

Insights into the neural correlates of consciousness from an EEG study of Buddhist jhāna meditation

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Abstract

EEG and fMRI research into the neural correlates of consciousness (NCC), mostly concerns our everyday waking consciousness, a dynamic neuronal balance between sensory inputs from the outer world, from our body via the brain stem, against a background of innumerable past experiences held in short and long-term memory, including their value to the “I” or “self”, and to current needs or actions. We refer to this as sensory consciousness. When the personal component of this complex disengages, as in deep sleep, coma, anaesthesia and some pathological states, the dynamic balance is drastically disrupted; most often replaced by high-voltage slow waves (SWs) or seizure-like phenomena in the EEG. In jhāna meditation (normally translated as “absorption”), the personal component is withdrawn deliberately, evoking EEG responses for some meditators remarkably similar (but with significant differences) to nREM sleep; intense SWs, including travelling SWs, spindles, and in some cases spike-wave complexes. In sleep and epilepsy studies such phenomena are generally regarded as involuntary states of unconsciousness, or very limited consciousness. The observation of similar activity in meditators, whose subjective experience is of a still and intense awareness, far from unconsciousness, raises intriguing questions about consciousness, and the related neural networks.

Introduction

While there have been many EEG studies of meditation^{1,2,3}, mainly focused on health benefits, there have been no in-depth studies of jhāna meditation⁴, the subject of this Report. This is largely because this form of meditation is rarely found, or indeed believed possible by some, in a lay context outside monastic and forest meditation traditions. Its teaching also depends on an oral transmission of the detailed techniques which is not widely available. The relevance for neuroscience, and in particular the study of the neural correlates of consciousness (NCC)^{5,6,7}, is that to achieve jhāna a meditator is required to withdraw attention from the default sensory consciousness, towards, first (usually), the touch of the breath at the nose tip or upper lip, and then towards an internal mental object that is the emerging sense of the quality or feeling of the meditator’s own consciousness. This refined and still jhāna consciousness later becomes the foundation for developing insight and wisdom, in Buddhist traditions. A short summary of the four rūpa (form) jhānas and the four arūpa (formless) jhānas is given later. The phenomena described in this report are not to be regarded as the signature(s) of the jhāna state, but rather as the brain’s response to withdrawal from everyday sensory consciousness in the approach to jhāna.

This sensory consciousness is the *de facto* subject of the many “content” studies of NCC⁵, where researchers examine which part of the cortical networks are stimulated or suppressed by a subject undergoing tasks or external stimuli. It is important to realise that the subjective component is ever-present in this default state of consciousness. Indeed, it is likely to be 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 memory⁸, then weighed as to their value to the “I” or “self”, in the light of current needs or actions⁹. Whilst content studies of NCC can reveal different aspects and components of this default consciousness, 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 for a person to intentionally withdraw their personal component from the default sensory consciousness, as this study suggests, a new window is opened into exploring NCC¹⁰.

Results

The subjects of this study are experienced lay meditators from a wide range of occupations, following a meditation tradition introduced to the UK in 1963¹¹. Supplementary Table 1 gives an overview of EEG recordings of 27 subjects made during 2014-16, mostly during 10-day intensive meditation retreats. All showed some degree of slow wave (SW) activity (< 1 Hz), with three apparent themes: weak and irregular SWs, mainly frontal (mostly shown by the less experienced meditators), and often accompanied by spindling; much stronger (200-600 μ V, p-p) clear and extensive “travelling” SWs¹² shown by 6 subjects; and again strong (200-1000 μ V, p-p), more localised and isolated SWs shown by 7 subjects. Examples are shown in Supplementary Figure 1; upper, middle and lower panels respectively. The spindling we observe in the early stages of this form of meditation is most often in the omega band (4-7.5 Hz), or less often the alpha band (7.5-14 Hz), rather than the “slow” and “fast” spindles in sleep which tend to be just below or above a subject’s dominant alpha rhythm¹⁴. We suggest this is a sign of the meditator directing attention away from the normal sensory mode, similar to the finding of enhanced alpha spindling in studies of driver-distraction and conflicted attention¹⁵. Supplementary Table 1 shows that for more than two-thirds of these subjects, the SW half-periods from a -ve peak to the following +ve peak lie in the range 3-5 seconds, corresponding to a SW frequency range 0.1-0.17 Hz. This is considerably slower than the typical ~1 Hz or slightly less of sleep SWs^{12,16}; in fact it is within the range sometimes referred to as infra-slow SWs¹⁷. A recent study¹⁸ has demonstrated a link between sleep SWs and the haemodynamic effect of a subject’s heartbeat, which explains why in sleep the SW frequency is typically around 1 Hz. Which in turn suggests, as does the spindle frequency, that the SWs we observe are of a different nature to sleep SWs.

The widespread travelling SWs and the more localised and often very powerful isolated SWs are so different that we believe they represent two different modes of achieving the same subjective meditative experience. In this report, because they affect such extensive cortical areas and are normally associated with unconsciousness, we examine the travelling SWs, of which Figure 1 is an example. This 2-minute segment shows SWs of p-p intensity 300-1000 μ V that completely dominate higher frequency activity, even though there is significant gamma band activity (30-150 Hz), particularly at posterior sites where it is modulated by the SWs.

