Neural Correlates of Induced Light Experience during Meditation: A Pilot Hyperscanning Study

Peter Fenwick[1]*, Caroline Di Bernardi Luft[2,3], Andreas A Ioannides[4], Joydeep Bhattacharya[3]

ABSTRACT

Certain individuals during deep meditative state can give out an aura or ‘light, which is perceived by others through some unknown connections, visual, telepathic or other. Despite various anecdotal, historical accounts of such induced light experience (ILE), its underlying neural mechanisms are not known. In this pilot study, we investigated the neural correlates of ILE by simultaneously recording the EEGs of an expert meditation Teacher, who is claimed to elicit ILE, and his Pupil (*N*=2) during joint meditation sessions under various instructions, given separately to the Teacher (transmit/do not transmit) and to the Pupil (receive/do not receive) and also during transmit/receive instruction but both wearing goggles, limiting the visual input. We observed a robust increase in the high frequency beta (12-30 Hz) and gamma oscillations (30-70 Hz) in the Teacher’s brain whenever he was instructed to transmit. Electric field tomography analysis localized these effects over a multitude of brain regions including the fusiform gyrus, angular gyrus and the cerebellum. Finally, we found that the Teacher’s and Pupil’s brain responses were synchronized especially in the alpha band (8-12 Hz) during transmit/receive condition, and the information flow was directional, i.e. from the Teacher to the Pupil; interestingly, this enhanced interbrain synchrony disappeared with goggles. These results were interpreted in terms of heightened internally selective attention as manifested by high frequency beta-gamma oscillations and of joint attention as manifested by interbrain alpha synchrony. Altogether, our results provide first neuroscientific evidence underlying the phenomenological experience of induced light. (Word count: 246)

Key Words: Meditation, Light, Energy, EEG, Hyperscanning, Oscillations, Interbrain Synchrony

DOI Number: 10.14704/nq.2019.17.01.1318 **NeuroQuantology 2019; 17(01):31-41**

Introduction

Anecdotal accounts of individuals who see light surrounding their meditation teacher when meditating are not uncommon. In fact, the occurrence of such induced light experience (ILE) dates back to early history. Greek philosopher Parmenides and Plato both associated ‘truth’ with light. Since then there are many accounts in the esoteric literature of spiritual teachers who are able to radiate ‘light and energy’ when meditating. For example, St. Francis of Assissi was reported by other monks to have been surrounded by a cloud of white light, as was St. Theresa of Avila. Puhle, (2014) has summarized the history of light phenomena in over 750 individual accounts and shows the widespread nature of light experiences. Light has also been associated with the dying just days before death. The light is seen by the dying themselves, carers and relatives, however, there is a subjective component as not all the relatives may see it, and interestingly, any light experiences often end with death (Fenwick and Fenwick, 2012).

In some cultures, subjective light experiences have been associated with the nature of the mind. For example, in the book, “Awakening the Luminous Mind”, Rinpoche, (2012) gives a number of Tibetan meditation practices to reveal this light of the mind.

Corresponding author: Dr. Peter Fenwick

Address: [1]Institute of Psychiatry (Emeritus), King’s College London, London, UK; [2]School of Biological and Chemical Sciences, Queen Mary University of London, London, UK; [3]Department of Psychology, Goldsmiths University of London, London, UK; [4]Laboratory for Human Brain Dynamics, AAI Scientific Cultural Services Ltd, Cyprus

e-mail ✉ peter_fenwick@compuserve.com

Relevant conflicts of interest/financial disclosures: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Received: 17 March 2018; **Accepted:** 20 September 2018

Meditation has been shown to affect brain physiology. Numerous studies suggest robust structural changes, i.e. brain's gray and white matter, associated with in the intense meditation training (Fox, Dixon *et al*., 2016). Further, changes in the functional brain responses are also widely reported during (Cahn and Polich, 2006). In a pioneering fMRI experiment, Beaureguard and Paquette, (2006) recorded the haemodynamic responses of Carmelite nuns, who often experience light and love in their meditation, while they were subjectively experiencing a state of union with God. A wide range of brain regions including right medial orbitofrontal cortex, right inferior and superior parietal lobules, right medial temporal cortex, left anterior cingulate cortex were activated during this mystical state. Further, high frequency gamma oscillations (> 30 Hz) are found to increase during meditation (Lehmann, Faber *et al*., 2001; Lutz, Greischar *et al*., 2004; Vialatte, Bakardjian *et al*., 2009; Cahn, Delorme *et al*., 2010). Gamma oscillations are widespread in human brain and generated out of the coordinated interaction between excitatory and inhibitory neuronal populations (Buzsáki and Wang, 2012); its functional roles are less specific as it is implicated with wide ranging cognitive and emotional processes in visual binding, selective attention, memory recall, to emotional arousal. However, to our knowledge, no study so far has connected the documented increase in occipital gamma during meditation with spontaneous visual imagery. Interestingly, the process of "seeing things" during meditation is a commonly reported phenomenon - "encounters with light" - amongst meditators (Lo, Huang *et al*., 2003, Lindahl, Kaplan *et al*., 2014). For example, Lindahl, Kaplan *et al*. (2014) wrote "Two practitioners also reported a proprioceptive dimension to their meditation-induced light experience. One practitioner explained that "my body just was breaking apart into sparkles and like electrical sparks being sent off everywhere in all directions"; the other "felt like I was radiating, like there were rays of light coming out of me."

Though these studies present some novel accounts on the experience of light during meditation, they do not directly address the transmission of light between teacher and pupil or the information exchange between the two brains engaged during the induced light experience (ILE). To the best of our knowledge, little empirical data are available on ILE and we know almost nothing about its neuronal mechanisms. The primary reasons, we believe, are two folds: first, it is not easy to identify a Teacher-Pupil pair having ILE in a robust and consistent manner, and second, more importantly, the severe reluctance of a Teacher to co-operate with neuroscientific researchers who would like to investigate the phenomenology of ILE with proper scientific rigor and controls. In this study, we carried out a pilot investigation on one meditation Teacher AF (male, 60 years) who has a reputation of evoking ILE in his pupils, and importantly, who was willing to co-operate so that a scientific understanding of such ILE could be attempted. In this pilot study, we investigated the neural correlates of ILE by simultaneously recording EEG of AF and his pupil (N=2) during the ILE and related controlled conditions.

