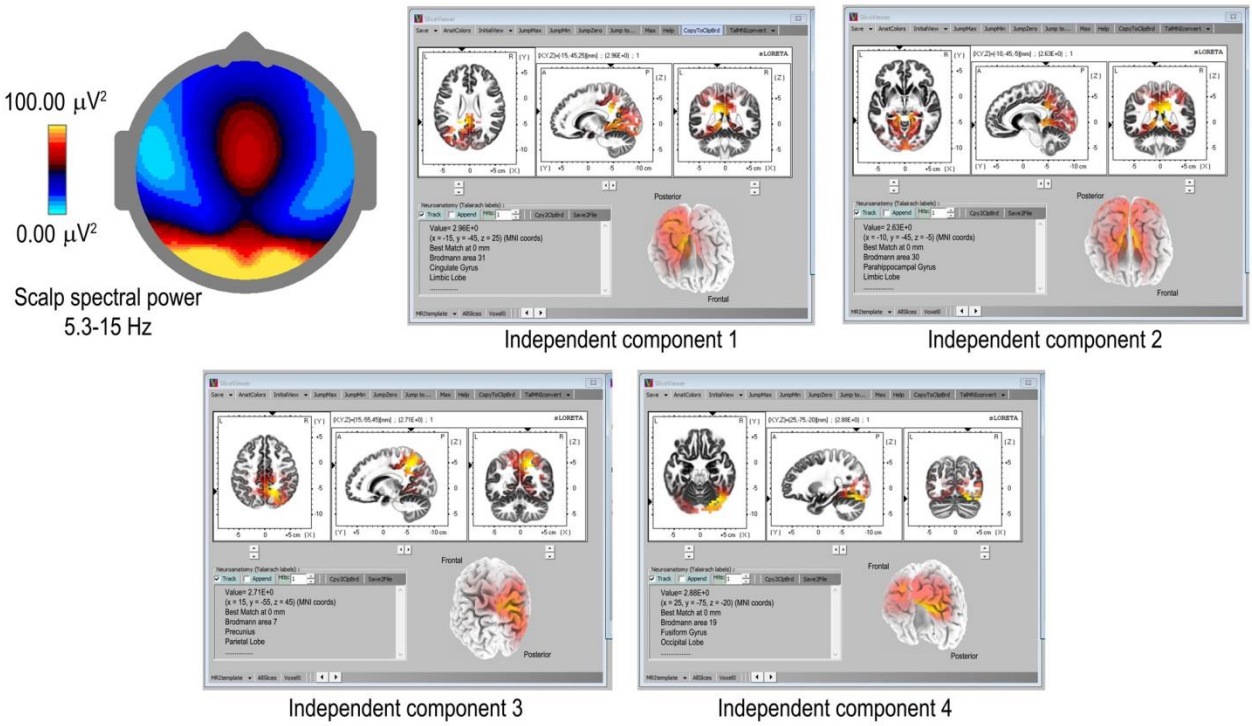

Figure 2 Spindle sources computed using eLoreta for a 60-sec sample of spindles (subject 14, 2016), bandwidth 5.3-15 Hz, 4-second epochs. The scalp mean spectral power distribution is shown upper left.

When summarised into dominant regions of interest (ROIs), normalised to 100% total signals' variance, the anterior-most frontal sources are in Brodmann areas B10, B11 and B47, amounting to 9.3%; frontal sources closer to the vertex at Brodmann B6, B4, B3 and B5 amount to 8.2%; parietal sources at Brodmann B7, B40 and B19 amount to 25.5%; limbic sources at Brodmann B30 and B31 amount to 10.3%; temporal sources amount to 24.8%; and occipital sources contribute 21.9%.

3.1.1 Discussion

Sleep spindles have been well-researched in neuroscience, and although there are superficial similarities to the spindles we observe, there are significant differences. Early work by Werth *et al*. (1997) identified two distinct types of sleep spindle, slow spindles centred on ~11.5 Hz and fast spindles centred on ~13.0 Hz. Similarly, Del Felice *et al*. (2014) researching cortical sources, found predominantly frontal sources for slow spindles in the 10-12 Hz band, and parieto-temporal sources with smaller frontal and occipital contributions for fast sleep spindles in the 12-14 Hz band. In our results, for this form of meditation, spindle frequencies are significantly different to the patterns seen in sleep, as shown in the bottom panel of Table 1; slower, extending from the low alpha range down to the theta band, and we do not observe two discrete frequency bands as in sleep, for any one subject. We believe it is significant that the disruption to the DCs as a person approaches deep sleep, results in spindling at the upper part of the alpha band (slow spindles), or displaces the alpha activity to a higher frequency range just higher than the alpha band (fast sleep spindles).

Sleep is not the only situation where spindling close to or within the alpha band occurs. For example, Sonnleitner *et al*. (2012) demonstrate enhanced alpha spindling in studies of driver-distraction and conflicted attention, even when drivers are not drowsy. In the context of this paper, we regard their findings as a relatively mild disruption of the DCs networks. Similarly, Foxe and Snyder (2011) review

Subject no. and year recorded	Spindle frequency Hz	B10 SFG (Frontal lobe)	B11/B47 MFG SFG IFG Rectal (Frontal lobe)	B6/B4/B3/B5 SFG PCL PCG PCoG (Frontal lobe)	B7/B40/B19 Pcun SMG IPL Subgyral (Parietal lobe)	B30/B31 pCing Cing PHG (Limbic lobe)	B20/21/22/37/39/40/42 ITG MTG STG SMG Ang Fus (Temporal lobe)	B17/B18/B19 IOG MOG Cun pCun Fus Ling (Occipital lobe)
1. 2014 Normalised to 50%	**7.57 Hz** **+ weak 9.03 Hz**	**19.1%** B10 SFG ±5 65 -5					**8.6%** B40 SMG 60 -55 20 **8.5%** B39 MTG -45 -80 20	**7.3%** B18 Ling 5 -90 -20 **6.5%** B19 Fus 40 -65 -20
1. 2016 Normalised to 50%	**7.81 Hz** **+ weak 9.28 Hz**				**13.9%** B40 SMG 55 -50 30		**10.2%** B20 Fus 55 -40 -25	**11.1%** B18 Cun -15 -100 15 **8.6%** B19 Fus 35 -70 -20 **6.2%** B19 MOG 30 -95 10
6. 2015 Normalised to 50%	**8.06 Hz**		**10.9%** B11 Rectal 5 50 -25 **8.5%** B11 SFG 5 65 -10	**8.9%** B5 PCL 0 -35 60 **9.4%** B3 PCG -20 -40 70	**12.3%** B40 SMG -60 -55 25			
7. 2015 Normalised to 50%	**9.77/10.01 Hz** **double peak** **+weak 8.06 Hz**				**15.2%** B7 Pcun 10 -50 55 **11.9%** B7 Pcun -5 -70 35 **10.2%** B7 Pcun -10 -65 40 (ext to PCG)		**6.4%** B22 MTG 65 -50 -10 **6.3%** B39 STG 55 -60 30	
10. 2015 Normalised to 50%	**9.52 Hz**			**9.0%** B6 SFG 5 5 70 **3.5%** B6 SFG -5 -5 70			**27.6%** B37 Fus 45 -55 -20 **9.9%** B40 SMG 55 -50 20	
16. 2016 Normalised to 50%	**10.25 Hz**					**8.4%** B30 pCing -10 -55 5		**17.0%** B19 Fus -25 -55 -15 **13.8%** B19 Cun 25 -85 30 **10.8%** B19 MOG 40 -70 5
24. 2016 Normalised to 50%	**10.5 Hz**		**5.5%** B11 Rectal 5 15 -25 **5.4%** B11 SFG 15 65 -15		**14.9%** B7 Pcun -20 -75 40 **13.0%** B7 Pcun -5 -65 40		**11.2%** B39 STG 55 -60 25	
14. 2016 Normalised to 50%	**9.52 Hz** **+ weak 4.64, 6.84 and 9.28 Hz**				**10.8%** B7 Pcun 15 -55 45	**17.9%** B31 Cing -15 -45 25 **15.6%** B30 PHG -10 -45 -5		**5.7%** B19 Fus 25 -75 -20
15. 2016 Normalised to 50%	**8.54 Hz** **+ weak 7.32 Hz**			**8.9%** B5 PCL 10 -45 60 **8.1%** B6 PCoG -60 -10 40	**12.1%** B7 Pcun 20 -75 40 **3.4%** B40 IPL 40 -45 40		**4.2%** B42 STG -65 -30 15	**13.3%** B18 IOG -40 -90 -10
9. 2015 Normalised to 50%	**10.01 Hz**		**8.4%** B11 MFG ±5 65 -15					**11.0%** B17 Cun ±5 -100 -5 **9.7%** B18 Ling 10 -100 -10 **5.9%** B17 Ling 15 -95 -5

								8.0% B18 MOG 15 -90 15 **7.0%** B18 Cun 5 -100 15
2. 2016 Normalised to 50%	**9.03/9.28 Hz double peak**			**16.5%** B4 PCG -10 -40 60	**9.7%** B40 Subgyral -35 -45 35 **7.0%** B40 IPL -35 -55 40	**10.4%** B30 pCing 20 -55 5		**6.4%** B31 Pcun -5 -70 20
28. 2017 Normalised to 50%	**8.30 Hz** **+ weak 7.57 Hz**		**10.6%** B47 IFG -50 30 -10 **5.7%** B11 MFG 30 35 -20				**17.1%** B20 ITG -65 20 -20 **16.6%** B20 ITG/Uncus -30 -5 -40	
27. 2016 Normalised to 50%	**9.03 Hz** **+ weak 8.06 and 10.5 Hz**				**6.9%** B40 IPL -60 -40 25	**20.6%** B31 Cing -10 -45 30	**8.6%** B21 MTG -65 -25 -15 **13.9%** B39 MTG/Ang 50 -75 25	
25. 2016 Normalised to 50%	**8.06 and 9.77 Hz**				**17.6%** B19 Pcun -5 -85 40 **5.4%** B19 Pcun -35 -80 40 **8.6%** B40 IPL 50 -50 25		**9.6%** B39 MTG -35 -65 25	**8.8%** B19 MOG 35 -90 15
21. 2016 Normalised to 50%	**9.28 Hz** **+ weak 7.81 Hz**					**10.4%** B31 Cing 20 -25 40	**11.7%** B22 STG 50 -35 0 **9.0%** B19 MTG 50 -80 10	**12.3%** B19 Cun -15 -95 25 **6.6%** B18 Ling -10 -90 -20
19. 2016 Normalised to 50%	**9.03 Hz**				**11.9%** B40 IPL 65 -35 30 **10.8%** B40 IPL 50 -60 40 **8.4%** B19 Pcun 5 -85 40		**11.0%** B20 ITG 65 -10 -25 **7.9%** B39 MTG/Ang -40 -75 35	
Sub-Totals		**19.1%**	**55.0%**	**64.3%**	**203.4%**	**83.3%**	**198.3%**	**176.0%**
Norm. to 100%		**2.4%**	**6.9%**	**8.0%**	**25.4%**	**10.5%**	**24.8%**	**22.0%**
ROIs **Norm. to 100%**		**B10 B11 B47** **Frontal 9.3%**		**B6/B4/B3/B5** **Frontal 8.2%**	**B7/B40/B19** **Parietal 25.5%**	**B30/B31** **Limbic 10.3%**	**Temporal** **24.8%**	**Occipital** **21.9%**

					…….. SLOW SLEEP SPINDLES ……..		**……. FAST SLEEP SPINDLES …….**	
	…….……MEDITATION SPINDLES …….…..							
Spindle frequency Hz	**7.0**	**8.0**	**9.0**	**10.0**	**11.0**	**12.0**	**13.0**	**14.0**
Occurrence		• • •• • •	••• •• •• ••	•• • •				

Table 1 Spindle sources with MNI coordinates.

SFG, MFG, IFG = superior, middle, inferior frontal gyri; PCL, PCG, PCoG, Rectal = paracentral lobule, postcentral, precognitive, rectal gyri; Pcun, SMG, IPL = precunius, supramarginal gyrus, inferior parietal lobule; pCing, Cing, PHG = postcingulate, cingulate, parahippocampal gyri; ITG, MTG, STG, SMG, Ang, Fus = inferior, middle, superior temporal, supramarginal, angular, fusiform gyri; IOG, MOG, Cun, pCun, Fus, Ling = inferior, middle occipital gyri, cuneus, precuneus, fusiform and lingual gyri.

other evidence that alpha band activity can play a role as a sensory suppression mechanism in selective attention, and Jensen and Mazaheri (2010) propose that alpha activity performs an important gating mechanism in interregional communication between brain networks.