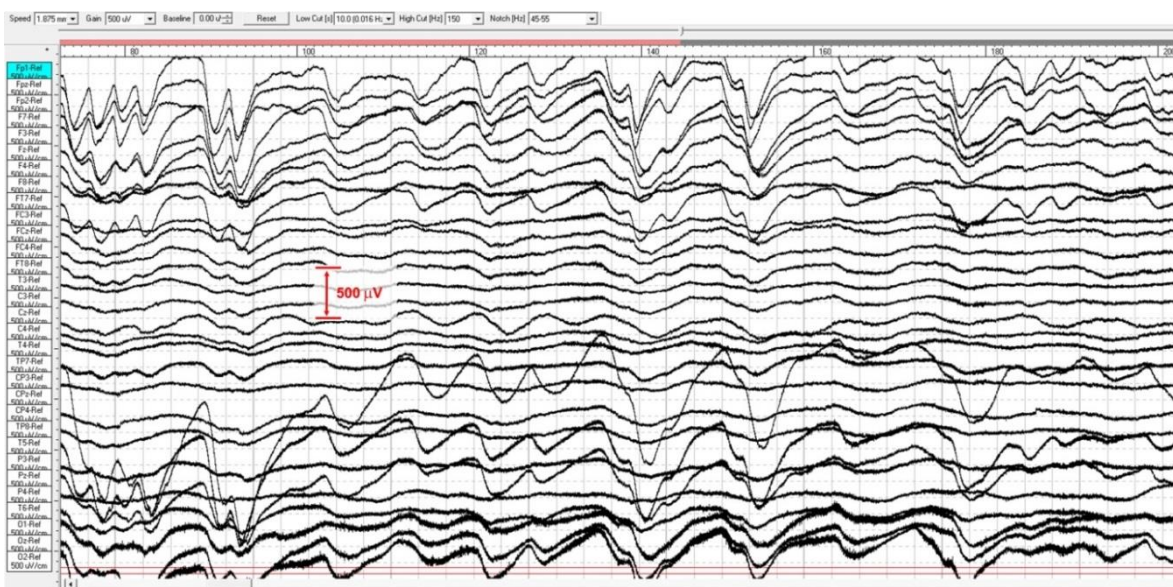


Figure 1 Travelling slow waves (subject 5).

This subject sustained very strong and clearly defined travelling SWs of 300-700 μV p-p consistently for over 20 mins, and were it not for the fact that central areas are relatively free of these strong SWs, the recordings are even reminiscent of high voltage delta coma¹⁹. Figure 2 illustrates the travelling nature of a typical SW from this same subject. The scalp intensity maps 1–6 show the –ve peak of the wave starting and then extending left-frontally, before travelling to occipital areas (mainly left).

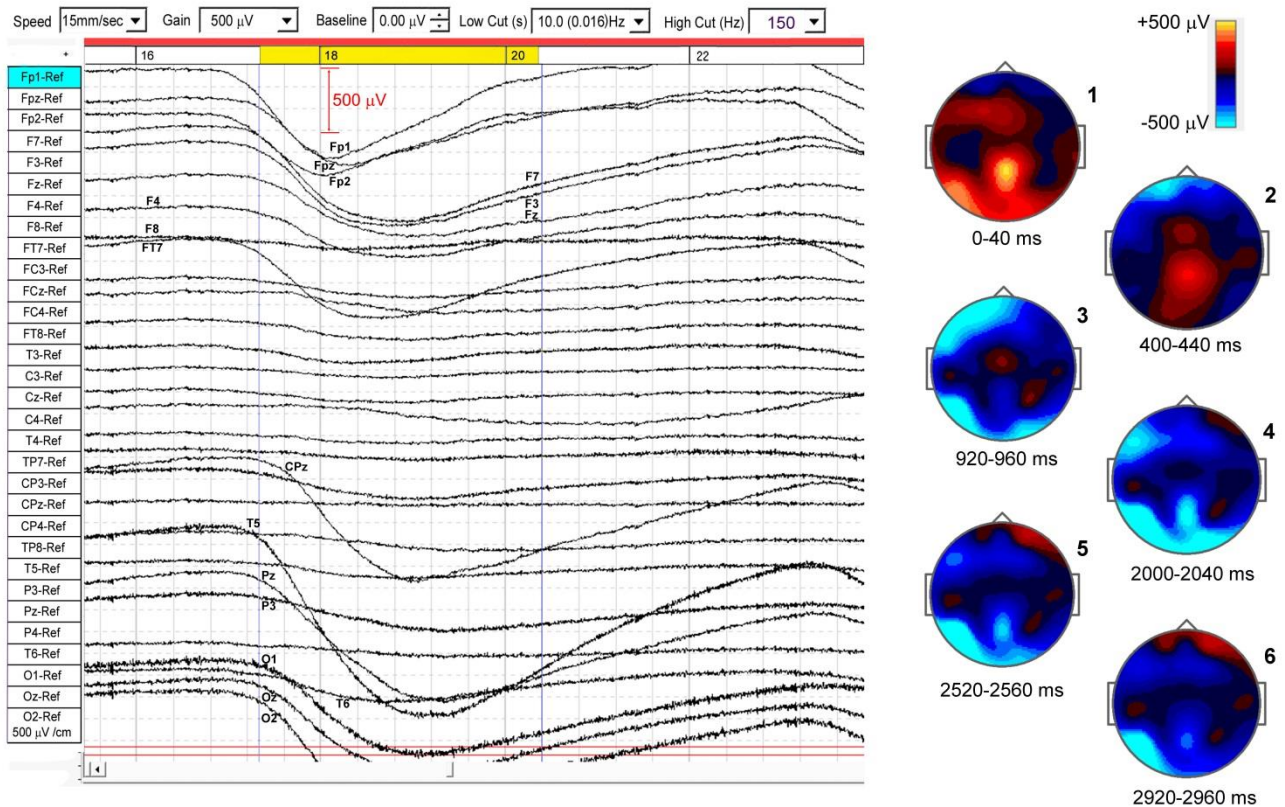


Figure 2 Travelling slow wave (subject 5). Scalp maps 1-6 trace the progression of the –ve peak across a 3-second interval. Maps 3 and 4 correspond roughly to the frontal and posterior –ve peaks. Note the localised midline peak, extending from the occipital area to just posterior to the vertex, at first +ve and later –ve. Also (from the raw data) the considerable, and typical, broadening of the wave as it reaches occipital areas.

Although for any particular meditator the sites of activity remain fairly constant during a recording (in this example, EEG sites Fp1, F7, T5, O1, O2 and CPz), transit times vary considerably. For this subject, the SW in Figure 2 shows a transit time, front to rear, of 1200 ms. For 20 successive SWs from this same subject (Supplementary Table 2), mean transit times were: Fp1 to O1/O2, 593 ± 300 ms; Fp1 to T5, 723 ± 230 ms; and Fp1 to CPz, 1278 ± 340 ms. The mean front to rear transit time ~ 600 ms corresponds to a mean transit speed for this meditator of ~ 50 cm/s across the head, considerably slower than typical values ~ 2 -3 m/s for sleep SWs¹², again, as noted above, suggesting a different mechanism to that in sleep.