Materials and Methods

Participants

A.F. is a 60 year old male French Philosopher and meditation teacher who had spent many decades sitting in silence in French cathedrals. Subsequently, he had a number of transcendental experiences, following which he discovered that he had developed the ability to cause ILEs in his students. By combining Eastern and Western philosophical concepts, AF has developed his unique 4-D meditation teaching philosophy as follows: distancing (a position of self-observation), discernment (an exploration of layered emotions), disidentification (an enhanced awareness of situations), and discrimination (the strict practice of metaphysical enquiry). In a typical joint meditation session with AF, his pupils sit in front of him and look at him, and he then induces in himself a mental state, which he describes as 'entering the void', and his pupils experience light in this state. The whole process is brief and lasts about two to three minutes. The pupils report experiencing light of various colours and intensities in the room and 'energy' moving in their bodies. Two male pupils age 45 and 47 years familiar with AF's meditation and philosophical concepts participated in this study. All participants were neurologically healthy, provided written informed consent before the experiment started, and the study protocol was approved by the Local Ethics Committee at Goldsmiths, University of London.

Procedure

The Teacher and his Pupil sat opposite and facing each other. Visual instructions were shown behind each participant but visible only to the other person.

We had five conditions and each condition was repeated once for each Teacher-Pupil dyad (Table 1). Each condition lasted for 3 minutes, and a break of few minutes was provided between conditions to bring back the mental states of both the Teacher and the Pupil to the baseline level as appropriate; both participants were given texts with neutral content to read during the breaks. No verbal communication was allowed between the Teacher and the Pupil throughout the experiment.

Table 1. List of five conditions used in our study. The Teacher (T) and his Pupil(P) were given individual instructions in a way that one could not see the instruction given to other. For each Teacher-Pupil dyad, all conditions were presented twice. The order of the conditions was randomized within each dyad

Condition	Instruction to (T)	Instruction to Pupil (P)
TsPr	Send energy	Receive energy
TnsPr	Do not send energy	Receive energy
TsPnr	Send energy	Nothing to receive
TnsPnr	Do not send energy	Nothing to receive
TsgPrg	Send energy after wearing an opaque glass	Receive energy after wearing an opaque glass

EEG Recording and Pre-processing

The EEG signals from both Teacher and Pupils were recorded with sixty four Ag-AgCl scalp electrodes placed according to the extended 10-20 electrode placement system (Jasper, 1958), and were amplified by two Biosemi ActiveTwo amplifiers. The vertical and horizontal EOGs were recorded in bipolar fashion by placing additional electrodes above and below the right eye, and at the outer canthus of each eye, respectively. An online reference by forming a feedback loop comprising two electrodes – CMS (common mode sense) and DRL (driven right leg) – was used (see http://www.biosemi.com/faq/cms&drl.htm). The EEG signals were continuously recorded, sampled at 1 KHz, and filtered (high pass 0.1 Hz, low pass 100 Hz). Two EEG devices were synchronized using a pulse signal from the stimulus computer delivered to both EEGs. The EEG signals were later referenced offline to the average of the left and right earlobe electrodes (Essl and Rappelsberger, 1998), and down sampled to 512 Hz. The EEG data were processed and analyzed mainly using the following MATLAB® toolboxes: EEGLAB (Delorme and Makeig, 2004) and FieldTrip (Oostenveld, Fries *et al*., 2011) for data analysis and statistical comparisons.

EEG Analysis

First, we performed spectral analysis of EEG signals. For each condition, EEG data were divided into non-overlapping epochs of 5 sec, and the spectral content was estimated using Welch periodogram with a time window of 2 sec with a 500 ms overlap (Welch, 1967). We divided the broadband EEG power spectrum into six standard frequency bands (Donner and Siegel, 2011): delta (1-4 Hz), theta (4-8 Hz), alpha (8-12 Hz), beta (12-30 Hz), gamma1 (30-45 Hz) and gamma2 (55-70 Hz). Spectral power differences between conditions was compared using *t*-tests, and statistically significant electrodes (Bonferroni corrected $p<0.00013 = 0.05/(6*64)$, 6 frequency bands x 64 electrodes) were highlighted in the scalp maps.

In order to detect the interbrain communication between AF's brain and student brain in different conditions, we applied phase slope index, PSI (Nolte, Ziehe *et al*., 2008), a measure that is able to capture the direction of information flow. PSI is based on the idea that a nonvanishing imaginary part of the coherence cannot be caused by the volume conduction (Nolte, Bai *et al*., 2004), which often leads to spurious connectivity at the sensor level EEG/MEG (Schiff, 2005). The PSI is only sensitive to noninstantaneous simultaneous functional connectivity between two signals and it is based on the slope of the phase of their cross-spectrum. PSI was calculated between all pair-wise electrodes (interbrains, between AF and student) in the six frequency bands as stated earlier. The PSI values were normalized to its standard deviations, estimated by the jackknife method. For Gaussian distributions with an unit s.d., absolute PSI values (normalized in units of s.d.) larger than 1.96 were considered significant at $p<.05$ (Nolte, Ziehe *et al*., 2008).

Source Localization

In order to source localize the brain activities, we performed Electric Field Tomography, EFT, which is an adaption of the method of Magnetic Field Tomography (Ribary, Ioannides *et al*., 1991; Ioannides, Liu *et al*., 1995), a noninvasive nonlinear technique based on distributed source analysis of neural signals that allows a 3-D reconstruction of brain activity with a superior spatio-temporal resolution. We describe briefly the basic steps as we used them in this study. The continuous data for each condition, dyad, and run were pre-processed removing noisy channels and artifacts with ICA and visual inspection and wherever necessary noisy chunks of data. Subsequently, for each condition and run, we separated three segments, one near the beginning (segment1), one near the middle (segment 2) and one near the end (segment 3). We selected 10 trials from each segment. Each trial was chosen away from large artifacts and was 2s long and had about 1,000 time slices (our sampling rate was ~500 Hz, i.e. at 2 ms separation between samples). The main body of data for the EFT analysis was thus composed of 30 trials, each with 1000 sample points (time slices) for each participants and for each condition and run. Using EFT, we computed an independent estimate of brain activation for each time slice of data, i.e. for every 2 ms. We stored the solutions in a rectangular grid covering the entire brain, with point-to-point separation of ~ 8 mm. For each point in the grid (refer to as voxel hereafter) we used FFT to compute the spectrum independently for each trial, from 0.2 to 100 Hz with a step size of 0.2 Hz. At the end of this initial analysis we had two sets of data for each voxel, participant and condition:

Set 1: 2 (runs) x 30 (trials) x 1000 (time-slices) = 60,000 samples for the time domain

Set 2: 2 (runs) x 30 (trials) x 500 (frequencies) = 30,000 samples for the frequency domain

The 30 trials of each run and condition for each participant were divided into three sets, each one with 10 trials. The main comparisons performed were between conditions (e.g. Ts_Rr vs Tns_Rr, or Ts_Rr vs Ts_Rnr). The statistical test identified changes for a given statistical contrast, from voxel-by-voxel comparisons between the spectral power of 3.2 Hz band, sliding this band by 1.6 Hz from 1.6 to 96 Hz; the changes were reported either as *t*-values or as *p*-values after applying Bonferroni correction for multiple voxel comparisons. For each comparison we did the following sequence of tests:

Level 1 analysis: (i) Separately for each participant, run and segment, e.g. Ts_Rr (set *i*) vs Tns_Rr (set *j*), with *i, j* = 1-3, meaning that for each side of the comparison we had10**n* samples (where *n* is the number of frequency values in each bin). These tests resulted in 9 statistical comparisons for each voxel and frequency, for each condition pair. (ii) Separately for each segment of each run, e.g. Ts_Rr (run *i*) vs Tns_Rr (run *i*), meaning that for each side of the comparison we had 30**n* samples. (iii) Separately for each participant, e.g. Ts_Rr (run 1 & 2) vs Tns_Rr (run 1 & 2), which meant that for each side of the comparison we have 60xn samples (where n is the number of frequency values in each bin we consider)

Level 2 analysis: This involved checking for what percentage of cases a number of the tests performed at level one agreed. For example, we could use all the 9 statistical tests for each available run, performed between the different segments, and compute for each voxel the percentage of tests for which change in that voxel of a given sign (increase or decrease) was identified with statistical significance with *p*-value (after Bonferroni correction) lower than a pre-defined level. This percentage was computed for the 36 tests (4x9) when all 4 runs were available, or for 27 tests (3x9) for the one case when one of the runs could not be used.

Level 3 analysis: The same as level 2 analysis but combining the results for the two subjects. We will report results from this level of analysis only.

Results

First, we investigated the changes in the spectral power in AF's and his student brain during the sending or transmission of energy, and Fig. 1 shows the scalp maps of the power difference in six classical EEG frequency bands for the contrast between two conditions, Ts_Rr and Tns_Rr, for the first dyad (AF and Student-1).

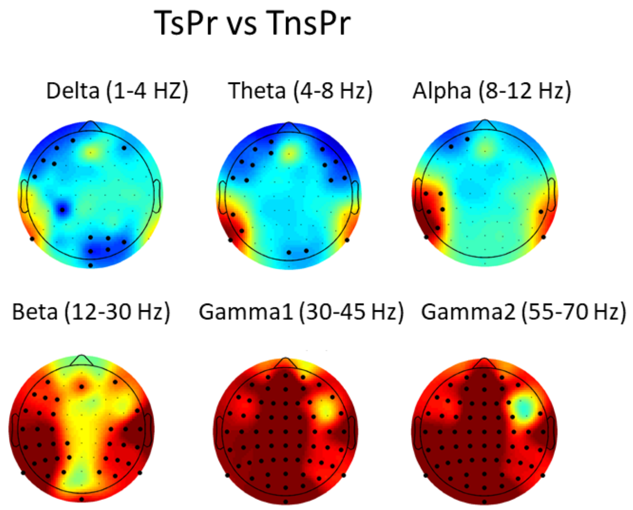

Figure 1. Maps of spectral power over the scalp in the classical six EEG frequency bands in the Teacher (T) during sending of energy (TsPr) as compared to not sending (TnsPr) for the first dyad (AF and Pupil-1); note that for both conditions, Pupil-1 received the same instruction, i.e. receive energy. Electrodes in bold indicate statistically significant ($p<0.05$, Bonferroni corrected) differences in the spectral power; blue indicates power decrease and red indicates power increase during energy transmission condition. Note the robust increase of high frequency brain responses distributed globally over the brain during the energy transmission condition.

In order to highlight the electrode regions showing statistically significant effects, we applied strict Bonferroni corrections for multiple comparisons ($p < 0.00013$, see *Methods*). For low frequency bands, in the delta (< 4 Hz) and theta (4-8 Hz), we observed a suppression of spectral power in the frontal electrode regions, bilaterally, during energy transmission, while parietal region, more in the left hemisphere, showed increased power in the alpha band (8-12 Hz); these parietal increases got stronger and more bilateral in the beta frequency band (12-30 Hz). However, most conspicuous effects were observed in the higher frequency bands, especially in the gamma1 (30-45 Hz) and gamma2 (55-70 Hz) bands, and further these high frequency effects during energy transmission were found almost all over the brain (more than 85% of electrodes showing statistically significant increases). We performed similar contrast on the second dyad (AF and Pupil-2) and the results are shown in Fig. 2. The robust high frequency increases in Teacher's brain during the energy transmission condition were found to be consistent and replicable.