Of the 27 subjects for whom we have good recordings, a high proportion, 24, show significant spindling. Although these subjects are very experienced in Samatha meditation, more than half would acknowledge being relative beginners in their experience of jhāna. We believe, therefore, that the widespread occurrence of spindling that we observe is most likely related to the approach to jhāna, and development of the first rūpa jhāna, where mastering attention is the dominant factor, and that the form of spindling we observe is an early sign of a meditator's growing success in resisting the habitual attention processes of naming (inevitably related to language), and recognition and discrimination (heavily visually-determined) within a sensorily-structured framework. Overall, we suggest that alpha activity as disrupted both in sleep and other disruptions of attention, and in this form of meditation, is an integral part of the human DCs, certainly more important than older views that it is simply an "idling rhythm"; one might even suggest it is the signature of the DCs. This is supported by Grandy *et al*. (2013), who show that a person's individual alpha frequency (IAF), predominantly in the range 8-12 Hz across persons, is remarkably stable for any individual across periods of months, and in response to a wide range of cognitive tasks. It is also relevant in considering alpha activity to be a key component of the DCs, that the ~100ms periodicity of the alpha rhythm is close to the human reaction time, with implied connectivity to sensorimotor networks and readiness for action.

If sleep spindles represent one kind of disruption to the DCs, and given the differences noted above to meditation spindles, how do the underlying cortical networks compare? As a meditator resists naming and recognition, turning attention inwards towards the qualia of consciousness, towards the *nimitta* mentioned in the Introduction, we expect that the underlying cortical sources might represent disruption to the dorsal and ventral processing streams heavily involved in attention and visual and auditory processing, that form the "what" and "where" of our DCs experience (Cloutman, 2012; Milner, 2017). Furthermore, we expect, in line with our discussion in the Introduction, that withdrawal from the DCs sensory attention systems will also impact cortical networks involved in memory, as well as spatial and temporal orientation, integral parts of our DCs experience of self.

Table 2 summarizes the ROIs from the detailed findings of Table 1. Given the limitations to spatial resolution of 31 or 21 electrodes, the overall picture shown by Table 2 fits surprisingly well with our hypothesis, and although there is some overlap with cortical sources found for sleep spindles, as in Del Felice *et al*. (2014), the pattern we find is notably different. The significant presence of limbic sources

SPINDLES SUMMARY 15 subjects (16 records 2014-17) Bandpass 5.3-15 Hz 4 sec. epochs	**B10 SFG** **Frontal Lobe** z-coord -5	**B11 B47 MFG SFG IFG Rectal** **Frontal Lobe** z-coord -10–-25	**B6 B4 B3 B5 SFG PCG PCL PCoG** **Frontal Lobe** z-coord +40–+70	**B7 B40 B19 Pcun SMG IPL Subgyral** **Parietal Lobe** z-coord +25–+55	**B30 B31 Cing pCing PHG** **Limbic Lobe**	**B20/B21/B22/B37/ B39/B40/B42 ITG MTG STG SMG Ang Fus** **Temporal Lobe**	**B17/B18/B19 IOG / MOG Cun pCun Fus Ling** **Ooccipital Lobe**
Sub-Totals	**19.1%**	**55.0%**	**66.0%**	**203.7%**	**82.4%**	**198.3%**	**175.5%**
Norm. to 100%	**2.4%**	**6.9%**	**8.2%**	**25.5%**	**10.3%**	**24.8%**	**21.9%**
ROIs Norm. to 100%	**B10 B11 B47 Frontal 9.3%**		**B6/B4/B3/B5 Frontal 8.2%**	**B7/B40/B19 Parietal 25.5%**	**Limbic 10.3%**	**Temporal 24.8%**	**Occipital 21.9%**
			Dorsal pathway		**Ventral pathway**		

Table 2 Meditation spindle sources, ROIs.

supports our expectation of effects on memory and spatial and temporal orientation, and is in accord with Kravitz *et al*'s (2011) view of limbic involvement in the ventral pathway. The ventral pathway links occipital sources via temporal and limbic sources, to frontal sources; while the dorsal pathway links to frontal sources via fronto-parietal networks. This is an average picture across 15 subjects, and no individual subject shows a clear preference for one or other path.

This leaves us with the interesting question - what determines the effects on alpha activity and the shifts in spindle frequency in these different modes of disruption of the DCs? Driver distraction or conflicting attention tasks set in protocols where a subject is asked to respond, are by definition within the activities of DCs, and the spindle frequency does not appear to be significantly different from the alpha frequency, from published reports. Moving away from the DCs towards sleep, the spindle frequency is either at the high end of the alpha band, or higher still, than the alpha typical of the DCs, while in approaching jhāna it is significantly lowered (Table 1). It is possible that this represents the difference between bottom-up and top-down processes, respectively, but more work is needed to clarify the mechanisms, as well as the role of the thalamus in determining the frequency in these different modes of disruption.

3.2. SLOW-WAVE (SW) ACTIVITY

We consider SWs as falling within the frequency band 0.1-1.0 Hz, to distinguish from delta waves in the 1.0-4.0 Hz band. Figures 3-5 show 9 independent recordings that illustrate some of the main features we find. In each case the EEG electrode sites are labelled at the left, from frontal sites at the top, to occipital sites at the bottom. The top bar indicates time in secs. The top panel in Figure 3 (subject 5, 2014) shows intense SWs at frontal, occipital and central-temporal sites. The inset scalp maps for the interval 64.8-71.9 secs (marked yellow, top bar) show what we find to be a typical pattern of alternating SW inhibition-excitation, that in this example reach 1350 μV p-p at CPz.

A similar pattern (reaching p-p values >350 μV) is shown in the middle panel of Figure 3 (subject 3, 2015), where the inset scalp maps for the segment 160.7-165.1 secs show an almost complete annulus of inhibition-excitation. In both cases there is also a more localised active region just posterior to the vertex, and both show enhanced occipital gamma activity superposed on the SWs. The bottom panel (subject 17, 2016) illustrates how for some meditators the SW onset can be very rapid. A very brief widespread gamma burst marks this subject hearing the instruction to start meditation, followed, ~12 secs later, by 100 μV and 300 μV inhibitions at temporal sites T3 and T4 respectively, with the main widespread SW activity beginning ~20 secs later still, reaching remarkable intensities exceeding 2000 μV p-p at times. The scalp map shows that the initial massive inhibition at ~40 secs forms a complete annulus of inhibition around central midline areas.

The top panel in Figure 4 (subject 24, 2016) shows SWs that are particularly strong at occipital sites. The inset maps for the SW at 212-216 secs again show an annulus of inhibition-excitation enclosing central areas. This subject also shows brief periods of enhanced gamma activity, as at 206-212 secs, as well as shorter spike-wave (S-W) bursts lasting 2-6 secs at occipital sites. In the middle panel (subject 26, 2016) the SWs are strongest at frontal sites; this subject also shows S-W activity and enhanced gamma activity at occipital sites. The inset maps for the SW at 66-70.5 secs again show the typical inhibition-excitation, but in this case the annulus is not quite complete.

Rather than the extensive and more or less continuous SW activity described so far, some meditators show isolated SWs with longer periods of recovery, or relative "silences" between. The lower panel of Figure 4 (subject 19, 2016) is an example. This subject shows fast responsiveness and SW onset similar to subject 17 in Figure 3. In this case the verbal instruction to "start meditation" at 120-123 secs elicited a widespread uptick, including gamma activity, in most channels at 122 secs, followed ~5 secs later by massive excitation at frontal sites reaching 2400 μV at Fp2, one of the highest levels we have recorded; followed ~3.6 secs later at temporal sites T3 and T4. For this subject, the intense +ve SWs are accompanied by strong increases in the gamma band.

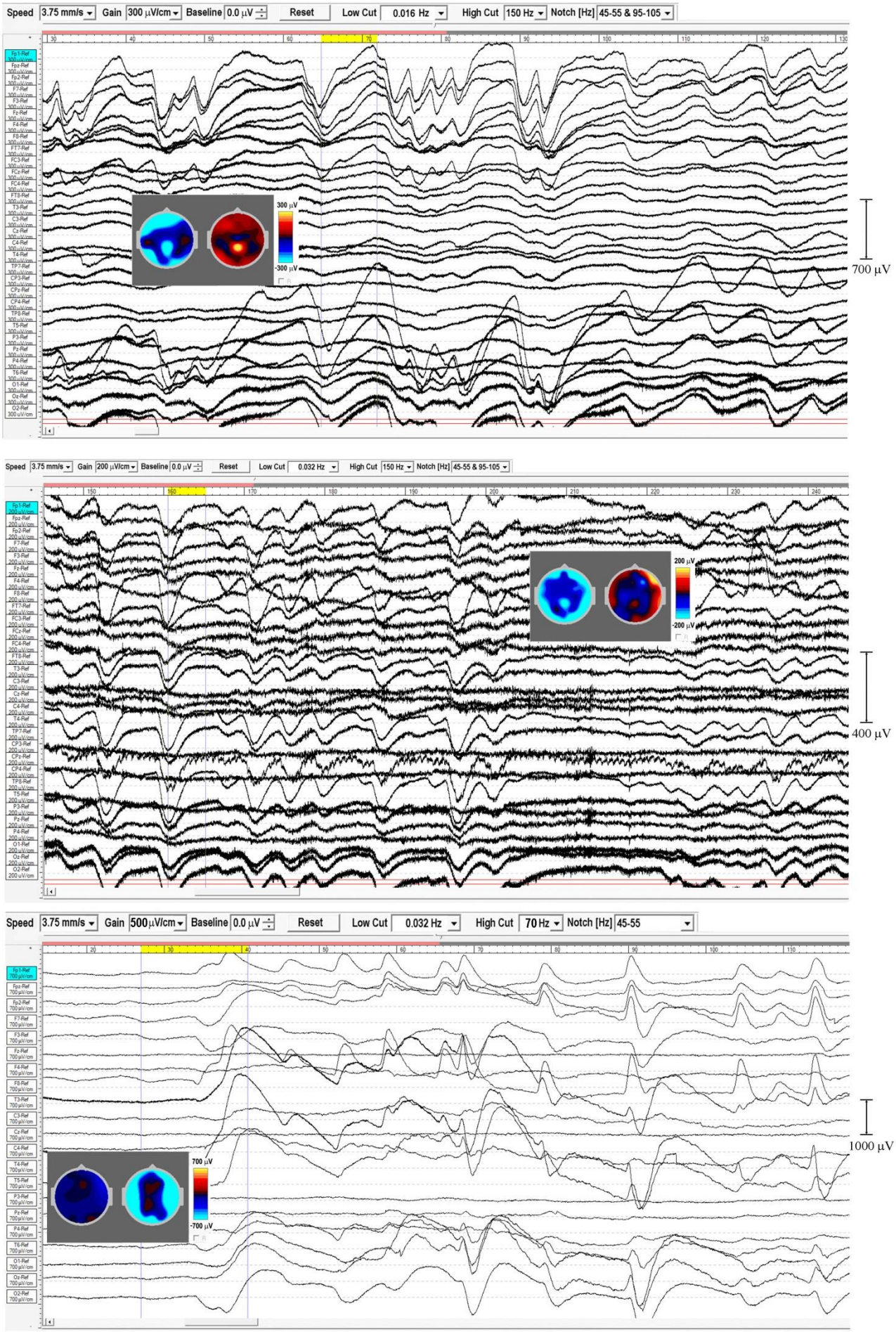

Figure 3 EEG recordings of Samatha meditators. Top panel subject 5, 2014; middle panel subject 3, 2015; bottom panel subject 17, 2016. Note the sudden onset of SWs for subject 17.