To explore cortical sources¹⁶, an independent component analysis was carried out using the Infomax algorithm, with corresponding sources computed using the reverse solution of sLoreta²⁰. Figure 3 shows an example of this analysis from a 3-minute segment of travelling SWs. The five strongest components accounting for 45.5% of the total signals' variance are shown, with the corresponding cortical sources. The source for component 1 (16.7% var.) is centred at Brodmann area 7, the postcentral gyrus; as is component 2 (7.4% var.). Component 3 (7.3% var.) is situated at Brodmann area 10, the middle frontal gyrus (right); while components 4 (7.2% var.) and 5 (6.9% var.) are again located at Brodmann area 7, the postcentral gyrus. The mean scalp intensity map for

the whole 3-minute segment (top right) shows an almost complete annulus of excitation/de-excitation, with a hot-spot over the postcentral gyrus area.

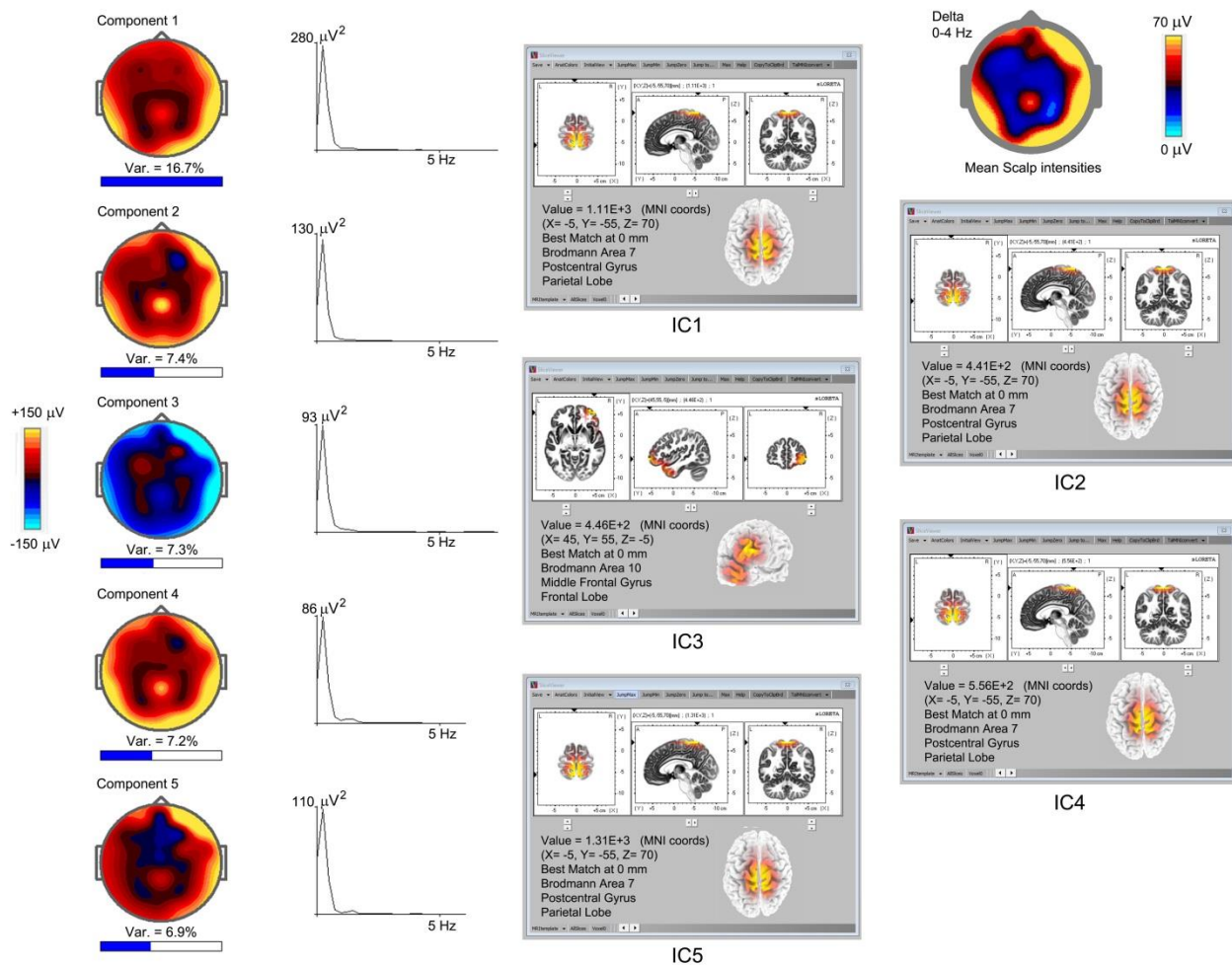


Figure 3 Independent components (ICs) and cortical sources computed using sLoreta. Subject 3, 3-minute segment of slow waves, bandpass 0.016-150 Hz. On the left are the scalp intensity maps for each component, with their spectra, and to the right the corresponding cortical sources. The mean scalp intensity map for the entire segment is at top right.

Although the rhythmic pulses of alternating excitation–de-excitation reach p-p values ~ 500 μV , the dynamic balance over 3-minutes shown by the mean scalp map is little different to the resting state eyes-closed values ~ 40 – 60 μV . The independent components 1, 2, 4 and 5 all point to a cortical source at the postcentral gyrus, which is likely to be the same cortical source, with the apparently separate “independent” components representing different phases of the fluctuating slow waves, as can be seen in the scalp maps for the different components.

For all the subjects that show strong travelling SWs, the rhythmic SWs tend towards creating an annulus of excitation–de-excitation extending over frontal, posterior, and lateral temporal and parietal areas, leaving much of the central area untouched apart from, in some cases more clearly than others, a localised area extending from occipital sites to around the postcentral gyrus. To illustrate this further, Figure 4 shows scalp intensity maps for five subjects who all show strong and clear travelling SWs in their EEG recordings. The alternations between excitation–de-excitation can be seen in each case, particularly: for subject 5, A–C; subject 17, C–D; subject 24, B–D; subject 3, B–D; and subject 26, C–D. The “annulus” becomes complete at times for subjects 17 (C), 24 (B), 3 (B), and 26 (D); and not quite complete for subject 5 (C). The localised region just posterior to the vertex that also undergoes excitation–de-excitation can be seen in all cases.