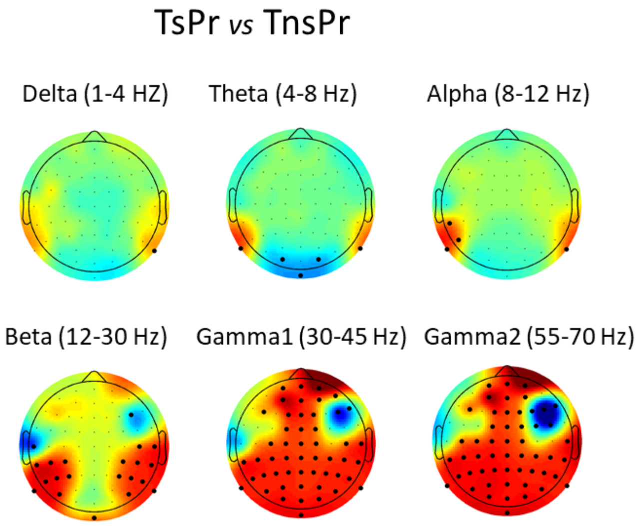

Figure 2. Same as in Figure 1 but for the second dyad (AF and Pupil-2). Increases in the high frequency gamma band responses were robust and consistent

Interestingly, though the high frequency increase was observed globally in the Teacher's brain, we also found an isolated right frontolateral region showing power decrease. In order to explore the condition specificity of these high frequency effects in the Teacher's brain, we calculated the spectral power in three high frequency bands (beta, gamma1, and gamma2) for five conditions (Table 1) separately, and the results (Fig. 3) clearly suggest that these high frequency effects were very much specific to the condition of the Teacher, i.e. whether or not he was in a "transmitting" state; these high frequency effects did not depend on the pupil's state. In short, there was a very large and significant high frequency response in the Teacher's brain whenever he was instructed to transmit energy, and this effect was found irrespective of the pupil's state.

Next, we explored the interbrain communication between the Teacher and Pupil using phase slope index (see *Methods*), a measure sensitive to the flow of information and robust against volume conduction (i.e. mixture of neural sources). We calculated PSI between all pairwise electrodes (Teacher-Pupil interbrain synchrony) in the six frequency bands, and for each frequency band we found the frequency corresponding to the largest PSI value, and subsequently plotted the head-in-head connectivity between all the electrodes of Teacher against all the electrodes of the Pupil. Fig. 4(a-b) shows the robust information flows from occipital and parietal regions bilaterally in Teacher's brain to left central region in Pupil's brain at the alpha frequency during energy transmission condition; this information flow was directional, i.e. from Teacher to Pupil, and no significant information flow in the reverse direction, i.e. from Pupil to Teacher, was observed at the alpha frequency. Further, this directional flow of information at the alpha band was crucially dependent on the instructions given to the pair (Fig. 4(c)): it was largest for the energy transmission condition but only when both the Teacher and the Pupil was given congruent information (TsPr) but not for incongruent one (TsPnr), and further a visual communication channel between the Teacher and the Pupil was found necessary as the inter-brain connectivity almost disappeared when the pair was wearing an opaque goggle during energy transmission-reception condition (TtgPrg). The PSI analysis was also performed for the other five frequency bands (Fig. 4(d)). For both delta and beta bands, we found a direction of information flow from the Pupil's to the Teacher's brain, but this was reversed in the high frequency bands. Furthermore, across all frequency bands, we observed that the energy transmission condition with congruent instruction was associated with the most distinct form of interbrain communication as compared to four other conditions, thereby suggesting a clear but implicit synchronization between the Teacher and the Pupil.

We have used electrical field tomography (EFT, see *Methods*) to obtain estimates of brain activity in the teacher's brain for each interaction between the Teacher and each one of the two pupils and separately for each one of the five conditions.

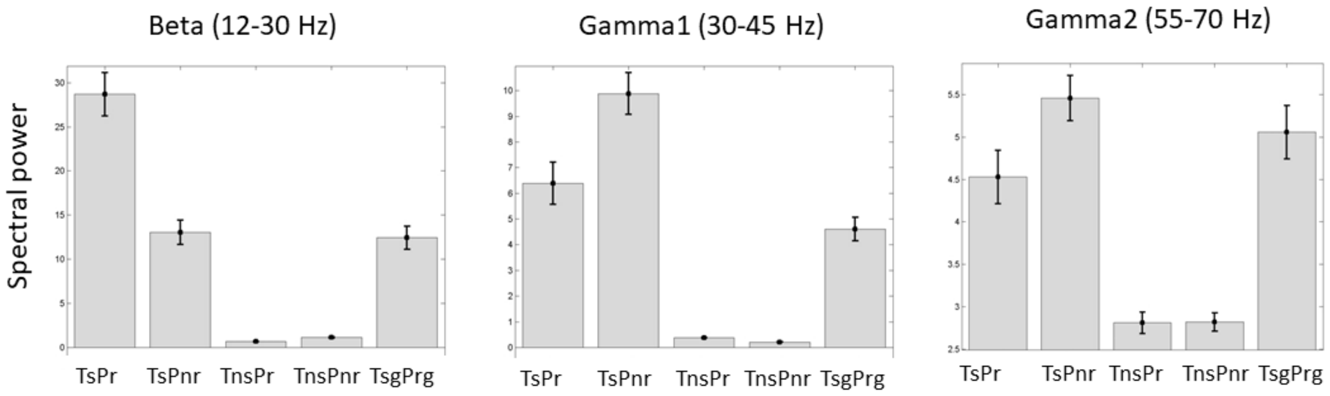

Figure 3. The EEG spectral power in the Teacher's brain in three high frequency bands (beta, gamma1, and gamma2) over the significant cluster of electrodes across five conditions (see Table 1 for details). Whenever the Teacher was in sending mode (with or without goggles), the high frequency brain responses were increased

