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Review

Complex continuous wavelet coherence for EEG microstates detection in insight and calm meditation

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ABSTRACT

Complex continuous wavelet coherence (WTC) can be used for non-stationary signals, such as electroencephalograms. Areas of the WTC with a coherence higher than the calculated optimal threshold were obtained, and the sum of their areas was used as a criterion to differentiate between groups of experienced insight-focused meditators, calm-focused meditators and a control group. This method demonstrated the highest accuracy for the real WTC parts in the frontal region, while for the imaginary parts, the highest accuracy was shown for the frontal occipital pairs of electrodes. In the frontal area, in the broadband frequency, both types of experienced meditators demonstrated an enlargement of the increased coherence areas for the real WTC parts. For the imaginary parts unaffected by the volume conduction and global artefacts, the most significant increase occurred for the frontal occipital pair of electrodes.

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1. Introduction

Longitudinal studies have demonstrated that meditation practice significantly changes early stimulus processing, improving the dynamics and flexibility of brain functions related to attention (Bishop et al., 2004; Malinowski, 2008; Moore, Gruber, Derose, & Malinowski, 2012). This effect is achieved by a more flexible allocation of attention sources that most likely modulate early processing based on independent stimuli. The training of attentional skills is thought to underpin other changes that lead to positive health outcomes and well-being (Chiesa & Malinowski, 2011). Current findings suggest that meditation practice may increase the efficiency of attention networks (Corbetta & Shulman, 2002; Posner & Rothbart, 2007; Raz & Buhle, 2006). Three different human brain neuron networks control the functions of wakefulness, orientation and execution control (Fan, McCandliss, Fossella, Flombaum, & Posner, 2005; Posner & Rothbart, 2007; Raz & Buhle, 2006).

The right frontal- and right parietal- cortex and the thalamus are important for maintaining wakefulness.

The superior parietal cortex, the temporal–parietal junction, the frontal eye fields and the superior colliculus function in orientation. The anterior cingulate cortex, ventral lateral cortex, prefrontal cortex and basal ganglia are associated with the control of executive processes (Dosenbach et al., 2007; Seeley et al., 2007; Sridharan, Levitin, & Menon, 2008). The anterior cingulate cortex (ACC) is involved in performance monitoring and response selection (Hanslmayr et al., 2008; Liotti, Woldorff, Perez, & Mayberg, 2000). However, two recent event-related fMRI studies suggest that the role of the ACC is more related to the anticipatory regulation of attention rather than the specific selection of responses (Aarts, Roelofs, & van Turennout, 2008; Roelofs, van Turennout, & Coles, 2006). If the attention is no longer focused on the meditation object, the "default mode" is activated, including the posterior cingulate, the medial prefrontal cortex, the posterior lateral parietal temporal cortex and the parahippocampal gyrus (Hasenkamp, Wilson-Mendenhall, Duncan, & Barsalou, 2012; Malinowski, 2013). Co-operation between these areas of the brain may, to some degree, be estimated by comparing the similarities of EEG signals read by electrodes placed over these areas. Vipassana meditation or insight meditation (especially its secularised version, mindfulness meditation) is an ever more frequent subject of research because of its clinical use (see overview studies Baer, 2005; Didonna, 2009). Mindfulness meditation practices entail at least two central components: the training of attentional skills and the development of an equanimous, non-judgmental attitude toward one's own experiences (Moore et al., 2012). This article shows the research comparing the EEG signal similarities in experienced meditators (more than 1000 h of meditation practice) and the non-meditators control group. During vipassana meditation, both types of attention regulation are used and are complementary to each other. Therefore, this type of meditation is also sometimes called samatha-vipassana. Concentration is necessary for the basic stabilisation of attention (Lutz, Slagter, Dunne, & Davidson, 2008; Lutz et al., 2009). In later stages of meditation practice, however, a greater emphasis is placed on mindfulness.

As the development and refinement of attentional skills appears fundamental to all forms of mindfulness meditation practice, it is not surprising that a major line of investigation focuses on revealing how meditation practice influences various aspects of attentional performance and the underlying brain mechanisms (Anderson, Lau, Segal, & Bishop, 2007; Chambers, Lo, & Allen, 2008; Chiesa & Serretti, 2011; Hodgins & Adair, 2010; Lutz, Greischar, Rawlings, Ricard, & Davidson, 2004; Valentine & Sweet, 1999; van den Hurk, Giommi, Gielen, Speckens, & Barendregt, 2010; van Leeuwen, Muller, & Melloni, 2009; Wenk-Sormaz, 2005; Zeidan, Johnson, Diamond, David, & Goolkasian, 2010).