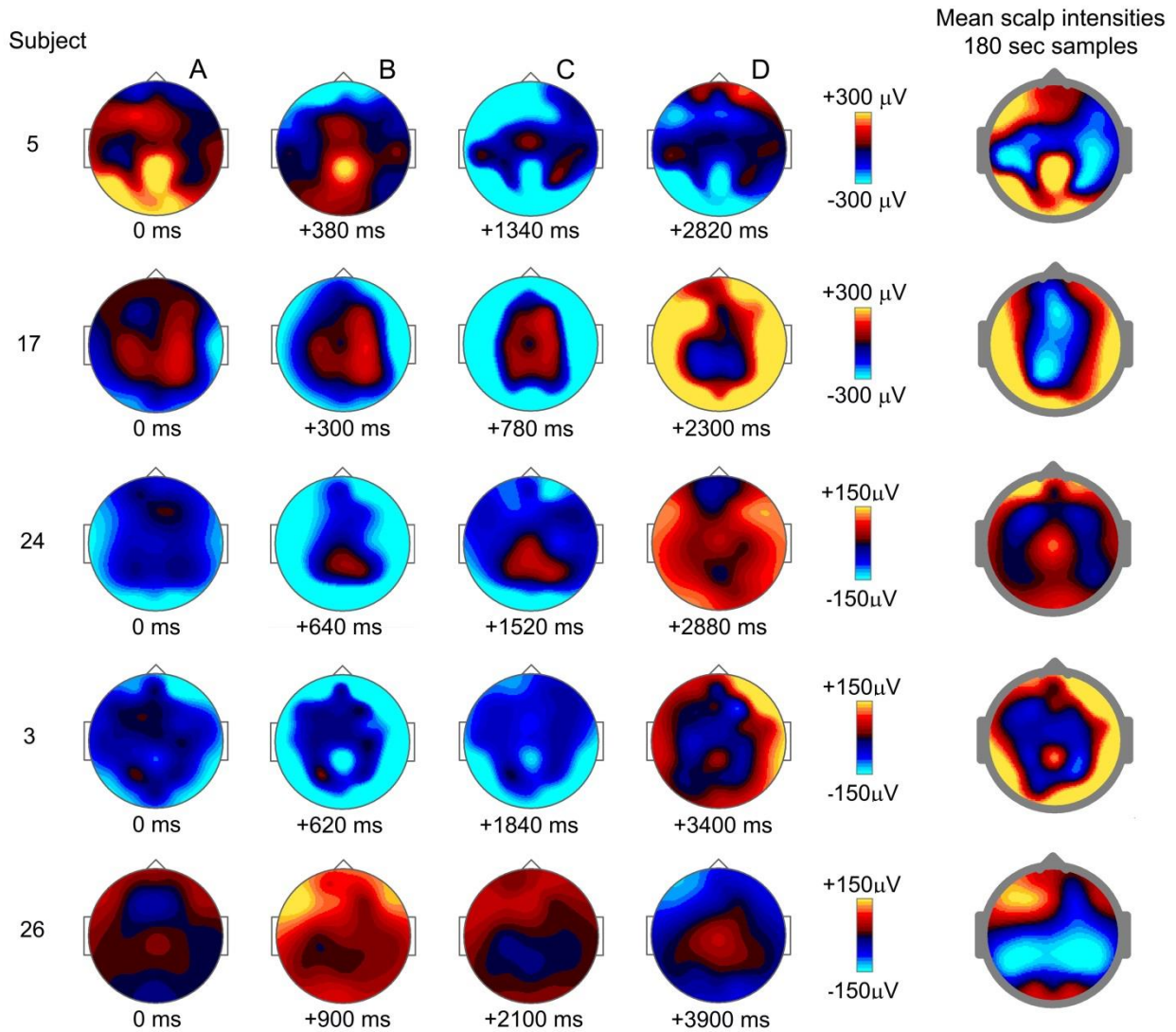


Figure 4 Scalp maps showing the changing excitation–de-excitation phases of single SWs for five subjects, with mean 180-second scalp intensity maps to the right.

Table 1 shows cortical sources calculated using sLoreta, for six subjects covering a total recording time of over 30 mins of travelling SWs. Averaged across the six subjects, sources are found in three areas, frontal regions (left-hand columns), occipital regions (right-hand columns), and around the postcentral gyrus and paracentral lobule (central columns). In fact, for subjects 5 and 3, who show the most consistent travelling SWs, these latter are the dominant sources.

| Subject | B47 IFG | B10 MFG SFG | B11 MFG SFG OFG | B6 MFG SFG | B4 PCL | B6 PCL | B5 PCG | B7 PCG | B21 MTG ITG | B18 Cuneus | B20 Uncus |
|---|------------------|-----------------------|---|----------------------|-------------------|-------------------|-------------------|-------------------|---|---------------------------|-------------------------|
| 5. (600 secs) Normalised to 50% | | | | | 18.4% (medial) | | 31.6% (medial) | | | | |
| 3. (180 secs) Normalised to 50% | | 7.9% (MFG medial) | | | | | | 42.1% (medial) | | | |
| 17. (240 secs) Normalised to 50% | | | 3.14% (SFG left) | | | | | | 22.23% (12.89% MTG right) (9.34% ITG right) | 24.63% (Cuneus medial) | |
| 24. (524 secs) Normalised to 50% | | 33.1% (MFG medial) | 15.3% (10.48% MFG medial) (3.26% OFG right) (1.56% SFG medial) | 1.6% (SFG medial) | | | | | | | |
| 26. (180 secs) Normalised to 50% | 3.85% (right) | | 32.95% (MFG left) | | | | | | | 4.07% (Cuneus medleft) | 9.12% (Uncus medial) |
| 10. (115 secs) Normalised to 50% | | 8.1% (SFG left) | 18% (MFG medial) | | | 16.9% (medial) | | 7.0% (medial) | | | |
| TOTAL (1839 secs) Normalised to 100% | 1.28% | 16.37% | 23.13% | 0.53% | 6.13% | 5.63% | 10.53 | 16.37% | 7.41% | 9.57% | 3.04% |

Table 1 Cortical sources computed using sLoreta for 30 minutes of travelling SWs across six subjects. IFG, MFG, SFG, OFG = inferior, middle, superior and orbital frontal gyri; PCL = paracentral lobule; PCG = postcentral gyrus; MTG, ITG = middle and inferior temporal gyri. For each subject the 4 or 5 strongest independent components were chosen that accounted for ~50% of the signals variance, and the values for each source normalised to exactly 50% of the variance. The final totals are normalised to 100%.