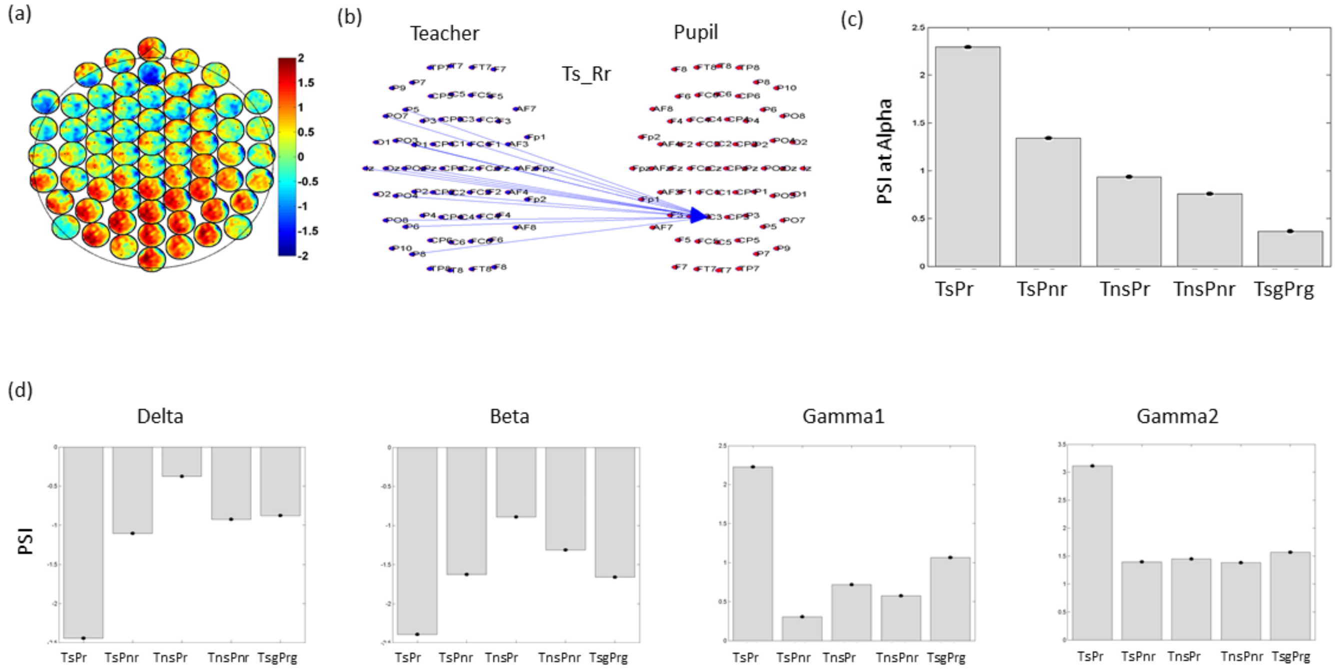

Figure 4. The panels show the interbrain synchrony analysis using the phase slope index (PSI). (a) Teachers scalp nose up. Red colors significant values Teacher driving Pupil. Condition, Teacher_sending and Receiver receiving, Ts_Rr. (b) Head diagrams Teacher and student facing each other. Shows significant couplings of PSI, Teacher driving student. (c) Significant relative PSI values for alpha band and conditions. (d) Note columns going down are student leading teacher. Relative number of significant PSI for each condition in the delta, alpha, beta, gamma 1 and gamma 2 bands. Note interbrain communication was always greater in Ts_Rr

We then contrasted the activity between each pair of conditions as outlined in the *Methods*. We found statistically highly significant changes in the brain of the Teacher between the periods when the Teacher was transmitting and conditions when the Teacher was not transmitting. There was no obvious dependence of these changes (in the Teacher's brain) on the pupils' state, i.e. we found no consistent changes in the activity of the Teacher's brain when the Pupil was receiving and when he was not receiving. The bulk of the changes in the brain of the Teacher were increases during the transmitting periods that were prominent in the left temporo-occipital-parietal cortex and the cerebellum. The spectral power of these increases during transmitting periods, were characterized by sweeps in the frequency domain that started in the occipito-temporal cortex (BA37) and the cerebellum on one hemisphere, then spread more in the cerebellum and over the lateral occipital and temporal cortex (BA37 and BA39) of the same hemisphere and then in the opposite cerebellum and hemisphere. The first and clearer sweep of spectral power (orderly spread in spatial extend as frequency increases, usually started in the left hemisphere around 8 Hz and by 12 Hz it also spread over the other hemisphere, starting again on the homologous sides in the cerebellum and BA37. Two more sweeps were seen next in the beta and gamma1 frequency range, with at least two more sweeps in the high gamma band. During the sweeps at higher frequencies, the increases spread further forward and are more extensive in the left hemisphere. These sweeps in the frequency domain in the teacher's brain were identified for each contrast (TsPr vs TnsPr) runs in the Teacher interaction with each one of the two pupils. The increases in spectral power were too widespread to clearly identify main foci, but such foci were clearly seen at the beginning and end of frequency sweeps, when these sweeps were not overlapping with each other. During such clear starts and ends of sweeps, the consistent foci of peak changes were in the cerebellum and in BA37 and BA39. These increases were bilateral, but with the increases in the left hemisphere much stronger than the ones on the right. Fig. 5 shows the foci of highly significant increases in activity that survived at *p*<0.00001 (after Bonferoni correction) in 27 separate comparisons between Ts_Rr) and Tns_Rr sets of data between 9 and 13 Hz. In this grand-statistic the traces of the first two sweeps can be identified, that are the tops of widespread changes seen in each one of the statistical comparisons. Decreases in spectral power (lower spectral power in transmitting compared to the not transmitting periods) were observed in the frontal cortex. The decreases were consistent, prominent and more persistent in the right hemisphere with the strongest foci in the inferior frontal gyrus and mid-frontal gyrus encompassing Brodmann areas 44, 45 and 46.

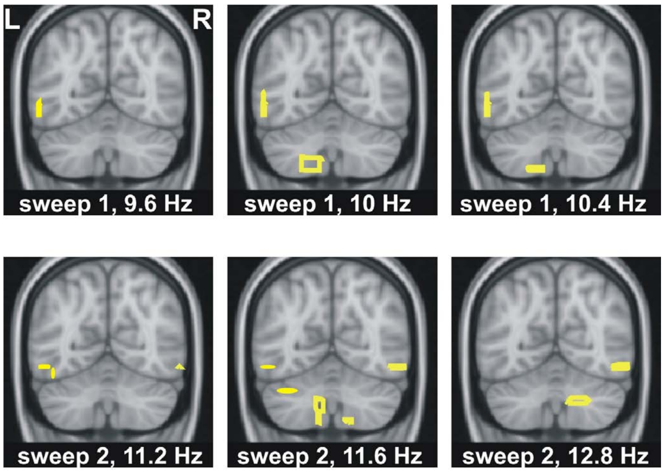

Figure 5. Common increases in spectral power in the contrast TsPr vs TnsPr. The yellow outline marks the foci of increases in the brain activity of the Teacher's brain that survived the threshold of *p*<0.00001 (after Bonferroni correction) for each one of 27 separate statistical contrast performed on the available data. The coronal slice contains the most prominent and consistent increases identified bilaterally in the cerebellum and in BA 37

Highly significant changes in spectral power were observed in the brain of the Teacher when the two transmitting conditions were compared to each other, i.e. when the normal transmitting condition (without goggles) was compared with the transmitting condition with goggles. This comparison revealed changes in activity that were prominent in the contrast "Teacher sending" vs "Teacher not sending" but this time these changes were lateralized. The most consistent changes were identified in the left hemisphere: they were highly significant increases over wide frequency ranges beginning in the alpha band and extending through the highest frequencies covered by our analysis (high gamma band). These changes were increases in spectral power (higher spectral power for transmitting without goggles) in the left occipito-parietal temporal areas and widespread decreases (reduced spectral power for transmitting without goggle) in the left frontal areas as shown in Fig. 6. Highly significant increases were identified in the early visual areas of the right hemisphere, confined to the low alpha frequency range.