Only one study to date has analysed the comparison between concentration and mindfulness within the same group of meditators from the performance spectrum perspective (Dunn, Hartigan, & Mikulas, 1999). A similar study of coherence has not been performed yet. Studies of the activity similarities within individual frequency bands are sporadic. An increased alpha and theta coherence between frontal and central electrodes was found in transcendental meditation (Gaylord, Orme-Johnson, & Travis, 1989). Some studies demonstrate synchrony within the gamma bands (Lutz et al., 2004). Travis and Arenander (2006) discovered, as far as transcendental meditation is concerned, that frontal coherence and lateralised asymmetry were higher in 13 subjects practicing transcendental meditation compared to 12 controls. A similar group, while solving simple tasks, demonstrated an increased broadband frontal coherence (Travis, Arenander, Tecce, & Wallace, 2002). Lo and Chang (2013) used WTC to identify alpha-dominated epochs in the entire EEG record in subjects under Chan meditation. They found a right-frontal dominance. This method of estimating the similarities between the signals shows an advantage compared to the coherence based on the Fourier transform because it is possible to use it with non-stationary signals and in greater time resolution. It is also possible to separately assess real and imaginary parts. While the real parts are affected by volume conduction, the contribution of the reference electrode and global artefacts, imaginary parts should not be affected by these factors (Nolte, Bai, Mari, Vorbach, & Hallet, 2004). Microstates represent the sub-second coherent activation within global functional brain networks (van de Ville, Britz, & Michel, 2010). In this work, we try to identify the EEG microstate by finding an optimal threshold of WTC. The objective of our study is to differentiate between experienced and non-experienced meditators by finding an optimal threshold for the real and imaginary parts of wavelet coherence and comparing the accuracy within the individual wavelet bands for the individual brain areas.

2. Methods

2.1. Participants

The experiment enrolled meditators practicing insight meditation (*samatha-vipassana*) as it is practiced in theravada buddhism. A prerequisite concerned active meditation experience and the length of meditation experience. Here, the meditation experience means a formal meditation experience, i.e. in a calm environment, while sitting or walking.

The following meditators were enrolled in the experiment:

(a) At the time of the experiment they have been actively formally practicing at least 2 h a week (e.g. 30 min, 4 days a week).
(b) The length of their meditation experience exceeded 1000 h (e.g. about 3 years of one-hour meditation a day, or about 4 months of intensive whole-day meditation experience, etc.).

This kind of experience allows us to assume that significant permanent changes (traits) may be apparent in the function and structure of the meditators' brains.

Group of meditators consists of 7 males aged 20–40. Group of controls consists of 6 males and 1 female aged 20–50. No further steps were taken to match control group to the meditator group.

2.2. Recording conditions

EEG data were collected using a 19-channel electrode cap from the following electrode locations: Fp1, Fp2, F3, F4, F7, F8, Fz, C3, C4, T7, T8, Cz, P3, P4, P7, P8, Pz, O1 and O2. The electrodes were referenced to linked earlobes using a forehead ground. Impedances were kept below 10 kV. The signals were recorded with a digitisation rate of 200 Hz.

2.3. Procedure

The participants were divided into two groups. The first group included meditators, and the second group included the controls. Each experimental participant gradually underwent five experimental phases. All phases were monitored using EEG. The phases were separated with a sound signal.

- Adaptation: idle EEG without meditation, 10 min
- Calm Meditation: concentrated attention on breathing and on raising and lowering the abdominal wall while breathing in and out, 30 min.
- Break: 18 min. For the first five minutes of the break, the EEG continued to be recorded. Then, the participant was allowed to have a slow walk, stretch, etc. For the last three minutes of the break, the participant took the appropriate position again and prepared for meditation.
- Insight Meditation: open observation of any objects that enter the consciousness moment by moment, 30 min.
- Idle EEG without meditation: the last 5 min of the experimental session.

In total, the experiments lasted 90 min.

For detailed instructions, please see Appendix.

2.4. Data analysis

Stored digitised data were zero-phase digitally filtered using a bandpass FIR filter (100 coefficients, Hamming window) of 0.5–60 Hz and a bandstop filter of 49–51 Hz.