Discussion

To take a metaphor from sleep studies, as attention is turned away from normal sensory consciousness and cognitive processing, extensive areas of the cortex as seen in the scalp EEG are “put to sleep”, or suppressed, by high-voltage rhythmic SWs. This occurs in the form of an annulus of excitation/de-excitation with a hot-spot over the postcentral gyrus and paracentral lobule area. The dominant underlying cortical sources are, from Table 1, frontal (41.3% of the EEG variance), occipital (20%), and just posterior to the vertex at the postcentral gyrus or paracentral lobule region (38.7%). We suggest that the extensive annulus seen in the surface EEG, represents just those cortical networks that support our everyday sensory consciousness, with the underlying cortical sources being key hubs of connectivity. The frontal area as a key hub is no surprise, being frequently associated, together with the adjacent anterior cingulate gyrus, with cognitive processing in the executive network^{21,22,23}. The annulus affected also covers areas related to memory, naming and discrimination, vigilance as to threat, and other areas necessary to support normal sensory consciousness^{5,6}. The occipital hub, we suggest, represents the importance of the dorsal and ventral visual streams that underpin much of our first-person “eye/I” of sensory consciousness²⁴. We further suggest that the central hub at the postcentral gyrus/paracentral lobule area plays a key associative role with its strong connections to the underlying posterior cingulate, and the deeper thalamus, known to be involved in the sleep-wake cycle²⁵, and in consciousness itself⁶. There is also growing evidence from lesion²⁶ and coma²⁷ studies that the posterior cingulate plays a pivotal role in maintaining consciousness²⁸. We suggest that it may also play a triggering role when the meditator withdraws his/her subjective “I” component from the dynamic balance of the sensory consciousness network, resulting in a “collapse” of the network dynamics to a default mode or limit cycle of the thalamo-cortical system, expressed by SWs²⁹. Thalamic bistability is of course familiar in the awake-sleep transition²⁵ but, as noted earlier, the SWs we see are considerably slower than in sleep, both in speed of transit and frequency. The default mode found here may be more fundamental than that in sleep, where the “default” activity still appears to be influenced by a haemodynamic attractor that affects the SW frequency¹⁸. In some cases the “trigger” or “collapse” during meditation is very rapid, as seen in Supplementary Figure 1 (lower panel) and Figure 2. These striking changes elicited by intentional changes in attention by meditators, highlight the highly sensitive balance between external drivings and internal dynamics that underlies the brain’s dynamic balance; rather than that balance being simply autonomously driven.

Whilst SW activity is the focus of this Report, we also find examples of seizure-like activity such as spike-wave complexes reminiscent of absence epilepsy, or the more dramatic ability of some experienced practitioners to consciously evoke intense excitation similar to clonic seizures. These will be described in a subsequent paper, with implications for understanding epileptic processes.

Methods

Supplementary Table 1 summarises the recordings of 27 subjects. Years of experience of this form of meditation range from 4–52 years, with most individuals maintaining a daily practise of 30-60 mins, with a more intensive 7-10 days “retreat” experience every 1–3 years. Twenty-four of the subjects are of graduate or postgraduate-levels of education; and include 4 senior psychotherapists, 1 medical doctor, and 13 school or university teachers. They therefore form an excellent pool for

subjective reports. Subjects practice seated on the ground, usually but not always seated on a cushion, with the body erect and composed, still but not rigid, and not resting or leaning on any supports. An EEG recording starts with a few minutes eyes-open and then eyes-closed, before moving into meditation, with an overall duration of typically 40 minutes. The meditation technique is progressive, moving through stages of increasingly internalised attention. The person managing the recording indicates with a few words when he requires the meditator to move to the next stage. For the purpose of this paper, we are interested in the brain's response as the meditator withdraws from attending to the outer senses, from discursive thinking, "naming" or "recognition", which implies also withdrawing from memory-based associations, and to a large extent from the anchor of time. Given that the recordings show features similar to deep sleep, it is important to stress that the meditator is fully conscious throughout the recording. He/she responds immediately to the verbal cues at each stage, and at the end of the practice shows no sign of sleep inertia or any sign of disorientation. Meditators describe their subjective experience as one of clear and heightened awareness, and of a powerful stillness, which persists after emerging from the practice. The protocol at the end of a recording is that the subject describes his/her recollection of the practice, in as much detail as possible, while the researcher monitors the recording in parallel.

Recordings were made using 24-bit Mitsar amplifiers³¹, either the 31-channel Mitsar 202 DC amplifier (subjects 1-12), or the 21-channel wireless Mitsar SmartBCI DC amplifier (subjects 13-27). The 31-channel system has a sampling rate of 500/sec and a frequency range up to 150 Hz, and was used with Easycaps and Ag/AgCl electrodes. The 21-channel system has a sampling rate of 250/sec and was used with MCScaps and Ag/AgCl electrodes. A combined conductive and mildly abrasive gel was used to obtain impedances as close to or less than 5K Ω as possible. Electrodes were placed according to the international 10-20 system, and a monopolar linked-ears reference was used. Software analysis was carried out using WinEEG³², which implements the Infomax algorithm as used in EEGLAB³³ to compute independent components. Cortical sources were identified for each independent component using sLoreta²⁰ for source location. For some meditators prone to eye-flutter, soft cotton-wool eye pads were used to effectively damp such artifacts that can be confused with frontal delta activity. Because meditators are generally very still and relaxed, movement and muscle artifacts are mostly absent. Any occasional adjustments to posture, if they occurred, are excluded from analysis.