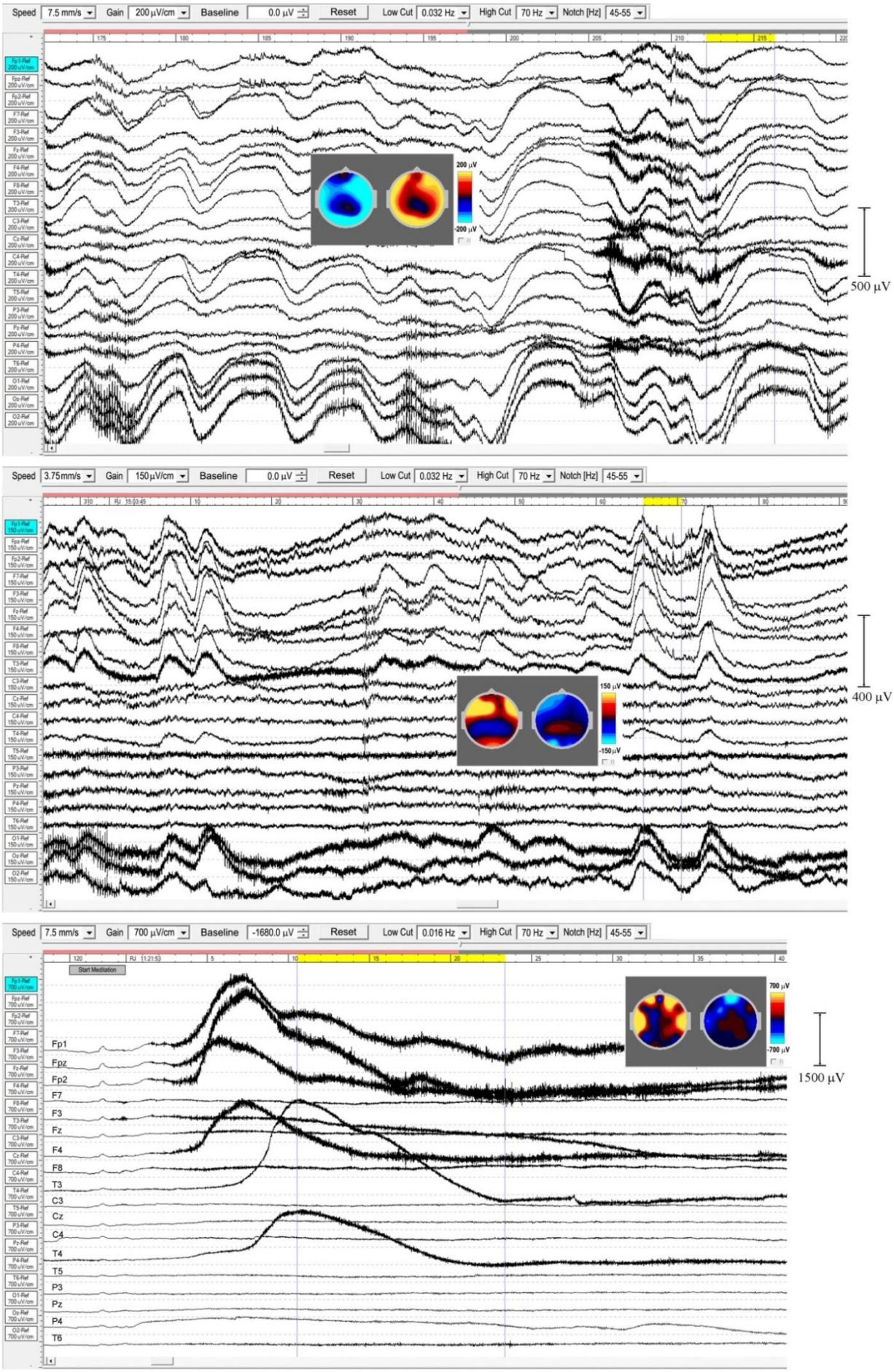

Figure 4 EEG recordings of Samatha meditators. Top panel subject 24, 2016; middle panel subject 26, 2016; bottom panel subject 19, 2016. Note the posterior spike-wave bursts for subject 24, and the isolated extremely high voltage SW shown by subject 19.

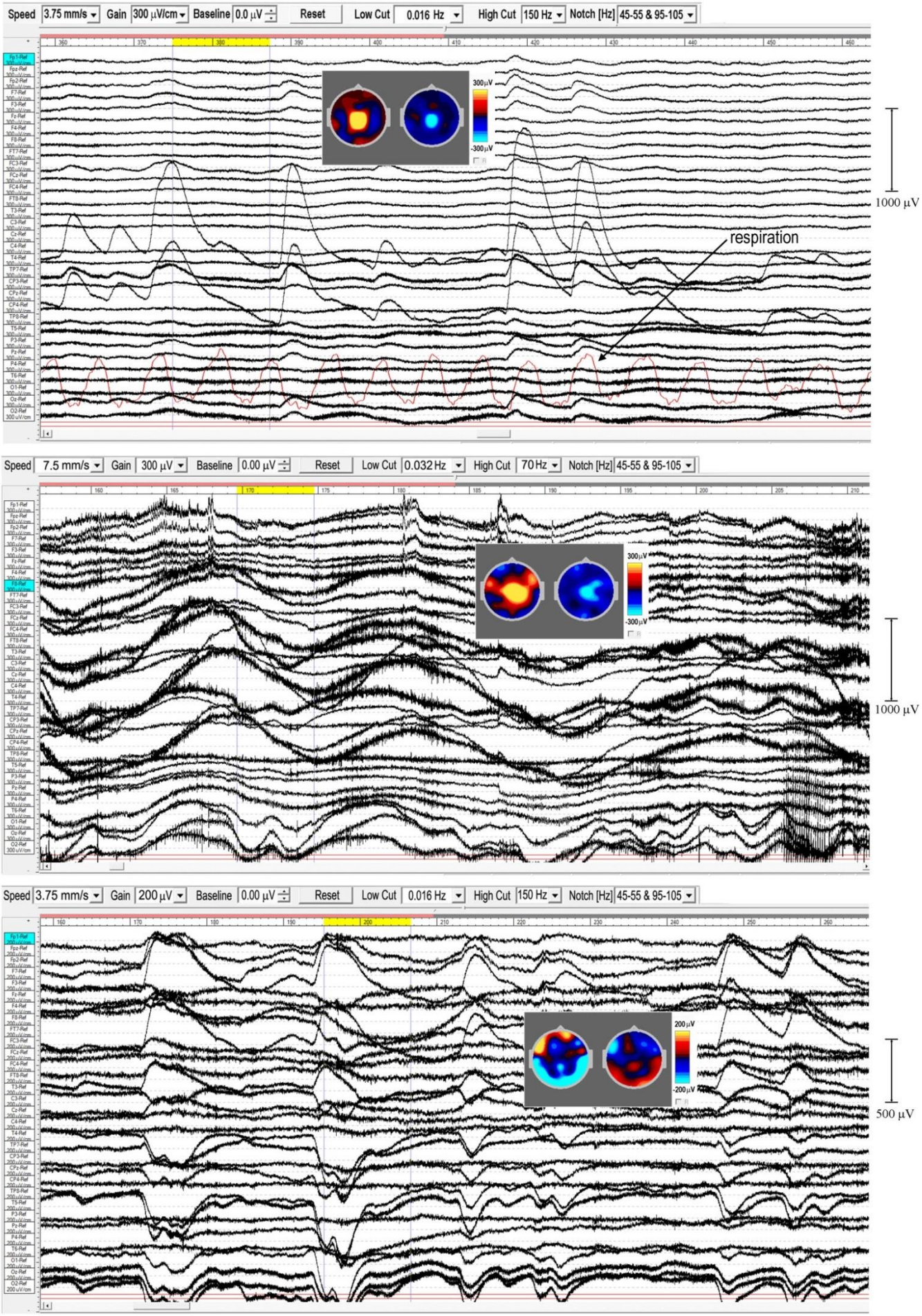

Figure 5 EEG recordings of Samatha meditators. Top panel subject 5, 2017; middle panel subject 24, 2017; bottom panel subject 3, 2017.

The scalp maps for the segment 10.5-23.3 secs again show the familiar alternation excitation-inhibition, which in this case is focused at frontal and temporal sites, with occipital sites unaffected. We believe that isolated SWs as in this example represent a different mechanism than the more continuous SWs, and require further analysis that will be the subject of a future paper.

Subjects 5, 24 and 3, previously recorded in 2014, 2015 and 2016 (Figures 3 and 4), were recorded again in 2017, with samples shown in Figure 5. By this time these subjects were more confident in jhāna practice. The SW activity for subject 5 in the top panel of Figure 5 is now focused very strongly near the vertex at sites Cz and CPz, with the familiar alternation of excitation-inhibition seen in the scalp maps for the marked section; compared to the previous recording of this subject in 2014, frontal and occipital sites are relatively silent. The form of the SWs is also different, with a more rapid +ve onset, and a slower recovery, reminiscent of patterns found for relaxation oscillators. The rate of rise for the SW at 418 secs reaches ~1400 μV/sec., during the rise from -200 μV to 1300 μV. Subject 24 in the middle panel also shows stronger SW activity at sites around the vertex, prominent in the sample scalp maps, compared to 2016; and again shows S-W activity at occipital sites as in 2016.

The recording of subject 3 in the lower panel was an attempt to explore arūpa (formless) jhāna, and is quite different to those described so far, including the previous recording of this subject 2 years' earlier. The most startling feature is that the frontal SWs are in almost exact antiphase to the occipital SWs, the implications of which will be discussed later in the Summary and Conclusions.

3.2.1. SW Statistics

Table 3 summarises SW statistics from over 90 mins (676 SWs) of EEG from 9 independent recordings of 6 subjects, 2014-17, who show strong and consistent SW activity. Eight of these are the same subjects as in Figures 3-5, but omitting subject 19 of Figure 4 who, as noted above, shows a different pattern of isolated SWs. Subject 10, 2015, is a new addition to Table 3, also showing consistent SWs over several minutes, though not as strong as those in Figures 3-5. Sections of at least 3 successive SWs were examined, and the periods between successive +ve to +ve, or –ve to -ve peaks measured, according to whether +ve or –ve peaks were dominant (Figure 5, top panel, is an example of +ve-dominant peaks). P-p voltages from either a +ve peak to the following minimum, or from a -ve peak to the following maximum were measured, giving a mean p-p SW amplitude of 382±70 μV, with individual amplitudes ranging from ≲100 μV to 2255 μV. Across all the recordings, the mean SW period was 8.32±0.57 secs, corresponding to a mean SW frequency of 0.120±0.008 Hz.

Subject	**Mean period (secs) between successive +ve or –ve SW peaks, excluding "silences"** (with SE of mean) **N = no. of SWs**	**Mean frequency (Hz)** (with SE of mean)	**Mean p-p amplitude (μV) of successive SWs, from +ve peak to following minimum, or –ve peak to next maximum, excluding "silences" N = no. of SWs**	**Transit time estimates**
5, 2017 At Cz, +ve peaks	9.59 ± 0.66 secs N=91	0.104 ± 0.007 Hz N=91	696 ± 47 μV N=94	Mostly near-simultaneous at Cz and CPz (and to a lesser extent at TP7), ±200 ms
5, 2014 At CPz, -ve peaks	10.45 ± 0.50 secs N=93	0.096 ± 0.005 Hz N=93	469 ± 26 μV N=99	Frontal to occipital (Fp1 to O1/O2), 593±300 ms Frontal to temporal (Fp1 to T5), 723±230 ms Frontal to central (Fp1 to CPz), 1278±340 ms
3, 2017 At FT7 +ve peaks	8.94 ± 0.47 secs N=108	0.112 ± 0.006 Hz N=108	245 ± 13 μV N=113	Fronto-central +ve peaks in antiphase with central-occipital –ve peaks, ~simultaneous ±200 ms, or some occipital peaks lead by ~0-200 ms
3, 2015 At F8, -ve peaks	5.74 ± 0.36 secs N=63	0.174 ± 0.012 Hz N=63	206 ± 14 μV N=67	Frontal sites lead occipital sites by 340 ± 100 ms
17, 2016 At F8, -ve peaks	6.65 ± 0.31 secs N=85	0.150 ± 0.008 Hz N=85	654 ± 42 μV N=84	Once SWs established, frontal, central and occipital sites near-simultaneous ±300 ms
24, 2017 At Cz and O1, Near-sinusoidal -ve peaks used	8.07 ± 0.43 secs N=76	0.124 ± 0.007 Hz N=76	492 ± 30 μV N=83	Early in this subject's practice, frontal sites lead central/parietal sites by ~1.5-3.5 secs. Later, **o**ccipital sites lead frontal sites by ~0.4-0.7 secs

24, 2016 At O1 and T3, -ve peaks	6.87 ± 0.40 secs N=74	0.146 ± 0.008 Hz N=74	371 ± 21 µV N=71	Mostly simultaneous ±300 ms, but occasionally occipital sites lead frontal sites by ~0.3-0.5 secs
26, 2016 At Fz and O2, +ve peaks	10.55 ± 0.83 secs N=42	0.095 ± 0.008 Hz N=42	204 ± 27 µV N=38	Frontal sites lead occipital sites by ~0.5-1.0 secs
10, 2015 At Fz and Cz, +ve peaks (irreg. and weaker)	8.05 ± 1.10 secs N=26	0.124 ± 0.020 Hz N=26	104 ± 7.4 µV N=27	Indeterminate
OVERALL MEANS N = total SWs	**8.32 ± 0.57 secs** **N=658**	**0.120 ± 0.008 Hz** **N=658**	**382 ± 70 µV** **N=676**	

Table 3 SW statistics for 7 subjects, 9 independent recordings, 2014-17.