2.5. Complex continuous wavelet coherence

With the development of digital signal processing, especially the development of wavelet transform, coherence has become a useful and popular statistical tool. Coherence is one of the modern statistical quantities that can be used to examine relationships between two time series. The concept is similar to correlation; coherence analyses the linear dependence of two signals in time–frequency space. Its values vary from 0 (independence) to 1 (linear dependence). As a standard, coherence is calculated using spectra based on the Fourier transform. However, EEG recording is a non-stationary recording, which means that the spectrum changes over time. Therefore, coherence must be regarded as a dynamic quantity, and for monitoring the development of spectral density, the continuous wavelet transformation is the most suitable.

Continuous wavelet transform (CWT) is a type of transform that detects similarities between the signals. Compared to the formerly used Fourier transform, its advantage lies in the possibility to obtain a time–frequency description of the signal. For signal $x(t)$, the transform is a function of scale a, and translation b and is defined as

$$C_x(a,b) = \frac{1}{\sqrt{|a|}} \int_{-\infty}^{\infty} x(t)\psi^*\left(\frac{t-b}{b}\right)dt \tag{1}$$

where $\psi(t)$ is the mother wavelet, * represents operation of complex conjugate and t stands for time.

Obtained wavelet spectrum C_x is characterized by the modulus and the phase.

The type of coherence used in this experiment is called complex continuous wavelet coherence. "Complex continuous" means that complex wavelets are used to calculate the continuous wavelet transform coefficients. Such wavelets include, for instance, a complex Morlet wavelet, a complex Gaussian wavelet, a complex Shannon wavelet and Frequency B-spline wavelets. This experiment used the complex Morlet wavelet because it provided the best results and because, in general, its shape most closely matches the shape of the EEG curve.

Because of the complexity of wavelets, it is possible to distinguish between the real and imaginary parts of wavelet coherence. This dichotomy is very important for time–frequency analysis of non-stationary signals.

To estimate the relationship between the two signals x and y in the time-scale, the plane wavelet cross spectrum (WCS) is used. The following equation may be used

$$WCS_{x,y}(a,b) = C_x(a,b)C_y^*(a,b) \tag{2}$$

The magnitude of WCS shows the similarity of the local frequency behaviour of the two time series in the time-scale plane (Torrence & Compo, 1998).

The complex continuous wavelet coherence is defined as WCS normalised by the wavelet spectra of both signals. For time series x and y, represented by signals from two electrodes, it can be written as

$$WTC_{xy}(a,b) = \frac{S(WCS_{xy}(a,b))}{\sqrt{S(|C_x(a,b)|^2)}\sqrt{S(|C_y(a,b)|^2)}} \tag{3}$$

where a is scale, b is position, $C_y(a,b)$ and $C_x(a,b)$ represent coefficients of the continuous wavelet transforms.

S is a smoothing operator in time and scale.

In this article, coherence refers to the full complex information between two electrodes. Though the real and imaginary parts contain the same information on magnitude and phase of coherence, their usage is superior for studying brain interactions (Nolte et al., 2004). The wavelet coherence can be interpreted as the local squared correlation coefficient in the time-scale plane (Shnibha & Albarbar, 2013).

Each spectrum is smoothed with a moving average filter along the wavelet scale axis and along the time axis. More information about the smoothing operation may be found in the literature (see Grinsted, Moore, & Jevrejeva, 2004; Torrence & Compo, 1998). The type of the smoothing operation depends on the type of wavelet and scale (Walker, 2008).

Because a reference is used while obtaining the EEG recording, this reference may significantly contribute to coherence. Thus, the assessment of relationships between the individual sources is affected by volume conduction. Volume conduction is generally defined as a phenomenon in which the activity of one source is measurable in several channels. This is particularly apparent with EEG recording because the electrodes are close to one another. One option for avoiding this problem requires assessing the imaginary part of the coherence; this aspect of coherence is only affected by the synchronisation of the two processes that are time-shifted to each other. Volume conduction does not cause a time shift; thus, the imaginary part of the coherence is not affected by volume conduction (Nolte et al., 2004). This assumption will be adopted for performing calculations using WCT. Therefore, this paper assesses the real and imaginary parts of coherence separately.

While observing the course of the WCT, the values are averaged out, always after one minute, i.e., with a sampling frequency of 256 Hz, $256 * 60$ values are averaged out.