Jhāna meditation

Buddhist meditation, whether Southeast Asian, Tibetan, Japanese or Chinese, comprises two strands, Samatha³⁴ and Vipassanā; 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 now accepted as useful in the treatment of recurrent depression, is in fact just one of the basic factors underpinning both samatha and vipassanā. Jhāna⁴, frequently translated as "absorption", falls within the samatha division, and is regarded as the foundation for developing insight and wisdom into the nature of self³⁵. Etymologically it has two roots, "meditation", but also "burning up"; the latter meaning to burn up the hindrances rooted in attachment to normal sensory consciousness. Jhāna is therefore a very active state, not passive, and is subjectively experienced as a state of heightened, yet tranquil and still, consciousness of an internal mental object. It comprises four rūpa (form) jhānas, and four arūpa (formless) jhānas. The first rūpa jhāna is specifically concerned with attention, and requires the meditator to master attention in two aspects – placing attention, and sustaining attention. We can immediately relate this to two components of the executive attention network, the first a mental act of turning the attention to an object, the second as some form of error-detection network to know when attention wanders. In the form of practice we describe, attention is directed first towards the touch of the breath at the nose tip or upper lip as the object. When this becomes familiar and stable, a feeling of satisfaction develops and the attention moves to an internal mental object that is the meditator's growing awareness of his/her consciousness, no longer dependent on the external world. The second and third rūpa jhānas are a

refinement of the feeling components of consciousness – both bodily and mental feeling in the second, and purely mental in the third, ranging from deep contentment to bliss. As dependence on even that pleasure and satisfaction fades, or in other words dependence on a “reward”, a finely balanced and still state of awareness remains in the fourth rupa jhāna, experienced as equanimity and one-pointedness of mind. Some meditators then proceed to develop the four arupa, or formless jhānas, that challenge assumptions of space and time, and indeed the “self”, and in a sense are an exploration of perception itself.

It is striking that this particular form of jhāna meditation can develop unusually high intensity EEG activity, safely. It is a practice that has evolved to suit lay practitioners, and the normal length of breath is not used, which means that there is an “entering” and a “leaving” to move safely in either direction between normal everyday consciousness, and meditation.

Additional information

Ethical approval and procedures

Ethical approval for the study was granted by the Trustees of The Samatha Trust (regd UK Charity No. 266367 [1974]) who oversee the teaching of the form of meditation described in this study. The study was conducted according to the principles and guidelines of the WMA Declaration of Helsinki, and all subjects have given written informed consent with the usual caveat of confidentiality. EEG recordings and analysis follow guidelines of the American Clinical Neurophysiology Society.

Author’s contribution

The EEG recordings and analysis were carried out entirely by the named author Paul Dennison.

Competing financial interests

The author declares no competing financial interests.

Data availability

All data generated or analysed during this study are included in this published article (and its Supplementary Information files). Further material generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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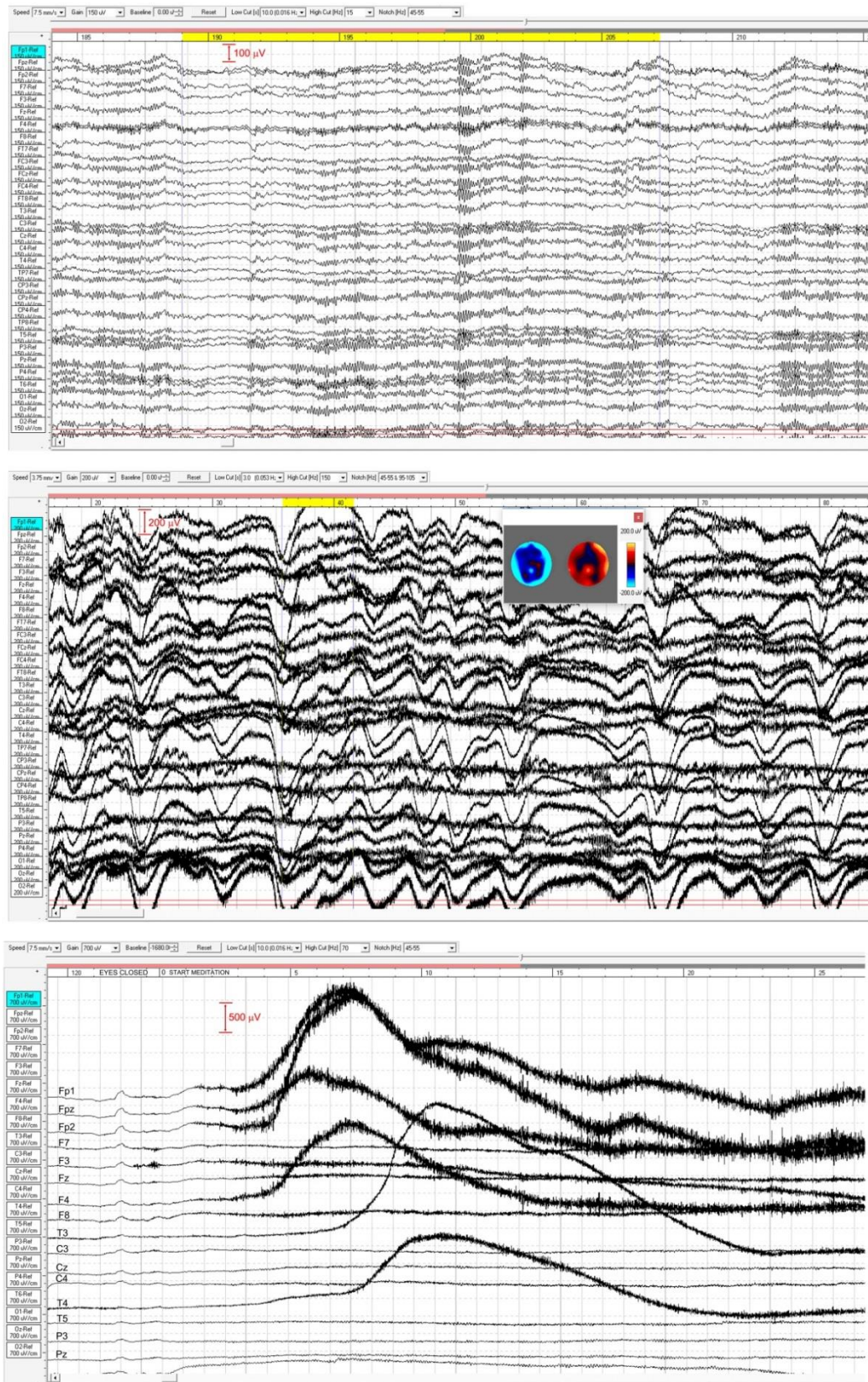
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Supplementary material