In some recordings, respiration was measured using an induction-loop chest-belt. Subject 5, 2017, for example (top panel of Figure 5), showed a mean SW period of 9.59 ± 0.66 secs (Table 3), and a mean respiration period for the same segment of 9.88 ± 0.33 secs, confirming what visual inspection of data for several subjects shows to be a close relationship between SW and respiration frequency. A more detailed correlation analysis has not been possible to date due to software limitations in WinEEG.

3.2.2 Travelling SWs

The final column in Table 3 gives an indication from visual inspection of the EEG, of the travelling nature of the SWs. In some cases they appear to be near-simultaneous for some 10's of seconds across wide areas, while other sections show frontal sites lead or lag posterior or temporal sites. As far as we can determine, there is no obvious relation to the stage of a subject's meditation. Subject 5, 2014 (top panel, Figure 3), sustained strong and well-defined travelling SWs, 300-700 µV p-p, for over 20 mins, and provides the clearest example of travelling SWs, one of which is shown in Figure 6.

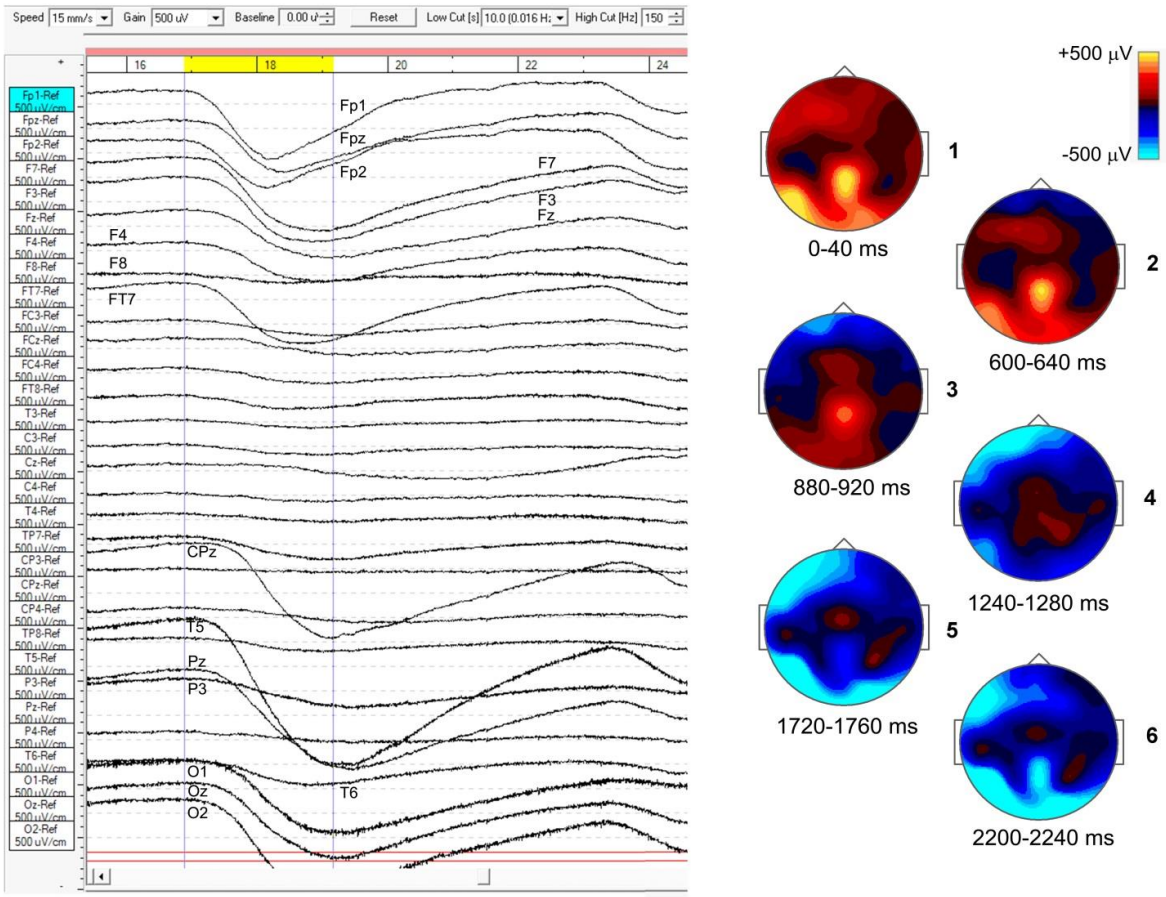

Figure 6 Example of a travelling slow wave (subject 5, 2014), bandpass 0.016-150 Hz.

The scalp intensity maps 1-6 in Figure 6 trace the development of the −ve SW peak across a 2.25-second interval (marked yellow, top bar). Note the localised midline peak, extending from the occipital area to just posterior to the vertex. Also, the considerable, and typical, broadening of the SW as it reaches occipital areas. Scalp map 1 shows the initial +ve phase of the wave, strongest at left-temporal site T5, and midline central-parietal CPz, less intense frontally. The –ve phase then develops frontally, extending left-frontally, before travelling to occipital areas (mainly left), as in maps 2-6. Maps 1 and 6 correspond roughly to the excitation-inhibition peaks. The localised midline peak, in this case just posterior to the vertex, is also apparent for other subjects who show strongly developed and extensive SWs.

Although for any particular meditator the sites of activity remain fairly constant during a recording (in this example, EEG sites Fp1, Fpz, Fp2, F7, F3, Fz, F4, FT7, CPz, T5, Pz, O1, Oz and O2), transit times vary considerably as noted for other subjects in Table 3. In this case, the SW in Figure 6 shows a transit time of the –ve peak, front to rear, of ~1200 ms. For 20 successive SWs from this same subject, transit times varied considerably, with means of: frontal (Fp1) to occipital (O1/O2), 593±300 ms; frontal (Fp1) to temporal (T5), 723±230 ms; and frontal (Fp1) to central-midline (CPz), 1278±340 ms. The mean front to rear transit time ~600 ms corresponds to a mean transit speed for this subject of ~50 cm/s across the head, significantly slower than typical values ~2-3 m/s for sleep SWs (Massimini et al., 2004).

3.2.3. Rhythmic Excitation−Inhibition

The SWs we observe are far from random, and exhibit a rhythmic pattern of powerful excitation−inhibition, as in the example in Figure 6, and also in the inset scalp intensity maps in Figures 3-5. In some cases the SWs form an almost complete annulus of excitation-inhibition surrounding less affected central areas (subjects 3 and 17, Figure 3; and subject 24, Figure 4), with frequent occurrence of a “hot-spot” at or just posterior to the vertex. For other subjects the annulus is only partial. For subjects 5 and 24, re-recorded in 2017 (Figure 5), the vertex hotspot has become the dominant feature.

3.2.4. Cortical Sources

Table 4 summarises a source analysis carried out in the same manner as for spindles, for eight independent recordings across 6 subjects showing the strongest examples of extensive SW activity. Subject 5 was recorded twice, in 2014 and 2017, both with the 31-electrode system; and subject 24 was also recorded twice, in 2016 and 2017, with the 21- and 31-electrode systems respectively. To study low frequency structure <1 Hz, epoch length is a key variable, since it introduces a smoothing factor of its own irrespective of the pass-band. Thus the commonly used epoch length of 4 seconds, while fine for medium and high frequency content, and our earlier spindles analysis, would introduce smoothing for frequencies <0.25 Hz. Similarly epochs of 8, 16, 32 and 64 secs will smooth frequencies below 0.125, 0.063, 0.031 and 0.016 Hz respectively. Depending on the segment lengths in Table 4, an epoch of 32 secs was used for 6 segments >300 secs, and an epoch of 16 secs for the two other segments of 170 and 203 secs, both with 50% overlap Hanning windows. We are therefore confident of capturing frequencies down to at least 0.06 Hz, and to 0.03 Hz for 6 of these recordings. And as noted from Table 3, a mean SW frequency of 0.12±0.008 Hz was estimated from visual inspection.

As with the spindle analysis, cortical sources were computed for the strongest ICs that accounted for at least 50% of the signals’ variance for each sample, with the total variance normalised to 50%, using the reverse solution of eLoreta (Pascual-Marqui, 2007). Averaged across all 8 recordings, amounting to 2796 secs of strong and persistent SWs, sources are found in: frontal sites, Brodmann B10, B11 and B8/9 (24.2% of the total variance across all recordings); at the frontal midline site B6 just anterior to the vertex (27.6%); at parietal midline sites B5 and B7 just posterior to the vertex (18.7%); at temporal sites B20, B21, B22 and B37 (10.2%); and at occipital sites B18 and B19 (19.3%).

The ROIs are summarised in Figure 7, with 3D source maps to aid visualisation, based on superposition of individual components computed from eLoreta that contribute to each ROI. Moving from left to right in Figure 7, frontal sources at Brodmann 10 and 11 give way upwards along the midline to Brodmann sites 8 and 9, and then to the vertex.

Subject **Individual source contributions normalised to 50%**	**B10** **MFG SFG** **(frontal lobe)** **X +ve/-ve = R/L**	**B11** **MFG SFG** **(frontal lobe)** **X +ve/-ve = R/L**	**B8/B9** **SFG MFG** **(frontal lobe)** **X +ve/-ve = R/L**	**B6** **MFG SFG** **PCL PCoG** **(frontal lobe)** **X +ve/-ve = R/L**	**B5** **PCG** **(parietal lobe)**	**B7** **PCG pCun** **(parietal lobe)**	**B20/B21/B22/** **B37** **MTG ITG STG** **(temporal lobe)** **X +ve/-ve = R/L**	**B18/B19** **MOG / IOG** **Cun** **(occipital lobe)** **X +ve/-ve = R/L**
5. 2017 0.032-150 Hz 360s segment 32s epochs				**27.9%** B6 MFG 5 -15 70 **12.9%** B6 MFG 5 -25 70 **9.2%** B6 MFG -5 -20 70				
3. 2015 0.032-150 Hz 170s segment 16s epochs	**9.0%** B10 MFG 35 60 -5	**5.1%** B11 MFG 10 65 -15				**26.9%** B7 PCG -5 -55 70		**9.0%** B18 MOG 20 -100 0
5. 2014 0.032-150 Hz 600s segment 32s epochs				**15.7%** B6 PCL 5 -35 70	**20.9%** B5 PCG 5 -45 70	**7.1%** B7 PCG 5 -55 70 **4.2%** B7 PCG -5 -55 70	**2.1%** B37 MTG -60 -50 -10	
10. 2015 0.032-150 Hz 420s segment 32s epochs		**5.5%** B11 MFG 5 65 -15	**7.0%** B8 SFG 5 40 55	**22.0%** B6 SFG 5 30 60		**7.7%** B7 pCun 5 -65 65		**7.8%** B18 Cun -5 -100 20
24. 2017 0.032-150 Hz 400s segment 32s epochs		**0.7%** B11 MFG 5 65 -15 **5.2%** B11 MFG -40 55 -10		**6.5%** B6 MFG 5 -25 70 **4.5%** B6 MFG -5 -30 70		**8.0%** B7 PCG 5 -55 70	**7.0%** B21 MTG 65 -55 0	**18.1%** B19 MOG -40 -90 -5 Extends through temp G to ~ -65 -10 -15
24. 2016 0.032-70 Hz 343s segment 32s epochs	**5.5%** B10 MFG 35 60 -10 **4.6%** B10 SFG -35 50 30	**9.7%** B11 SFG 10 65 -10 **6.6%** B11 SFG 15 65 -15	**2.0%** B9 MFG 10 50 40	**5.5%** B6 SFG -20 10 70 **3.0%** B6 SFG -5 5 70 **3.1%** B6 PCoG 25 -15 70				**10.0%** B18 IOG -40 -90 -5
17. 2016 0.032-70 Hz 300s segment 32s epochs		**10.8%** B11 SFG -25 55 -15					**16.1%** B22 STG -60 -60 15	**15.1%** B18 Cun ±15 -100 15 **8.0%** B18 Cun ±5 -100 15
26. 2016 0.032-70 Hz 203s segment 16s epochs	**1.5%** B10 MFG -30 55 -10	**12.0%** B11 SFG -20 65 -10	**1.8%** B9 SFG 10 50 35 **9.7%** B9 SFG ±10 55 40				**15.7%** B20 ITG -65 -25 -20	**9.3%** B18 Cun ±5 -100 15
TOTALs **Normalised to 100%**	**20.6%** **5.2%**	**55.6%** **13.9%**	**20.5%** **5.1%**	**110.3%** **27.6%**	**20.9%** **5.2%**	**53.9%** **13.5%**	**40.9%** **10.2%**	**77.3%** **19.3%**
ROIs **Normalised to 100%**	**B10/B11/B9 Frontal** **24.2%**			**B6 Frontal** **midline vertex** **27.6%**	**B5/B7** **Parietal midline vertex** **18.7%**		**B20/B21/B22/B37** **Temporal** **10.2%**	**B18/B19** **Occipital** **19.3%**