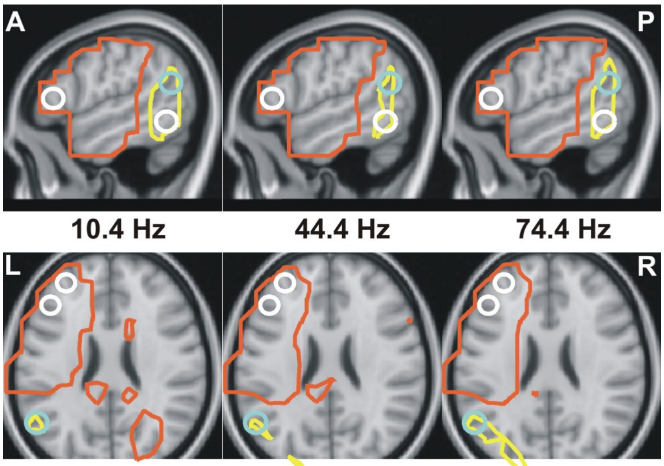

Figure 6. Changes in spectral power in the contrast TsPr vs TsgPrg. The changes captured the peak of the changes, which correspond to the middle of frequency sweeps seen in changes between conditions when the Teacher was sending and when he was not. The top row shows a sagittal and the lower row an axial slice. Yellow contours show increases (spectral power higher without the goggles) while orange contours show decreases (spectral power higher with the goggles). The two cuts are through the BA39, marked by the light blue circle in each figurine, with center in Talairach Coordinates (TC: -50, 60, 22). On the sagittal cut, the white circle ventrally of the BA39 ROI is at the peak of BA37 increase in activity (TC: -53, -53, -4) and the frontal white circle marks the peak in BA45/BA46 (TC: -52, 24, 20). On the axial cut, the two circles mark peaks in the BA9 the most rostral at (TC: -28, 41, 36) and the one just caudally to it at (TC: -39, 23, 36). Other areas of reduced activity in the left frontal cortex are over the Broca area covering much of the areas BA45 and BA46

Discussion

In this study, we provided, to the best of our knowledge, a first preliminary account on the neural correlates of an induced light experience during meditation. Meditation practices are studied in the empirical neuroscientific research field by focusing on the meditators in isolation (Goleman and Davidson, 2017), yet meditation in the context of traditional religions is practiced, especially at the beginning stage, in the presence of a meditation Teacher or a Guru. Perceiving the inner light and self-awakening may be the final goal of most meditators, but light can also be subjectively perceived by a meditating pupil as being transferred by his/her expert meditating Teacher. This kind of directional exchange of energy/ light, as manifested by the phenomenological ILE, is often associated with a serene, ecstatic mental state during meditation, and further, may lead towards a significant improvement in the intellectual, emotional and spiritual lives.

EEG spectral analysis clearly demonstrates a very robust increase in the high frequency neural oscillations, especially in the gamma frequency band, in the Teacher's brain when he was giving light/ energy, and further, the scalp maps suggest this effect to be at the global brain level, when averaged over the entire session of light giving condition. As stated earlier in the Introduction, broad gamma oscillations (> 30 Hz) are consistently associated with meditating states (Cahn, Delorme *et al.*, 2010; Berkovich-Ohana, Glicksohn *et al.*, 2012; Hauswald, Ubelacker *et al.*, 2015); further, the enhanced gamma oscillations are usually reported more over the posterior parieto-occipital regions, and correlated with the meditation expertise (Lutz, Greischar *et al.*, 2004; Cahn, Delorme *et al.*, 2010). Most of these studies involve mindfulness or Vipassana meditation states or meditators, which are not essentially the same mental state as reported by the Teacher, AF, who described it as "standing back into the void." AF mastered his ability to give light after decades of silent vigils in French cathedrals and thus his meditation method is clearly idiosyncratic, although his description suggests more like an objectless meditation rather than an object driven state. Although the precise nature of this very large increase of gamma oscillations is difficult to decipher, we suggest that this could be related to with intense spontaneous visual imagery as experienced during "encounters with light" phenomenon (Lo, Huang *et al.*, 2003; Lindahl, Kaplan *et al.*, 2014). Interestingly, a recent paper (Braboszcz, Cahn *et al.*, 2017) has studied Isha Shoonya meditation, which is based on a related concept "nothingness/ doing nothing", and found high gamma synchronization in both parieto-occipital and frontal regions during meditation; the results are interpreted in terms of higher top-down control mediated by frontal oscillations (Ossandon, Vidal *et al.*, 2012).

Our source reconstructions based on the embedded field tomography (EFT) spectral analysis identified widespread changes in the Teacher's brain activity during energy sending mode that were organized in frequency sweeps that started in the cerebellum and occipito-temporal cortex and spread widely over temporal (BA37, BA39) and frontal areas (BA44, BA45, and BA46); the areas showing consistent decreases in activations were observed in the homologous areas in the right hemisphere. Prominent changes in these same occipitotemporal and frontal areas were identified when the normal "transmitting" condition was contrasted with the transmitting condition with goggles. Interestingly, these activated brain areas are part of the lexical-semantic system of the language network (e.g. see Table 2 in Ardila *et al.*, 2016).