| Subject | Yrs practice | Non med ⁿ Eyes- Closed p-p μV | Meditation Slow waves (SWs) p-p μV (Half-cycle secs) | Meditation SWs Well-defined or Ill-defined | Meditation SWs V. frequent >50% Frequent 20-50% Infrequent <20% | Comments |
|---------|--------------|--|--|--|---|---|
| 1 | 41 | ~65 μV | SWs ~200 μV (3-5s) | Well-defined but not clearly travelling | Frequent | Also shows repetitive spindling followed by short "silences". Includes periods of high gamma superposed on SWs |
| 2 | 39 | ~50 μV | Weak frontal SWs | Ill-defined | Infrequent | Considerable occipital spindling |
| 3 | 52 | ~55 μV | SWs ~350-400 μV (3-7s) | Well-defined, travelling | Very frequent | Occasional brief episodes of occipital spike-waves, and (unrelated) episodes of strong frontal delta ~4Hz |
| 4 | 16 | n.a. | | | | Data not useable – unstable impedances at some electrodes |
| 5 | 30 | ~40 μV | Strong SWs ~600-700 μV (3-5s) | Well-defined, travelling | Very frequent | Also shows strong frontal gamma |
| 6 | 39 | ~45 μV | Weak SWs ~100-150 μV (3-6s) | Ill-defined | Infrequent | Frequent spindling followed by short "silences" |
| 7 | 28 | ~35 μV | Irreg. weak SWs 100-150 μV (3-5s) | Mostly weak and ill- defined. One isolated very strong and well-defined >700 μV | Infrequent | Frequent spindling followed by "silences". Intentional arousing of high energy state evokes SW with superposed spike-waves |
| 8 | 37 | ~45 μV | SWs ~150-200 μV (2-4s) | Well-defined, but see Comments | Frequent | SW phase reversals (on monopolar ref. montage) correspond to alternating +ve and -ve peaks at frontal left F7/Fp1 and posterior right P8/O2. Pulsing rather than travelling waves? |
| 9 | 6 | ~35 μV | Irreg. weak SWs 100-150 μV frontal; later occipital very slow 150-200 μV | Ill-defined frontally; better defined occipitally | Infrequent | Some frontal SWs show phase reversals. Some spindling, later superposed on occipital SWs (very slow ~0.1 Hz) |
| 10 | 32 | ~30 μV | Strong frontal SWs ~200 μV (2-3s) | Well-defined, but note sawtooth shape; sharp rise slow decay | Frequent | Frequent posterior spindling. Intentional arousing of high energy state evokes frontal 1500-2000 μV sawtooth slow wave (~0.1 Hz) |
| 11 | 25 | ~35 μV | Irreg. weak SWs 100-150 μV (3-5s) | Ill-defined | Infrequent | In later part of recording some SWs show phase reversals |
| 12 | 27 | ~45 μV | Irreg. weak frontal SWs 100-150 μV (~4s) | Ill-defined; very slow (~0.1 Hz); faster rise-slow decay | Infrequent | In later part of recording a few SWs show reversals. Intentional arousing of high energy state evokes temporal/posterior SWs |
| 13 | 6 | ~70 μV | SWs ~200 μV mostly frontal (4-6s) | Ill-defined | Infrequent | Intermittent frontal delta ~1 Hz |
| 14 | 30 | ~65 μV | V. Strong SWs ~500-700 μV (2-4s) | Well-defined, some show travelling nature | Infrequent | SWs particularly strong temporally, but extend to fronto-central regions later; with associated strong spindling, then "silences" |
| 15 | 41 | ~45 μV | Only isolated episodes SWs ~200-500 μV ; see Comments (3-7s) | Well-defined | Infrequent | Occasional occipital spike-waves, followed by spindling. Some posterior SWs and spindling later in recording. Also <u>harmonic</u> <u>spectral structure</u> at times. Single, strong +ve SW later in recording |
| 16 | 24 | ~35 μV | Frontal ~200 μV SWs (cf subject 10) (~3s) | Well-defined, but note sawtooth shape; sharp rise slow decay | Frequent | Widespread and very well-defined occipital alpha spindling |
| 17 | 20 | ~50 μV | V. Strong SWs 800-1200 μV (2-3s) | Well-defined, travelling | Very frequent | This subject showed the strongest SWs. Also frequent ictal-type spikes at 2.75Hz |
| 18 | 42 | ~55 μV | Isolated SWs 100-150 μV (4-6s) | Ill-defined | Infrequent | |
| 19 | 33 | ~55 μV | V. Strong SWs 500-1200 μV (3-5s) | Well-defined, intense one- off episodes. Not clearly travelling, but still define inner/outer areas | Frequent | NB these SWs show +ve peaks with a slow decay. Also very strong frontal gamma, and episodes of frontal spike-waves. Some sections show <u>harmonic</u> spectral structure |
| 20 | 7 | ~40 μV | Strong frontal SWs ~400- 500 μV (5-6s) | Well-defined, but "square" form; very slow | Frequent | Occasional spindles |
| 21 | 36 | ~40 μV | Weak SWs ~100 μV (~4s) | Ill-defined | Infrequent | |
| 22 | 42 | ~60 μV | See Comments | | | Suspect recording - unstable impedances at some electrodes |
| 23 | 8 | ~45 μV | Frontal SWs ~150 μV (~3s) | Ill-defined | Infrequent | |
| 24 | 43 | ~45 μV | Strong SWs 400-600 μV (3-4s) | Well-defined, travelling | Frequent | Repetitive ictal-type episodes mixed with SWs and short "silences". Episodes of frontal spikes and occipital spindles |
| 25 | 4 | ~50 μV | Frontal SWs ~100-150 μV (~3s) | Well-defined | Infrequent | Frequent spindling |
| 26 | 37 | ~55 μV | SWs ~300 μV with isolated huge ~2500 μV SW later (3-4s) | Well-defined, travelling | Frequent | NB these SWs show +ve peaks. Frontal and then later occipital spike-wave episodes |
| 27 | 4 | ~55 μV | Possible occipital SWs later (~2s) | Ill-defined | Infrequent | Frequent spindling |