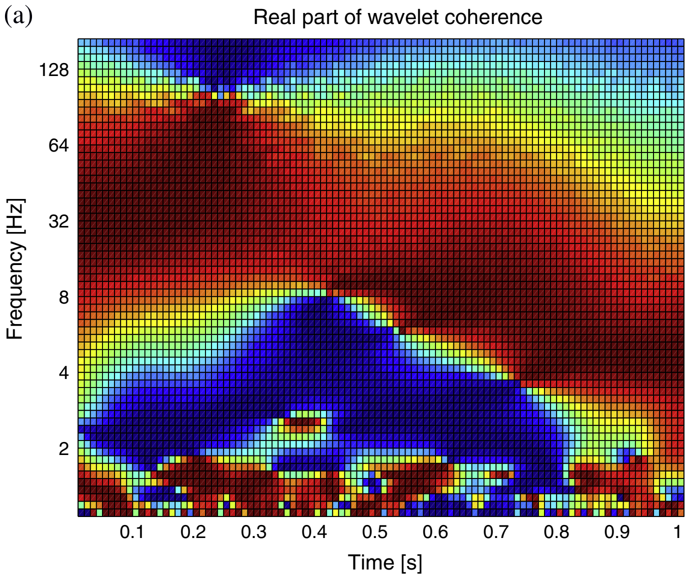
2.6. ROC analysis and optimal threshold

The calculation of the WTC provides two distribution maps of the real and imaginary parts of coherence in time and frequency (Fig. 1a). Because our effort is focused on detecting microstates, it is necessary to set a threshold for the map (Fig. 1b). The average coherence depends on the distance between the electrodes; therefore, the threshold for defining microstates differs for each pair, dropping as the distance increases.

With the threshold set in this manner, the comparable quantity for all recordings can be determined based on the map, thus defining the relative microstate area. The relative microstate area comprises all points in the map with coherence above the threshold, divided by the length of the recording and the number of scales for which the coherence is calculated.

The threshold for defining the microstates was selected as that which the difference between the relative microstate area in the experienced meditators and that of the controls was the biggest. To verify that this procedure is correct, groups of meditators and controls were randomly divided in half and mixed together to form two new groups. The same analysis was performed, and no significant differences were observed, demonstrating that the original computed thresholds are appropriate. The same procedure was applied for both the real and imaginary coherence parts.

ROC analysis was used for the binary classification of two data sets. The ROC curve depicts the relationship between sensitivity and specificity (Fig. 2). This tool is mostly used in medicine because the results describe statistical accuracy.



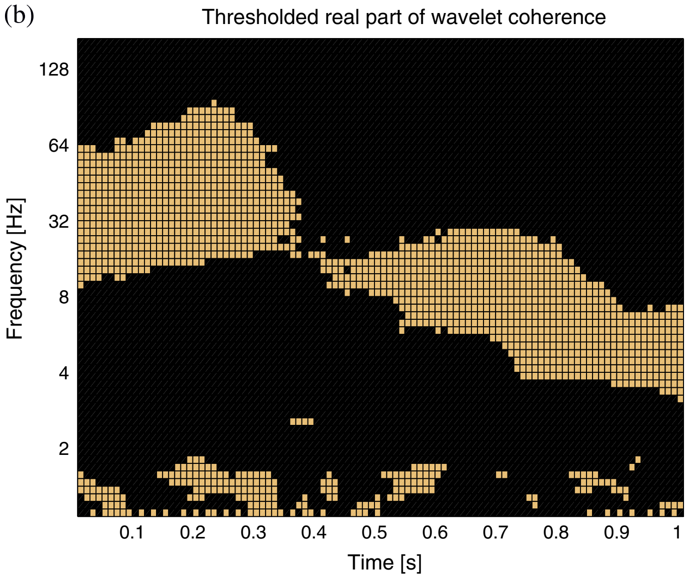


Fig. 1. Map of the values of the real complex continuous wavelet coherence part (a) and the threshold map (b) with only values of 0 and 1. Meditator, electrodes F8-P4, start of calm meditation.

The ROC curve finds the optimal threshold for classifying two sets. Based on this threshold, it is possible to determine the accuracy as the probability of correct classification (see Fig. 3).

Statistical accuracy is defined as

$$accuracy = \frac{true\,positive + true\,negatives}{true\,positives + false\,positives + true\,negatives + false\,negatives} \tag{4}$$

In our case, the two classes are represented by the meditator and control groups. The optimal threshold for differentiating between these two states is that which has the highest accuracy. All the following results are presented in the form of accuracies.