Table 4 Cortical sources for 8 independent recordings of 6 subjects, 2014-17, with bandwidth 0.032-150 Hz for the 31-electrode system, and 0.032-70 Hz for the 21-electrode system. Epoch lengths either 16 secs or 32 secs were used as appropriate for segment length. MFG, SFG, PCG, MTG, ITG, STG, MOG, IOG, PCoG, PCG = medial frontal, superior frontal, postcentral, middle temporal, inferior temporal, superior temporal, middle occipital, inferior occipital, precognitive and postcentral gyri; PCL = paracentral lobule; pCun = precunius; Cun = cuneus. Each contributing source is listed with its MNI xyz coordinates.

The midline area near the vertex, bridging the frontal-parietal junction is the dominant ROI, accounting for 46.3% of the total signals' variance. Temporal sources are predominantly left, and diffuse, and merge with, again predominantly left, inferior and middle occipital sources, and finally at far right the midline cuneus.

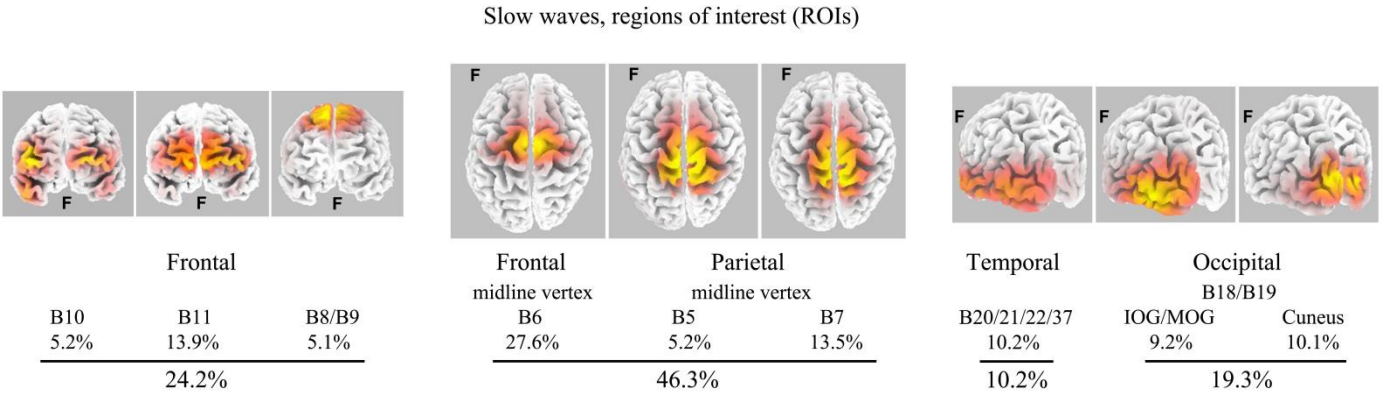

Figure 7 Summary of SW regions of interest, based on Table 4, for 8 independent recordings of 6 subjects, 2014-17

3.2.5. Infra-Slow-Wave (ISW) Activity

Infra-slow EEG activity (defined here as 0.01-0.1 Hz) has been little studied in the literature, largely due to difficulties with DC drift and confusion with noise and artifacts, as well as the requirement of long records to allow epochs ideally greater than 60 secs to be used. We have two examples of particularly strong SW activity where the raw data suggest an underlying slower rhythm than the mean 0.12 Hz SWs analysed above. However, software limitations of a minimum low-cut frequency of 0.016 Hz and a maximum epoch of 64 secs, impose a frequency cut-off at $\lesssim$0.02 Hz, so at this point we can only offer provisional estimates based on visual inspection of the EEG data.

Figure 8 shows segments from subject 17 (2016), and subject 5 (2017) with, to the right, superposed SWs from the longer recordings (300 and 600 secs respectively) showing a similar pattern of rapid leading edge, with much slower, over-shooting recovery. The superpositions show half-periods ~21 and ~26 secs respectively, suggesting an underlying ISW frequency of ~0.02 Hz. Bearing in mind the software limitations noted above, a spectral analysis of a 600-sec segment from subject 5, using 64-sec epochs and 0.016 Hz low cut, shows some evidence of a peak at 0.02-0.03, and also at 0.05 Hz.

3.2.6. Discussion

While at first sight the SWs we observe are reminiscent of those in nREM sleep, or high-voltage delta coma (Sutter and Kaplan, 2012), there are important differences. First, the mean frequency 0.12 Hz is significantly lower than that of SWs in either sleep or coma (typically 0.8-1.2 Hz); while the mean p-p intensity, 382 μV, with individual SWs reaching over 2000 μV p-p, is much greater than typical values 100-300 μV found in sleep or coma (Libenson, 2012). The frequency of SWs in sleep or coma is believed to be determined by haemodynamic pressure (Mensen *et al*., 2016), hence the similarity to typical pulse rates, while the SWs in this study appear to be related to the respiration rhythm. In addition, our observation of a much slower underlying ISW frequency ~0.02 Hz, points to an even more extensive endogenous or metabolic component, that we believe indicates metabolic integration or self-regulation during the deeper levels of this form of meditation. We can speculate that this infraslow activity corresponds to the slow alternations seen in fMRI/BOLD imagery of subjects in the resting state (Grooms *et al*.,, 2017), and that it may represent a harmonic "beating" between the other SW frequencies present in the same subject, in a similar manner to Steyn-Ross *et al*.'s (2010) model for ultra-slow oscillations.

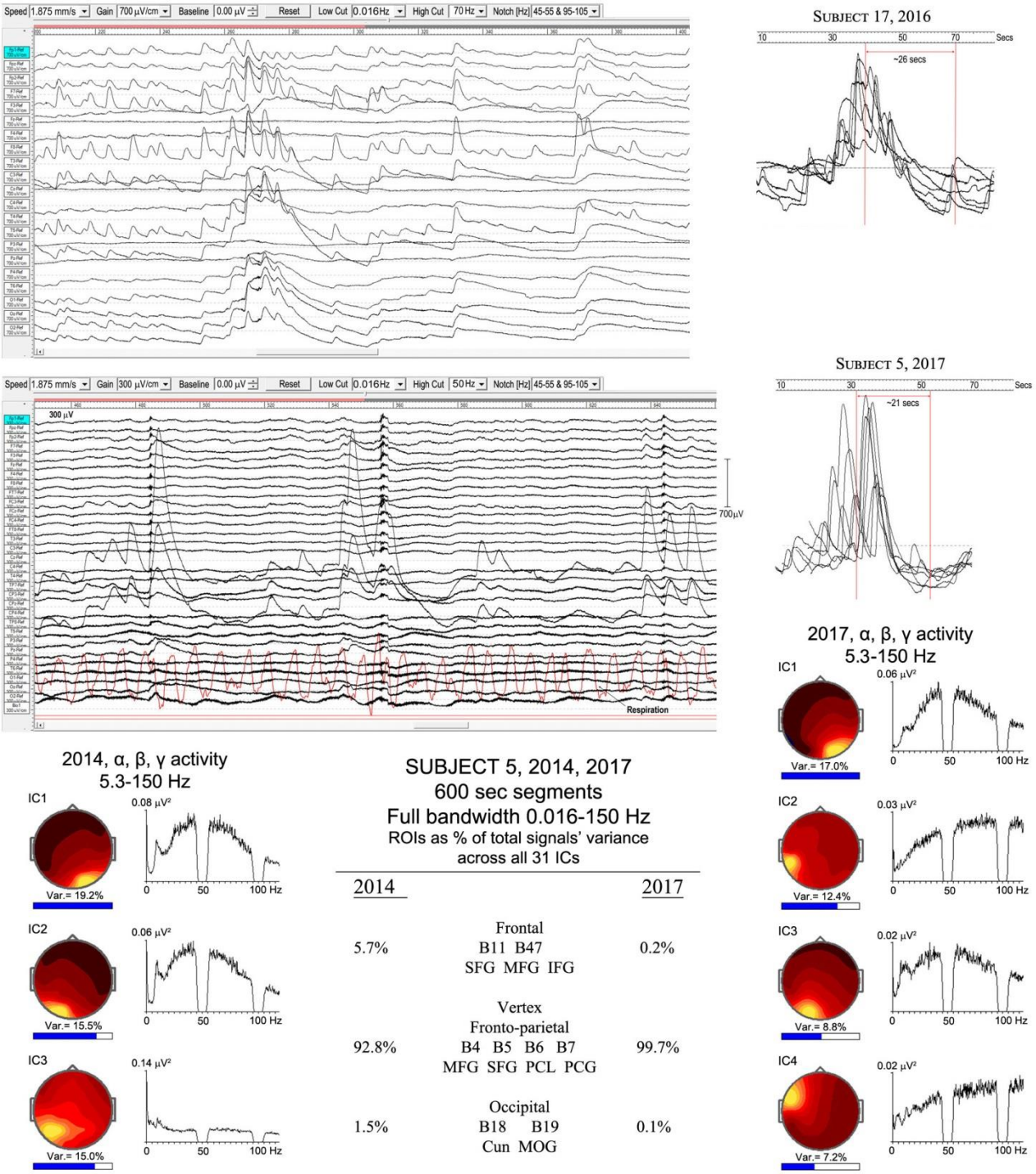

Figure 8 Infraslow-wave (ISW) activity: top panel, subject 17 (2016); middle panel subject 5 (2017). Below is a comparison of the high focus vertex activity for subject 5 in 2014 and 2017, with the strongest ICs from 600-sec samples for each year shown, and the overall % contributions of ROIs across all 31 ICs for each year. At each side, the IC spectra show higher frequency activity only (bandwidth 5.3-150 Hz), revealing broadband gamma with only small residual traces of alpha activity.

Secondly, the SWs we observe are significantly more rhythmic and extensive than those seen in sleep, and tend to form an annulus of alternating excitation-inhibition around relatively untouched central areas, apart from a localised region near the vertex, a pattern quite different to anything described elsewhere in the literature. It is tempting to take a metaphor from sleep studies and to infer that extensive areas of the cortex are "put to sleep", or suppressed, by these high-voltage rhythmic SWs, yet the subjective experience does not support this, since meditators describe an experience of enhanced consciousness, rather than any diminution. We shall return to this point in the final Conclusions. The

cortical source analysis reveals the midline vertex region, bridging the frontal-parietal divide, to be the dominant region of interest, with frontal and occipital regions second, and temporal sources third. These ROIs are again significantly different to those described for SWs in nREM sleep, which, among other regions, are believed to involve the lateral sulci, the medial, middle and inferior frontal gyri, the anterior and posterior cingulate, and the precuneus (Murphy *et al*., 2009). The significance of our observed ROIs in terms of the stages of jhāna, and implications for consciousness, will also be discussed in the Summary and Conclusions.