A novel aspect of this study was that we could investigate the communication between two meditating brains, i.e. interbrain synchrony between Teacher-Pupil during the ILE. We used an effective connectivity measure, phase slope index, that is not only suitable for revealing the direction of the information flow between the two interacting brains, but also is quite robust against volume conduction that often leads to spurious synchrony at the sensor level analysis (Nolte, Ziehe *et al.*, 2008). For the condition associated with the ILE (TsPr, Teacher sending/ Pupil receiving), we observed a conspicuous flow of information from the Teacher's brain to the Pupil's brain in the alpha, gamma1 and gamm2 frequency bands. Interbrain synchrony, though not a mechanism in itself, reveals something unique about the underlying neuronal dynamics in the two interacting brains that are associated with some distinct psychological processes under investigation. For example, in a seminal study, Dikker *et al.*, (2017) demonstrated that the degree of interbrain synchrony between a group of students in a classroom predicts the overall classroom engagement, and further a brief face-to-face contact prior to the class was found to significantly boost interbrain synchrony during subsequent classroom activities (Bhattacharya 2017, Dikker, Wan *et al.*, 2017). One of the principal psychological mechanisms by which two brains show more synchronized responses is joint attention, i.e. "two individuals know that they are attending to something common", and is considered to provide a foundation for social cognition and interaction (Tomasello, 1995). A recent study has shown that during a visual search task, joint attention leads to enhanced interbrain synchrony than individual attention, and further the team efficiency is correlated with the increase in interbrain synchrony values (Szymanski, Pesquita *et al*., 2017). Interbrain synchrony is also shown to be dependent on interpersonal relationship (Müller and Lindenberger 2014; Hu, Hu *et al*., 2017), implicit social interaction (Yun, Watanabe *et al*., 2012), coordinated performance (Lindenberger, Li *et al*., 2009). Joint attention is often mediated by eye contacts between interacting individuals (Farroni, Csibra *et al*., 2002), and it has indeed been found that exchange of information in the direction of mutual gaze is associated with an enhanced interbrain synchrony (Dikker, Wan *et al*., 2017; Leong, Byrne *et al*., 2017). This account of joint attention or shared intentionality by mutual gaze leading towards the largest interbrain synchrony during the ILE is supported by our finding that interbrain synchrony in the alpha band, i.e. the marker of joint attention, dropped drastically for the ILE condition after blocking the mutual gaze by using opaque goggles. Of course, it is important to remember that mutual gaze only cannot be the sole explanatory factor as mutual gaze was maintained for three other conditions (TsPnr, TnsPr, TnsPnr) yet the degrees of alpha interbrain synchrony was still considerably lower than for the TsPr condition. It could be that the pupil might have picked up implicit cues, albeit unconsciously, from the Teacher during the TsPr condition, leading to a stronger physical entrainment to each other, thereby amplifying the degree of interbrain synchrony. However, future research could elucidate further on this possible mechanism.

Let us discuss a few practical remarks and potential limitations of the current study. The first issue is about the generality of effects as we have tested only one Teacher and two of his Pupils. Although the Teacher's brain responses were found to be remarkably consistent across both pupils (Fig. 1,2), it is still debatable whether one would expect similar effects with a different Teacher. As stated earlier, finding a meditation Teacher who can consistently induce ILE in his Pupil and is ready to be subjected to rigorous empirical investigation would remain difficult, so these results should be treated as preliminary. Second, the high frequency gamma activity is sometimes associated with microsaccades, i,e, miniscule jerky eye movements (Yuval-Greenberg, Tomer *et al*., 2008), but microsaccades were unlikely to contribute towards the reported high frequency effects during ILE for the following reasons. Microsaccades contaminated EEG data when recorded with nose reference whereas we used average of two earlobes as a reference, which is less likely to be contaminated by this artefact (Braboszcz, Cahn *et al*., 2017). Further, the scalp maps of the reported high frequency effects are too widespread to be accounted for by the microsaccades.

In summary, this paper reveals the neural correlates of a little studied but subjectively highly valued phenomenological state of induced light experience during meditation. We have provided evidence that an expert meditation Teacher's brain in this light giving meditative state was accompanied with very high frequency brain oscillations observed over a widely distributed brain network including lexical system of the language brain. Further, the Teacher's brain was in synchrony with the Pupil's brain during ILE, but this interbrain communication disappeared when the visual communication between the Teacher and his Pupil was limited. These findings are interpreted in the framework of joint attention and shared intentionality. Altogether, these results offer new promise in the study of meditation in a social interactional context, and hopefully stimulate the broader research on subjective conscious experience.

Author Contributions

PF, JB conceived and designed the research; CDBL collected the data; CDBL, JB, AI analyzed the data; JB, PF wrote the paper with contributions from CDBL, AI. The authors are thankful to Jasmine Tan and Amna Ghani for their help with data collection.

References

Ardila A, Bernal B, and Rosselli M. How Localized are Language Brain Areas? A Review of Brodmann Areas Involvement in Oral Language. Arch Clin Neuropsychol 2016; 31(1): 112-122.

Beauregard M and Paquette V. Neural correlates of a mystical experience in Carmelite nuns. Neurosci Lett 2006; 405(3): 186-190.

Berkovich-Ohana A, Glicksohn J, Goldstein A. Mindfulness-induced changes in gamma band activity - implications for the default mode network, self-reference and attention. Clin Neurophysiol 2012; 123(4): 700-710.

Bhattacharya J. Cognitive Neuroscience: Synchronizing Brains in the Classroom. Curr Biol 2017; 27(9): R346-R348.

Braboszcz C, Cahn BR, Levy, Fernandez JM, Delorme A. Increased Gamma Brainwave Amplitude Compared to Control in Three Different Meditation Traditions. PLoS One 2017; 12(1): e0170647.

Buzsáki G and Wang XJ. Mechanisms of gamma oscillations. Annual Review of Neuroscience 2012; 35: 203-225.

Cahn BR, Delorme A, Polich J. Occipital gamma activation during Vipassana meditation. Cognitive Processing 2010; 11(1): 39-56.

Cahn BR and Polich J. Meditation states and traits: EEG, ERP, and neuroimaging studies. Psychological Bulletin 2006; 132(2): 180-211.

Delorme A and Makeig S. EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. Journal of Neuroscience Methods 2004; 134(1): 9-21.

Dikker S, Wan L, Davidesco I, Kaggen L, Oostrik M, McClintock J, Rowland J, Michalareas G, Van Bavel JJ, Ding M, Poeppel D. Brain-to-Brain Synchrony Tracks Real-World Dynamic Group Interactions in the Classroom. Curr Biol 2017; 27(9): 1375-1380.