3. Results

For both types of meditation, the highest accuracies among the real parts of the WTC across all bands were obtained in the frontal areas, mostly near the Cz electrode or between the frontal electrodes; the highest accuracies were found in the

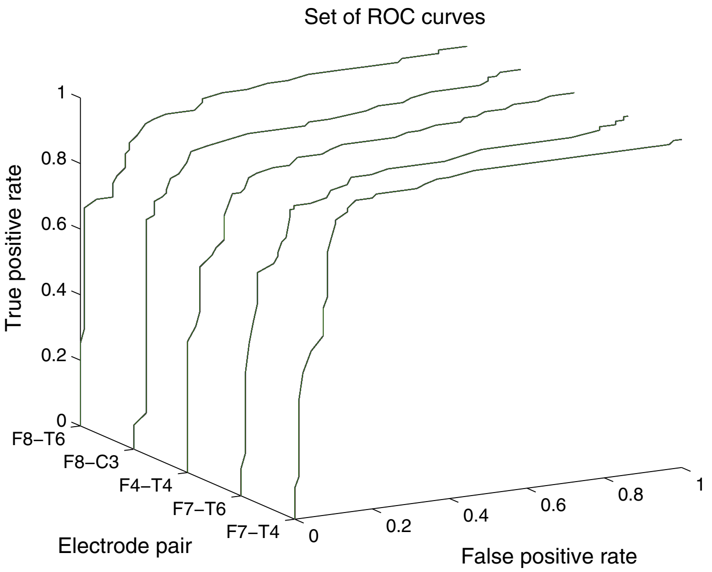


Fig. 2. Test accuracy was determined using Receiver Operating Characteristic (ROC) curve analysis.

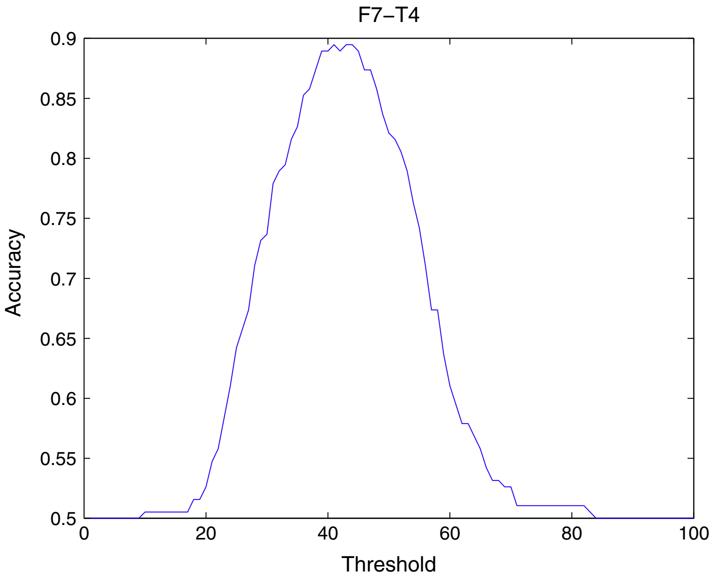


Fig. 3. Setting the optimal threshold. The highest accuracy value is the optimal threshold.

gamma, theta and alpha bands (Table 1). The imaginary parts of the WTC offer a different picture. The highest accuracies were between the frontal and occipital or parietal electrodes. Once again, they were similar for both types of meditation (Table 2). In contrast with the real WTC, the highest accuracies were obtained not in the gamma band, but in the beta, alpha and theta bands. The imaginary parts for occipito-frontal pathways demonstrate an increased coherence compared to the real parts. The most apparent difference between the two types of meditation lies in the increased WTC areas within the delta band for insight meditation. The relative area of microstates remained constant throughout the whole meditation (Fig. 4a and b). This applies to both types of meditation and the real and imaginary parts of WCT (see Figs. 5 and 6).

4. Discussion

These findings parallel the results from previous studies, where experienced meditators showed increased coherence in frontal areas (Travis & Arenander, 2006). There are, however, noteworthy differences to our study. Travis and Arenander

Table 1
Accuracies of the real complex continuous wavelet coherence part during calm meditation and insight meditation in the experienced meditators and the controls. The last column shows the ratio of the relative microstate areas between the meditators and the controls.