Whilst, as noted in the Introduction, it is not straightforward to assess a person's skill in jhāna, certainly not simply on the basis of years' of practice, it seems reasonably clear that spindling, by its prevalence, is related to the earlier stages of experience, while high-voltage SWs indicate more proficiency in jhāna, in line with the jhāna factor of *pīti* and energisation associated with transition into the second and then higher jhānas. The sheer degree of energisation observed for some meditators, however, was unexpected, with several examples described in this paper showing p-p SW amplitudes exceeding 2000 μV, and corresponding increases in power approaching four orders of magnitude; unprecedented, as far as we know, in the neuroscience literature.

3.3. SPIKE-WAVE AND SEIZURE-LIKE ACTIVITY

3.3.1 Spike-Wave Activity

In addition to the spindle and SW activity described, we also find examples of seizure-like activity, either as spike-waves (S-Ws) reminiscent of absence epilepsy (Sadleir *et al*., 2009), or the ability of some subjects to intentionally evoke intense states with tonic features similar to epilepsy. However, unlike epileptiform seizures the meditator remains fully conscious without discomfort.

Ten subjects (Supplementary Table 1) show brief episodes of S-Ws, mainly occipital, three of whom were recorded during different years, again showing S-Ws, although at different frequencies, giving 13 independent records. Three examples are shown in Figure 9. For some subjects the S-Ws occur spontaneously, with the meditator not aware of any specific change in their subjective experience, apart from feeling more energised. For some others, S-Ws develop during the deliberate arousing of strong *pīti*, the third jhāna factor mentioned in the Introduction, accompanied by epileptiform clonic features. Whilst S-Ws seen in absence epilepsy are characterised by a sharp initial spike, followed by a relatively smooth decay, the examples during meditation show reverberatory or harmonic structure between spikes, as seen in the examples in Figure 9. Also, the S-Ws we observe occur predominantly at occipital sites, mainly O1, Oz and O2, unlike more widely varying locations, particularly frontal, in absence epilepsy (Stefan, 2013).

The meditation S-Ws occur in bursts of 5-12 secs duration, similar to epilepsy, although one subject maintained a burst for 50 secs. However, the key difference is that meditators retain clear consciousness. An independent component (IC) analysis using eLoreta was performed on S-W segments from 7 subjects showing the clearest S-Ws; subject 15 was recorded both in 2016 and 2018, giving 8 independent records. A bandpass of 0.53-70/150 Hz was used, depending on the amplifier model, to reduce SW contributions. As an example, the Figure 9 inset shows the IC spectra for subject 11, showing clear harmonic structure, with the corresponding 3D source maps for the two strongest components. Harmonic structure is found in the IC spectra for all seven subjects, with a range of spectral peaks, as in the examples in Figure 9. Cortical sources were computed as for spindles and SWs, with mean ROIs shown in the summary box in Figure 9. Occipital sources dominate accounting for 87.2% of the total signals' variance, with 10.8% and 2.0% contributions from frontal, and frontal-near-vertex, sources respectively. Since some SW breakthrough remains (e.g. subject 24, Figure 9), this occipital dominance is likely an underestimate.

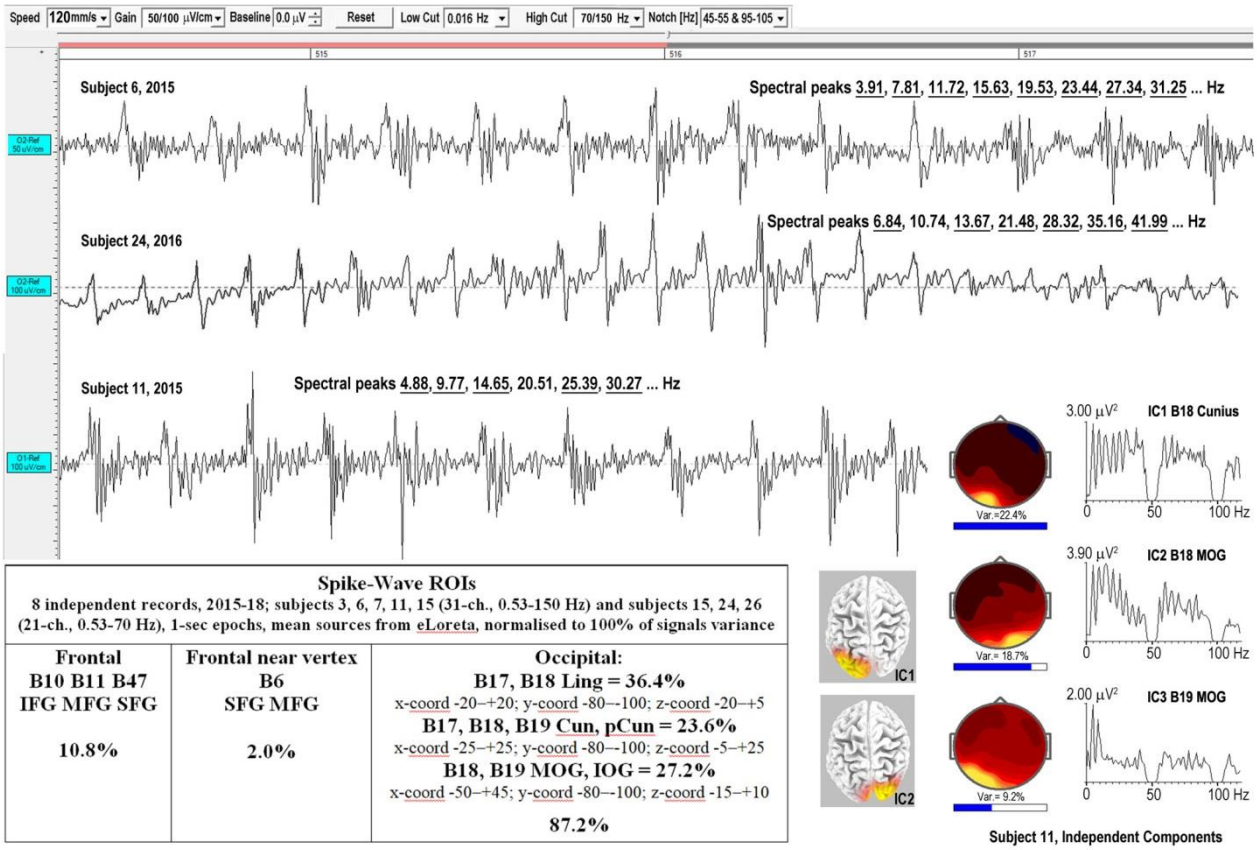

Figure 9 Three examples of spike-wave (S-W) complexes at occipital sites O1 or O2. Top, excerpt from a 12-sec S-W burst, subject 6, 2015; middle, from a 5-sec burst, subject 24, 2016; bottom, from a 8.6-sec burst, subject 11, 2015. The main spectral peaks are shown for each, with harmonics underlined. At right are the independent components for subject 11, computed using eLoreta, showing harmonic spectral structure. The lower box summarizes the ROIs from 8 independent recordings of S-Ws.

3.3.2. Seizure-Like Activity

As noted in the Introduction, the transition from the first rūpa jhāna to the second and higher jhānas requires the meditator to become familiar with bodily energisation *pīti*. This typically develops in a natural way during Samatha meditation, but in the Yogāvacara tradition (as in Tibetan Buddhist yoga) there are specific techniques, involving breath control, to deliberately evoke high energy states. This is not a fixed requirement of the practice, but is undertaken by those with a special interest. The rationale is to become familiar not only with the ability to evoke higher energy states, but, more importantly, the ability to then tranquilize that energy back into a more intense experience of absorption. To an observer, the subject typically displays clonic features similar to epilepsy, but without discomfort, with the ability to evoke the state and leave it at will. Figure 10 shows two examples.

These two examples are taken from a wide range of presentations of this form of activity, analysis of which is at an early stage, and may be the subject of a future paper; these examples are included to complete this overview and to illustrate some of the broad features. Example 1 is from an experienced practitioner. The first sign of increasing energisation is the development of occipital S-Ws, followed immediately by a ~½sec global ictal burst, a second burst 3 secs later, another ~7 secs later, followed by the main body of the "seizure" 15 secs later. Physically, the meditator shows mild clonic jerks or bodily vibration during these events, mostly along the vertical bodily axis. The expanded view below the top panel shows the S-Ws at occipital sites, with a rather remarkable near-sinusoidal rhythm at the right temporal site T6, reaching p-p values approaching 3000 µV. To the right are shown the two strongest independent components (ICs) from an eLoreta source analysis for the main 26-sec event, highlighted yellow. The activity is highly localised at Brodmann 37, MTG (MNI coordinates xyz 60 -60 -5), with S-W frequency 5.62 Hz, and the temporal frequency at the harmonic, 11.23 Hz.

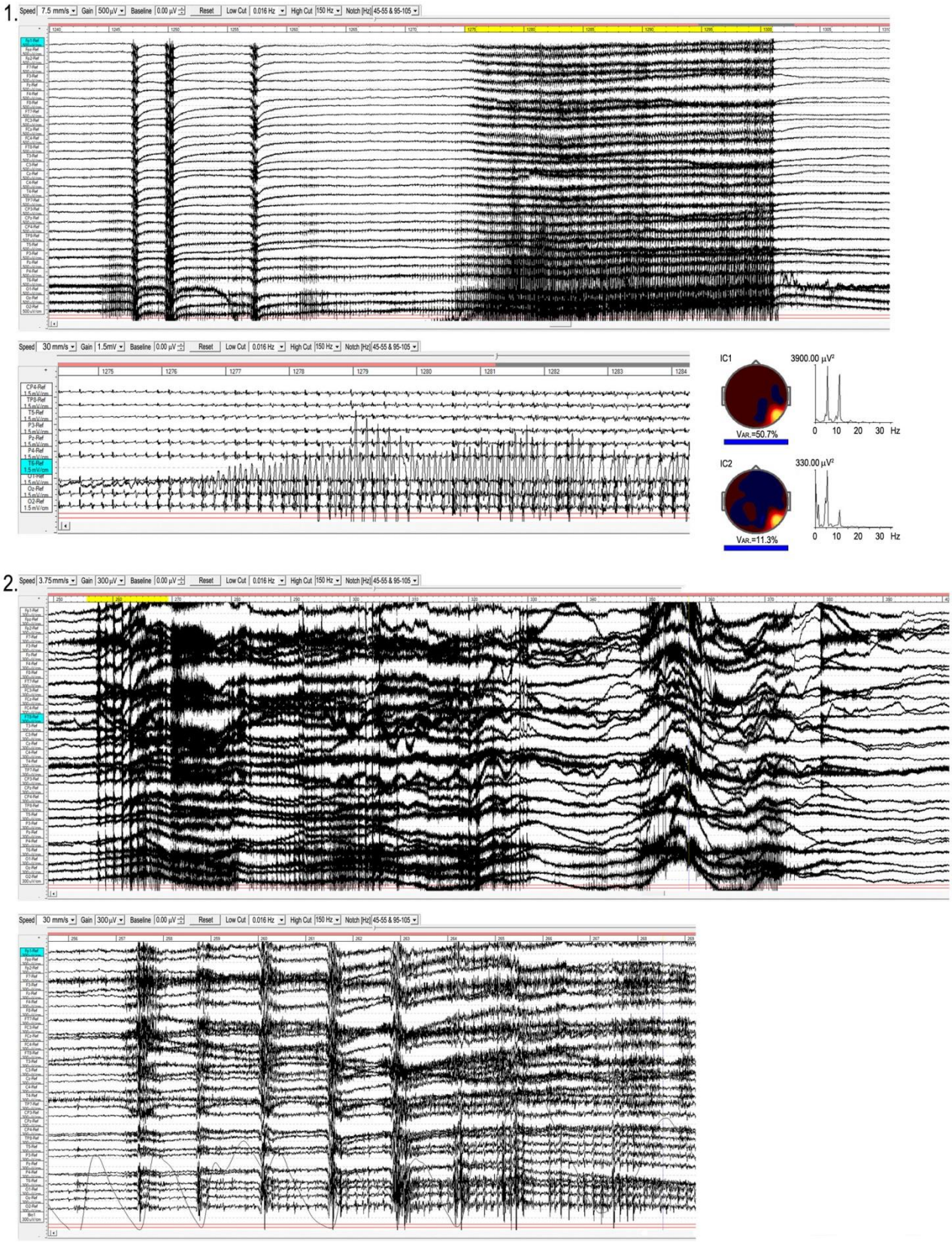

Figure 10 Examples of seizure-like activity. **1.** Top panel, subject 15, 2018, with an expanded view of the occipital activity inset below, with a source analysis of the main body of the "seizure" (marked by the yellow bar in the upper panel). **2.** Upper panel, subject 7, 2015 with, inset below, an expanded view of the early part of the "seizure" (yellow bar in panel above), together with respiration trace.