Supplementary Table 1 Overview of subjects. Twenty-seven subjects were recorded during 2014-16. Two recordings (4, 22) were discarded due to impedance problems at some electrodes. Of the remaining 25 records, all showed slow waves (SWs) to some degree. From the half-cycle durations (col. 4) the SW frequencies are in the range 0.1-0.2 Hz. The weaker and less well-defined SWs are often associated with alpha spindling. Thirteen subjects showed sufficiently strong (200-1,000 μV p-p) and well-defined SWs, to merit further analysis. Six of these 13 showed clear and extensive "travelling" SW behaviour, while a similar number showed more localised and isolated SWs, sometimes of very high intensity. The strong travelling SWs are the main subject of this paper.



Supplementary Figure 1 Slow waves and spindles. Top panel, weak and irregular frontal SWs with widespread spindling, in this case at 10.25 Hz (subject 9). Middle panel, a 70-second segment of travelling SWs (subject 3); the inset shows scalp maps at the $-ve$ peak and the point of $+ve$ recovery for the marked slow wave (yellow bar). Lower panel, powerful, isolated SWs (subject 19); note the slight $+ve$ “blip” coinciding with the verbal cue to start meditation; this recording is shown with an offset of $-1680 \mu\text{V}$ to show the full extent of the SWs, which reach $1500 \mu\text{V}$ p-p at Fp2.

Time delays ms (subject 5)

1. Waves travelling frontal to occipital

Fp1 to O1/O2

797, 994, 1368, 581, 778, 285, 275, 266, 463, 246, 659, 866, 758, 660, 305, 581, 708, 630, 286, 364
Mean 593 St. Dev. 293

Fp1 to T5

965, 935, 1053, 669, 807, 374, 413, 266, 882, 773, 1092, 895, 815, 660, 640, 581, 740, 615, 964, 600, 443
Mean 723 St. Dev. 229

Fp1 to CPz

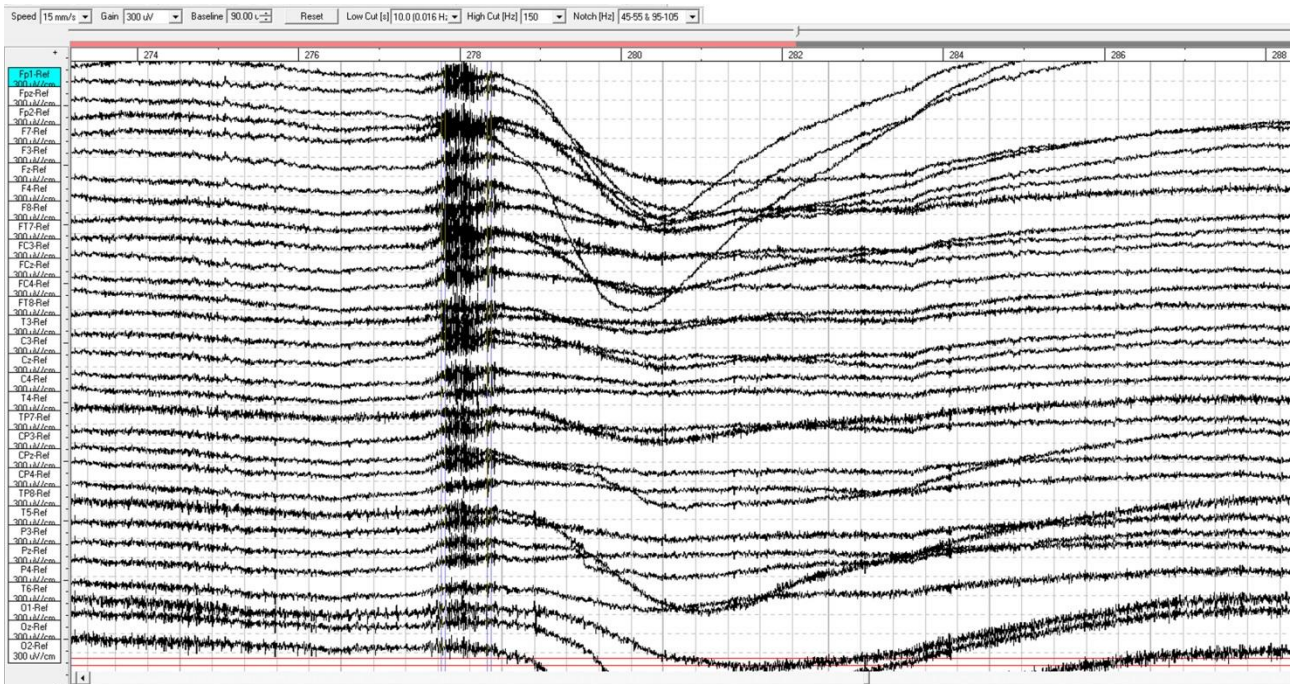
1348, 1417, 2007, 1791, 1634, 1436, 1014, 1456, 1020, 925, 1555, 934, 1034, 1098, 876, 1260, 1476, 738, 1269
Mean 1278 St. Dev. 337

2. Waves travelling occipital to frontal

O1/O2 to Fp1/Fp2

512, 974, 522, 541, 197, 482, 197, 197
Mean 453 St. Dev. 263

Supplementary Table 2 Travelling SW mean transit times. (1) front to rear. (2) approx. 20% of this subject's SWs move in the reverse direction, occipital to frontal, and these tend to have lower occipital intensities than the majority travelling frontal to posterior.



Supplementary Figure 2 Sudden onset of SWs after a relatively “silent” period (subject 5). Note the preceding gamma burst, duration ~0.6 secs and mean frequency 78 ± 7 Hz.