Donner TH and Siegel M. A framework for local cortical oscillation patterns. Trends in Cognitive Sciences 2011; 15(5): 191-199.

Essl M and Rappelsberger P. EEG coherence and reference signals: experimental results and mathematical explanations. Med Biol Eng Comput 1998; 36(4): 399-406.

Farroni T, Csibra G, Simion F, Johnson MH. Eye contact detection in humans from birth. Proc Natl Acad Sci U S A 2002; 99(14): 9602-9605.

Fenwick P and Fenwick E. The Truth in the Light: An Investigation of Over 300 Near-Death Experiences. Guildford, UK, White Crow Books, 2012.

Fox KC, Dixon ML, Nijeboer S, Girn M, Floman JL, Lifshitz M, Ellamil M, Sedlmeier P, Christoff K. Functional neuroanatomy of meditation: A review and meta-analysis of 78 functional neuroimaging investigations. Neurosci Biobehav Rev 2016; 65: 208-228.

Goleman D and Davidson RJ. Altered Traits: Science Reveals How Meditation Changes Your Mind, Brain, and Body, Penguin, 2017.

Hauswald A, Ubelacker T, Leske S, Weisz N. What it means to be Zen: marked modulations of local and interareal synchronization during open monitoring meditation. Neuroimage 2015; 108: 265-273.

Hu Y, Hu Y, Li X, Pan Y, Cheng X. Brain-to-brain synchronization across two persons predicts mutual prosociality. Social Cognitive and Affective Neuroscience 2017; 12(12): 1835-1844.

Ioannides A, Liu M, Liu L, Bamidis P, Hellstrand E, Stephan K. Magnetic field tomography of cortical and deep processes: examples of “real-time mapping” of averaged and single trial MEG signals. International Journal of Psychophysiology 1995; 20(3): 161-175.

Jasper HH. The ten twenty electrode system of the international federation. Electroencephalography and Clinical Neurophysiology 1958; 10: 371-375.

Lehmann D, Faber P, Achermann P, Jeanmonod D, Gianotti LR, Pizzagalli D. Brain sources of EEG gamma frequency during volitionally meditation-induced, altered states of consciousness, and experience of the self. Psychiatry Research: Neuroimaging 2001; 108(2): 111-121.

Leong V, Byrne E, Clackson K, Georgieva S, Lam S, Wass S. Speaker gaze increases information coupling between infant and adult brains. Proceedings of the National Academy of Sciences 2017; 114(50): 13290-13295.

Lindahl JR, Kaplan CT, Winget EM, Britton WB. A phenomenology of meditation-induced light experiences: traditional Buddhist and neurobiological perspectives. Frontiers in Psychology 2014; 4: 973.

Lindenberger U, Li SC, Gruber W, Müller V. Brains swinging in concert: cortical phase synchronization while playing guitar. BMC Neuroscience 2009; 10(1): 22.

Lo PC, Huang ML, Chang KM. EEG alpha blocking correlated with perception of inner light during Zen meditation. The American Journal of Chinese Medicine 2003; 31(04): 629-642.

Lutz A, Greischar ALL, Rawlings NB, Ricard M, Davidson RJ. Long-term meditators self-induce high-amplitude gamma synchrony during mental practice. Proceedings of the National academy of Sciences of the United States of America 2004; 101(46): 16369-16373.

Müller V and Lindenberger U. Hyper-brain networks support romantic kissing in humans. PloS One 2014; 9(11): e112080.

Nolte G, Bai O, Wheaton L, Mari Z, Vorbach S, Hallett M. Identifying true brain interaction from EEG data using the imaginary part of coherency. Clinical Neurophysiology 2004; 115(10): 2292-2307.

Nolte G, Ziehe A, Nikulin VV, Schlögl A, Krämer AN, Brismar T, Müller KR. Robustly estimating the flow direction of information in complex physical systems. Physical Review Letters 2008; 100(23): 234101.

Oostenveld R, Fries P, Maris E, Schoffelen JM. FieldTrip: Open source software for advanced analysis of MEG, EEG, and invasive electrophysiological data. Comput Intell Neurosci 2011: 156869.

Ossandon T, Vidal JR, Ciumas C, Jerbi K, Hamame CM, Dalal SS, Bertrand O, Minotti L, Kahane P, Lachaux JP. Efficient “pop-out” visual search elicits sustained broadband gamma activity in the dorsal attention network. J Neurosci 2012; 32(10): 3414-3421.

Puhle A. Light Changes: Experiences in the Presence of Transforming Light. Guildford, UK, White Crow Books, 2014.

Ribary U, Ioannides A, Singh KD, Hasson R, Bolton J, Lado F, Mogilner A, Llinas R. Magnetic field tomography of coherent thalamocortical 40-Hz oscillations in humans. Proceedings of the National Academy of Sciences 1991; 88(24): 11037-11041.

Rinpoche TW. Awakening the Luminous Mind: Tibetan Meditation for Inner Peace and Joy. Hay House, 2012.

Schiff SJ. Dangerous phase. Neuroinformatics 2005; 3(4): 315-317.

Szymanski C, Pesquita A, Brennan AA, Perdikis D, Enns JT, Brick TR, Muller V, Lindenberger U. Teams on the same wavelength perform better: Inter-brain phase synchronization constitutes a neural substrate for social facilitation. Neuroimage 2017; 152: 425-436.

Tomasello M. Joint attention as social cognition. In: Moore C and Dunham PJ (Eds) Joint attention: Its origins and role in development. New York, Psychology Press, 1995; 103-130.

Vialatte FB, Bakardjian H, Prasad R, Cichocki A. EEG paroxysmal gamma waves during Bhramari Pranayama: a yoga breathing technique. Consciousness and Cognition 2009; 18(4): 977-988.

Welch PD. The use of fast Fourier transform for the estimation of power spectra: A method based on time averaging over short, modified periodograms. IEEE Transactions on Audio and Electroacoustics 1967; 15(2): 70-73.

Yun K, Watanabe K, Shimojo S. Interpersonal body and neural synchronization as a marker of implicit social interaction. Scientific Reports 2012; **2**: 959.

Yuval-Greenberg S, Tomer O, Keren AS, Nelken I, Deouell LY. Transient induced gamma-band response in EEG as a manifestation of miniature saccades. Neuron 2008; 58(3): 429-441.