Example 2 is more complex, with more clonic activity. The EEG again shows brief global ictal bursts at the onset, which are shown in the expanded view below, together with respiration. The ictal bursts

coincide with the end of the out-breaths, and occipital S-Ws develop progressively, rather than precede the "seizure" as in example 1. Probably because of the complex mix of activity in this example, that includes very strong SW bursts, as well as the occipital S-Ws and complex activity extending into the gamma band, a source analysis is inconclusive, returning a range of small sources rather than any one or two dominant sources. Strong SWs as in this example, feature regularly in the more clonic examples of this activity, and we believe perform a containment function for the disturbance.

3.3.3 Discussion

Whilst epileptic S-W discharges were for many years described as "generalized", rather than focal, often frontal, more recent work such as Ji *et al.*'s (2015) fMRI study, identifies specific thalamo-cortical networks that show increased connectivity during S-W discharges. These include prefrontal-thalamic, motor/premotor-thalamic, parietal/occipital-thalamic, and temporal-thalamic networks. Similarly, Chiosa *et al.* (2017), using dense-array EEG, find significant connectivity changes between thalamus to frontal sites, and from frontal and temporal sites to thalamus, preceding S-Ws. However, the S-Ws we observe are overwhelmingly occipital, indicating a different mechanism, as does the range of S-W frequencies, and the harmonic structure, rather than the typical 3.0-4.0 Hz single focal frequency of epileptic S-Ws. As far as we are aware, there have been no reported findings of harmonic structure in the vast literature on epileptic S-Ws, which makes our finding all the more intriguing.

The increased functional connectivity during epileptic S-W discharges noted above, is believed to reflect a high level of excitation and synchronization in one or more of the cortico-thalamic feedback loops, caused by pathological conditions, locking the network(s) into fixed ~3.5 Hz oscillation. The meditation condition, however, is intentional rather than pathological, and we suggest the meditational S-Ws reflect a different form of destabilisation of the thalamo-cortical feedback loops when the personal element is withdrawn. And, further, because of the dominance of the occipital hub, that it is the "I/Eye" occipital-thalamic loop that is disrupted.

The intentionally evoked "seizure-like" activity gives an interesting insight into an overlap between high-energy states during jhāna meditation, including for some meditators S-Ws, all of which do not appear to disturb the meditator's tranquillity, and the ability to push the energisation beyond a threshold of instability.

4. SUMMARY AND CONCLUDING REMARKS

These results would be puzzling indeed, if not for the rich textual material on jhāna meditation, summarised in the Introduction, that allows us to attempt a cross-discipline interpretation. The starting point is that in the Buddhist tradition the rūpa jhānas represent a progressive withdrawal from the default sensory consciousness, and we interpret our observations in that context. The following are presented as "informed hypotheses".

4.1. PROGRESSIVE WITHDRAWAL FROM THE DCs

Stage 1 We have suggested that spindling is an early sign of success in withdrawing attention from the DCs. Following the Introduction, this stage would correspond to the approach to jhāna ("access concentration", Cousins, 1973), and the development of the first rūpa jhāna. From the cortical source reconstruction and earlier discussion, the results suggest disruption of the dorsal and ventral perception/attention streams that are, by definition, an integral part of the DCs networks. The meditational spindle frequencies, 7.5-10.5 Hz, are significantly lower than alpha spindles typical of attentional distraction within the DCs, such as driver distraction, and even further lower than those of sleep spindles, 10.0-14.0 Hz (Table 1). In fact, the range we find of 7.5-10.5 Hz corresponds well with the lower frequency ventral component of the alpha rhythm as recently described by Barzegaran *et al.* (2017); which in turn corresponds to our finding of significant limbic sources underling the meditation spindles (Table 2).

The typical human peak alpha frequency ~9-11 Hz, and its close relationship to the mind-body reaction time ~100 ms, suggests that the alpha rhythm performs the key time-synchronizing role within the DCs networks, and is biologically and evolutionarily favoured for optimal response to threat and for species survival. Those networks of the DCs (the NCC of current neuroscience) are formed around complex thalamo-cortical feedback loops, and we suggest that this network structure is the result of an *attractor* process towards a state of optimum metastability (Deco *et al*., 2017), corresponding to Friston's (2010) principle of minimisation of the brain's free energy, and characterised by the centrality of the alpha rhythm. This key role of the alpha rhythm in turn accounts for the scale structure of the α, β and γ bands in the DCs EEG (Palva and Palva, 2007). The nature of the meditational spindles we observe suggests that when the personal component begins to be withdrawn from the cortico-thalamic feedback loops, that the DCs is disrupted to the extent that the alpha *attractor* fails, and the feedback loop is unable to retain the alpha focus. The possibility of other *attractor* modes will become clear in the following.

Stage 2 As the meditator continues to develop jhāna consciousness, increasingly free from sensory distraction, and "held" by the *nimitta* (see Introduction), a growing awareness and interest in the bodily energies supporting that consciousness develops in the form of the jhāna factor *pīti*. This presages the development of the second and (once *pīti* is mastered) higher rūpa jhānas, and we believe is reflected in the unusually high energy states, in particular high-voltage and widespread SWs, observed in the EEG.

While the scalp EEG activity is intriguing – the near-annulus of excitation-inhibition from high-voltage SWs, with a separately active region near the vertex – the source analysis reveals that the dominant cortical ROI is in fact at the vertex, bridging a midline area extending from B6, just frontal to the vertex, to parietal sites at B5 and B7 just posterior to the vertex, accounting in total for 46.3% of the total signals' variance across 8 independent records (Figure 7). The next strongest ROIs are frontal (24.2% of variance), occipital (19.3%) and temporal (10.2%).

These cortical "hubs" are also interesting when considered against the nature of jhāna as progressively moving from a sensorily-determined subject-object basis of consciousness, towards inner absorption common to all the jhānas and described by the jhāna factor *ekaggatācitta*, or one-pointedness of mind. On that basis, we suggest that the occipital and frontal hubs represent the residual subject and object poles, respectively, of the sensory DCs, the temporal contribution the residual part of the ventral perceptual stream, while the vertex hub is a sign of the emerging second rūpa jhāna consciousness. In this model, the occipital hub, integral to the dorsal and ventral perceptual streams of the DCs, carries the first-person "I/eye" pole of sensory consciousness (Merker 2013); while the frontal hub, well researched as part of the executive attention network, carries the object pole due to its role in cognitive processing (Petersen and Posner, 2012).

The vertex sites, B6, B5 and B7 include the supplementary motor area (SMA), strongly connected to the thalamus and projecting directly to the spinal cord, and the highly connected medial parietal associative cortex, believed to be involved in a wide variety of high-level processing tasks, and with dense links to the underlying cingulate, thalamus and brain stem. This vertical-axis connectivity is striking in contrast to the (suggested) front-back axis of the DCs, and suggests involvement of the ascending reticular activating system (ARAS), with its known involvement in arousal, attention and consciousness (Maldonato, 2014). It is known that disruptions to the ARAS can lead to coma (Norton, 2012), and disruption of posterior cingulate connectivity can cause unconsciousness (Herbet, 2014), but the form of disruption we see in this form of meditation does not lead to unconsciousness, even though the strong SWs have some similarities to coma, as discussed earlier.

Stage 3 As noted in the Introduction, the third rūpa jhāna is described as "completely conscious" in the 5th-century text *Vimuttimagga*, which quality is continued into the fourth rūpa jhāna, the two being essentially very similar except that the fourth no longer depends on the "reward" of happiness or pleasure to sustain its equanimity. It might therefore be expected that the frontal and occipital residuals of the DCs described above might finally disappear during progression from the second to the third and fourth jhānas. The recordings of subject 5 in 2014 and 2017 appear to confirm this, showing as they do

an almost complete dominance of the vertex sources, particularly in 2017 (Table 4) when this subject had considerably more experience of jhāna meditation. Figure 8, lower section, compares two 600 sec segments for each year, for this subject, from which the entire 31 ICs were examined for their contributions to the total variance. In 2014, vertex sources accounted for 92.8% of the total variance, with small 5.7% frontal and smaller 1.5% occipital contributions. In 2017, the vertex activity was more highly focused at an astonishing 99.7%, with tiny residual frontal and occipital contributions of 0.2% and 0.1% respectively. The vertex sources are almost entirely, if not completely, due to high-voltage SWs, as confirmed by plots of the residual higher frequency activity shown at each side of the lower panel of Figure 8, computed for the restricted bandwidth 5.3-150 Hz to largely exclude SW activity. Very small residual alpha components can be seen in ICs 1 and 2, 2014, overshadowed by broadband occipital gamma activity; whilst in 2017 the residual alpha is even further diminished, again with stronger gamma activity. Implications of this remarkable focus are discussed below.

4.2. CONSCIOUSNESS

To date, research on the NCC has been limited to what we have termed the DCs, the human default sensory consciousness. The DCs is supported by a highly complex array of cortical networks in a dynamic equilibrium that minimises free energy (Friston, 2010), central to which has to be the personal component, in which case it should be no surprise that task-based studies reveal a sometimes bewildering, and it has to be said confusing, array of NCC networks within the DCs. There is growing convergence of evidence, which our study supports, that the temporal scale factor for the DCs is the alpha frequency, linked as it is to a minimum processing time from sensory input, through cognitive processing and evaluation as to significance to the "self", to decision and action involving the body via the sensory-motor and motor systems of the brain. The EEG frequency bands δ, θ, α, β and γ then become expressions of that scale factor, each independent and carrying different functions, but highly inter-connected, as postulated by Klimesch (2013). In terms of different functions, it might be said that α activity characterises a minimum processing time for perception to action (a conscious "thought"); β the underling faster unconscious cognitive processes; θ the slower function of bridging more than one α process, facilitating memory; and γ higher-level functions perhaps related to consciousness of the whole.

As meditators withdraw attention from the DCs, the first disruptions we observe are to the dorsal and ventral perceptual attention streams of the DCs. The alpha attractor begins to fail, evidenced by the nature of the spindles we see. As withdrawal deepens, and powerful SWs develop, the active cortical networks simplify to near-midline frontal and occipital ROIs, and an increasingly strong, and eventually dominant vertex ROI, with θ, α and β activity typical of the DCs now virtually absent, leaving only broadband gamma activity in the background. This suggests that attention processes constitute the "outer" cognitive shell of the DCs, and that the more personal subject-object nature of the DCs is carried by reciprocal occipital-frontal (respectively) cortical networks, that are progressively disrupted as jhāna consciousness develops. The point that consciousness has to have an object is sometimes overlooked in the literature, and certainly for the DCs it is unrealistic to imagine the NCC could be located in a single region, such as the front or back of the head.

Both in textual description and as subjectively experienced, the jhānas are regarded as states of consciousness, with the object of each jhāna becoming increasingly subtle. From our study, jhāna consciousness appears to be characterised by the scale factor of the respiration cycle, with the SW periodicity (Table 3; 8.32±0.57 secs, or 0.12±0.008 Hz) very close to that of respiration; not entirely a surprise given that the breath is the primary object in the early stages. However, as a scale factor this is almost two orders of magnitude slower than the 100 ms of the DCs, which might explain the expanded sense of time and spaciousness meditators describe during this form of meditation, and the frequent rendering of Samatha as undisturbed peace or tranquillity.

The development of a vertex-body axis, rather than the frontal-occipital axis of the DCs, and the evidence of an underlying ISW activity ~0.02 Hz, suggests an even slower metabolic scale factor integrating the entire mind-body system in the deeper levels of jhāna. The intense vertex focus, unlike the dual frontal-occipital ROIs of the DCs, also raises the interesting question as to what is the nature of

the subject-object structure of jhāna consciousness, since an object is still required to be conscious of. In the oral jhāna tradition, several views are expressed. One is that each moment of consciousness becomes the object of the next, giving the illusion of perfectly still and continuous undisturbed consciousness. This is envisaged as a high level and very fast process, and we might wonder at the role of the background gamma activity and brief γ bursts we observe. A second view is that the body itself is the supporting object of jhāna consciousness, as part of a deep metabolic integration, and perhaps related to the intriguing term "body witness" sometimes encountered in the ancient texts (e.g. *Vimuttimagga*).

In deep nREM sleep, the scale factor is the heart rhythm (Mensen, 2016), with corresponding SW frequencies ~1.0-1.2 Hz. The fact that SW nREM sleep is unconscious, unlike either the DCs, or jhāna consciousness also characterised by SW activity, raises the intriguing question as to what is different in cardio-cortical connectivity during nREM sleep, that disconnects from sensory and motor networks in the absence of any intense stimulus to cause awakening. And what is the purpose of the disconnect?

4.2.1. Harmonic structure

The meditation spike-waves (S-Ws) we observe, either involuntary or as part of deliberately enhancing energisation beyond a threshold of instability, all show harmonic spectral structure, unlike those in epileptic or pathological states, and do not appear to disturb the meditator's conscious experience. Their very specific occipital location around the lingual, cuneal and occipital gyri suggests disruption to the "I/Eye" component of consciousness, and in particular to the occipito-thalamic feedback network. We believe this is additional evidence of disruption to the δ, θ, α, β scaled activity of the DCs, and that the harmonic structure is evidence that withdrawal of the personal "I" component from the occipito-thalamic network triggers the thalamus into harmonic activity in an attempt to stimulate scaled network activity similar to that of the DCs. The implication is that harmonic or fractal structure is an integral part of thalamo-cortical network connectivity, and that the δ, θ, α, β structure of the DCs is but one example, that we presume is optimal for sensory consciousness and minimisation of free energy.

4.3. ENERGY AND STABILITY

Several of our examples describe SW amplitudes >2000 μV p-p, compared to typical EEG resting-state values 25-45 μV p-p. Also, in some cases the SWs develop very quickly following the instruction to start meditation, as in the lower panels of Figures 3 and4, showing high cortical responsiveness. A striking example is that of subject 5, 2017. Before SW onset, the signal amplitude at the vertex site Cz was ~25-30 μV p-p; there then quickly developed a de-excitation reaching -2630 μV p-p 50 secs later, followed by a recovery to the familiar pattern of alternating excitation/de-excitation at ~400-2000 μV p-p for the next 20 mins. The initial voltage ratio ~95, corresponds to a change in power >9000, almost 4 orders of magnitude. The strongest individual SWs, such as in the middle panel of Figure 8, show a rapid rise as high as 1100-1300 μV/s, followed by a much slower over-shooting decay, similar in morphology to that of a relaxation oscillator.

The corresponding subjective experience during these high-energy states is one of deep equanimity, and as several have described, a sense of vivid presence, rather than any instability or disturbance. In the case of those subjects that show occipital S-Ws, they also are not aware of any disturbance, other than mild enhanced energisation. And for those subjects who are able to intentionally evoke clonic seizure-like states (Figure 10), they do so with no discomfort, are able to vary the duration at will, and to leave the state when they choose, quickly recovering composure and equanimity. The comparison to epileptic states is however intriguing, and example 1 from Figure 10 may add another piece to the puzzle. In this example, strong occipital S-Ws appear to trigger an exceptionally strong resonance (reaching 3000 μV p-p) in the right middle temporal gyrus, at the first harmonic of the S-W frequency. What lies behind the sensitivity of the temporal gyrus, a frequent site of pathological seizures, to be destabilised in this way?

We believe that the capacity to manage and contain high-energy states is the result of careful and detailed development of attention, often over many years, coupled with the deliberate use of non-normal lengths of breath as noted in the Introduction. Over 50 years, and with currently over 400 practitioners,

this particular practice has proved remarkably safe, and we wonder whether some of the basic features of its attentional development could be adapted for epilepsy sufferers with the goal of reducing frequency of seizures. We are also interested to explore potential health implications of the high energy focus and development of what appears to be a vertical vertex-brainstem-body axis, inevitably passing through core brain regions known to be involved in dementia and other degenerative conditions.

Finally, while recent neuroscience has explored in depth the minimisation of free energy, as a key factor in the brain's default energy balance, this study highlights that disruption of the DCs reveals a hitherto unrecognised and remarkable reservoir of *available* energy. It also demonstrates an equally remarkable *responsiveness* of the brain's cortical networks during this form of meditation, which we presume is related in some way to the more common focus on plasticity.

4.4. LIMITATIONS

- Spatial resolution. At some point in the future we hope to have the capacity to record with at least 48, or preferably 64-electrodes.
- An observer effect? Most subjects adapt well to being recorded, but a number have commented that they do not experience the same depth of absorption as in their regular meditation practice, when being recorded, i.e. "observed". We intend to explore protocols that might address this.

4.5. CONFLICTS OF INTEREST

This research has been conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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SUPPLEMENTARY MATERIAL

Subject		Eyes closed	Spindles	SWs extensive and/or travelling, or isolated V. frequent >50%; frequent 20-50%; infrequent <20% Well-defined or ill-defined p-p µV and approx. ½ period (secs) by vis. Inspection	Comments
Year recorded	Years' practice	p-p µV			
1 2014 2015 2016	41	~40-50 ~20-40 ~20-30	Yes, extensive Yes, extensive Yes, extensive	Yes, extensive, frequent, well-defined, not clearly travelling ~130-200 µV p-p ; ~5 secs Yes, extensive, but infrequent, ill-defined, not clearly travelling ~100-200 µV p-p ; ~4-10 secs Yes, mainly frontal, but infrequent, ill-defined, not travelling ~150-250 µV p-p ; ~3-6 secs	Includes periods of high gamma superposed on SWs Includes periods of high gamma superposed on SWs and brief occ. S-Ws ~5.3 Hz Brief episode occ. S-Ws ~5 Hz
2 2016	39	~20-35	Yes, extensive, mainly occ.	Yes, frontal, but infrequent, ill-defined, not travelling ~50-150 µV p-p ; indeterminate periodicity	-
3 2014 2015 2017	52	~25-35 ~40-55 ~40-50	Yes, infrequent, mainly occipital Insignificant Yes, extensive	Yes, extensive, but weak ill-defined infrequent, not travelling, ~100-125 µV; ~3-6 secs Yes, extensive, well-defined, v. frequent, travelling ~150-400 µV; ~3-5 secs Yes, extensive, well-defined, v. frequent frontal-occ. antiphase; 200-400 µV; 3-5 secs	- Single brief burst frontal S-Ws ~3.2 Hz -
4 2014	16	n.a.			Data not useable –impedances problem
5 2014 2017	30	~20-35 ~30-45	No No	Yes, extensive, well-defined, v. frequent, travelling ~400-900 µV; ~4-6 secs Yes, focused at Cz and CPz, v. frequent and well-defined, near-simultaneous, ~400-2000 µV; ~4-6 secs	Strong frontal gamma, and occ. gamma mod. by SWs Strong occipital gamma modulated by SWs
6 2015	39	~30-40	Yes, extensive	Weak, absent or indeterminate, except for three 20-60 sec episodes of extensive, well-defined, not clearly travelling, 200-400 µV; ~4-6 secs.	Strong SWs only develop when *pīti* deliberately aroused, during which S-W bursts also occur.
7 2015	28	~30-50	Yes, extensive	Weak, indeterminate, except for 2 brief ~ 20 sec episodes of extensive, ill-defined, not travelling, ~150-200 µV; indeterminate periodicity	Brief episodes of moderately strong SWs only develop when *pīti* deliberately aroused, during which S-W bursts also occur.
8 2015	37	~25-35	Yes, extensive but rather weak	Irregular and atypical SWs with repeated phase-reversals ~150-200 µV; indeterminate periodicity	Query T6 electrode problem? Atypical SWs related to other biological cause?
9 2015	6	~30-40	Yes, extensive	Weak and irregular mainly frontal, 100-150 µV; later develop occipitally 150-200 µV; ~7-10 secs	
10 2015 2016	32	~30-40	Yes, extensive mainly occ. Ditto	Mainly frontal, non-sinusoidal, not travelling ~150-300 µV; 2-3 secs Weak, absent or indeterminate	
11 2015	25	~30-40	No	Weak, absent or indeterminate	Brief episodes of occipital S-Ws ~5 Hz
12 2015	27	~15-30	Brief, infrequent	Weak, irregular, frontal, not travelling 100-150 µV; ~4 secs	Muscle tension at T3
13 2016	6	~30-40	Yes, extensive but rather weak	Weak, irregular, frontal, not travelling 75-150 µV; indeterminate periodicity	

14 2016	30	~45-65	Yes, extensive	Isolated, +ve SWs, initially frontal, travelling to temporal sites, reach 2500-3500 µV. ½ period from peak to minimum ~10 secs	
15 2016 2018	41	~30-40	Yes, extensive	Weak, indeterminate; possible uSWs occasionally at occipital sites	Occasional occipital S-Ws, followed by spindling. Harmonic spectral structure at times
16 2016	24	~30-40	Yes, extensive mainly occ.	Yes, frontal but non-sinusoidal, ~150-250 µV; ~3-4 secs	
17 2016	20	~20-45	No	Yes, extensive, well-defined, v. frequent, travelling, 800-2500 µV; 3-5 secs	Frequent ictal-type spikes at 2.75Hz, mainly occipital
18 2016	42	~20-40	Yes, extensive weak, mainly occ.	Weak, absent or indeterminate	
19 2016	33	~20-40	Yes, extensive	Isolated, +ve SWs, initially frontal, travelling to temporal sites, reach 2500-3500 µV; ½ period from peak to minimum ~10 secs	Also very strong frontal gamma, and episodes of frontal S-Ws. Some sections show harmonic spectral structure
20 2016	7	~30-40	Yes, occasionally	Yes, extensive, frequent, well-defined but near "square"; mainly frontal, not travelling; ~350-500 µV; 4-6 secs	
21 2016	36	~25-35	Yes, extensive	Weak, irregular, ill-defined, ~100 µV; 3-5 secs	
22 2016	42	~25-45	Yes but ill-defined	See Comments	High frontal gamma; or suspect recording - unstable impedances?
23 2016	8	~30-45	Yes, weak, fairly extensive	Yes, frontal, irregular, ill-defined, not travelling, ~100-200 µV; 4-8 secs	
24 2016 2017	43	~35-55 ~40-60	Yes, extensive Occasional	Yes, extensive, well-defined, travelling, 400-600 µV; 3-4 secs Yes, extensive, well-defined, travelling, 400-600 µV; 3-5 secs	Some evidence of occipital S-Ws ~6 Hz Occipital S-Ws more prevalent ~6.75 Hz with harmonic structure
25 2016	4	~45-55	Yes, extensive	Yes, mainly frontal, well-defined, infrequent, not travelling, ~100-150 µV; ~3-5 secs	
26 2016	37	~50-70	Infrequent	Yes, well-defined, frequent, travelling, ~300-400 µV; 4-5 secs. Some isolated +ve SWs later, up to ~2500 µV; 5-10 secs half-period	Frontal and then later occipital S-W episodes ~3.5 Hz
27 2016	4	~30-40	Yes, extensive	Weak, absent or indeterminate;	Occipital problem later in recording – impedances degrade?
28 2017	40	~30-40	Yes, extensive	Yes, mainly frontal, well-defined but non-sinusoidal (fast +ve then slow decline), non-travelling 120-175 µV; ~6-12 secs	
29 2017	30	~20-35	Yes, extensive but rather weak	Weak, irregular, ill-defined, mainly frontal, ~80-120 µV; periodicity indeterminate	

Supplementary Table 1 Participants in the study; 29 subjects, 36 independent recordings 2014-17. Recordings during 2014, 2015, 2017 were made using a 31-electrode system, and those during 2016 using a 21-electrode system.