Accuracies – real part of coherence
Meditation of calm

Electrode pair	Frequency band					Ratio of relative areas
	Delta	Theta	Alfa	Beta	Gamma	
Fp1-Cz	0.79	0.86	0.79	0.79	0.86	1.22 ± 0.15
Fp2-Cz	0.71	0.79	0.79	0.79	0.79	1.16 ± 0.19
F7-F4	0.64	0.86	0.79	0.79	0.79	1.16 ± 0.13
F7-Cz	0.71	0.86	0.79	0.79	0.79	1.18 ± 0.12
F3-Cz	0.71	0.79	0.71	0.79	0.79	1.14 ± 0.25
Fz-Cz	0.71	0.86	0.86	0.79	0.86	1.22 ± 0.27
F4-Cz	0.71	0.79	0.79	0.86	0.86	1.16 ± 0.22
F8-Cz	0.71	0.79	0.79	0.79	0.79	1.15 ± 0.15
C3-Cz	0.57	0.79	0.79	0.79	0.79	1.08 ± 0.14
T3-Cz	0.71	0.79	0.71	0.71	0.71	1.05 ± 0.22
Insight meditation						
Fp1-Cz	0.86	0.86	0.79	0.79	0.86	1.18 ± 0.13
F7-F4	0.79	0.86	0.86	0.79	0.79	1.11 ± 0.14
F7-Cz	0.79	0.86	0.79	0.86	0.93	1.18 ± 0.09
Fz-Cz	0.86	0.79	0.79	0.79	0.86	1.20 ± 0.22
F4-Cz	0.86	0.86	0.79	0.86	0.86	1.15 ± 0.17
F8-Cz	0.79	0.79	0.86	0.93	0.86	1.21 ± 0.18
Fp1-F4	0.71	0.79	0.71	0.79	0.86	1.06 ± 0.09
F3-F8	0.79	0.79	0.79	0.71	0.71	1.16 ± 0.27
Fz-F4	0.71	0.79	0.79	0.71	0.86	1.08 ± 0.18
F4-C3	0.71	0.79	0.71	0.79	0.86	1.12 ± 0.14

Table 2
Accuracies of the imaginary complex continuous wavelet coherence part during calm meditation and insight meditation in the experienced meditators and the controls. The last column shows the ratio of the relative microstate areas between the meditators and the controls.

Accuracies – imaginary part of coherence
Meditation of calm

Electrode pair	Frequency band					Ratio of relative areas
	Delta	Theta	Alfa	Beta	Gamma	
Fp1-T5	0.64	0.71	0.86	0.79	0.71	1.09 ± 0.13
Fp2-T5	0.57	0.79	0.79	0.79	0.71	1.10 ± 0.17
Fp2-T6	0.57	0.71	0.79	0.71	0.71	1.14 ± 0.22
Fp2-O1	0.50	0.79	0.79	0.86	0.71	1.12 ± 0.18
Fz-O1	0.64	0.71	0.86	0.86	0.71	1.13 ± 0.23
F4-O1	0.57	0.71	0.79	0.79	0.71	1.10 ± 0.37
F8-T6	0.57	0.79	0.79	0.71	0.71	1.15 ± 0.26
C3-O1	0.50	0.79	0.79	0.79	0.64	1.16 ± 0.33
Cz-T5	0.50	0.79	0.86	0.64	0.71	1.17 ± 0.29
Cz-T6	0.50	0.86	0.79	0.71	0.71	1.20 ± 0.27
Insight meditation						
Fp1-O1	0.57	0.79	0.86	0.86	0.64	1.13 ± 0.18
Fp2-Pz	0.64	0.79	0.86	0.71	0.71	1.17 ± 0.29
Fp2-O1	0.50	0.79	0.86	0.79	0.71	1.15 ± 0.19
F7-O1	0.64	0.79	0.79	0.71	0.71	1.11 ± 0.17
F3-C3	0.64	0.79	0.71	0.71	0.79	1.30 ± 0.30
F4-T6	0.64	0.79	0.79	0.71	0.71	1.15 ± 0.25
F8-T6	0.57	0.79	0.79	0.79	0.79	1.13 ± 0.23
C3-O1	0.57	0.79	0.79	0.79	0.64	1.13 ± 0.31
Cz-P4	0.50	0.79	0.79	0.79	0.64	1.40 ± 0.42
Cz-T6	0.50	0.79	0.79	0.71	0.64	1.26 ± 0.30

(2006) only studied coherence based on the Fourier transform, whereas we studied both the real and imaginary parts of WTC. Complex continuous wavelet coherence was used by Lo and Chang (2013) to estimate the spatially nonlinear interdependence of alpha-oscillatory neural networks under Chan meditation. Chan meditation is close to one of two types of meditation in this study (mindfulness meditation). They used WTC to identify alpha-dominated epochs in the entire EEG record. For the alpha range, they found a right frontal dominance. Similar to our work, they found maximum changes in frontal

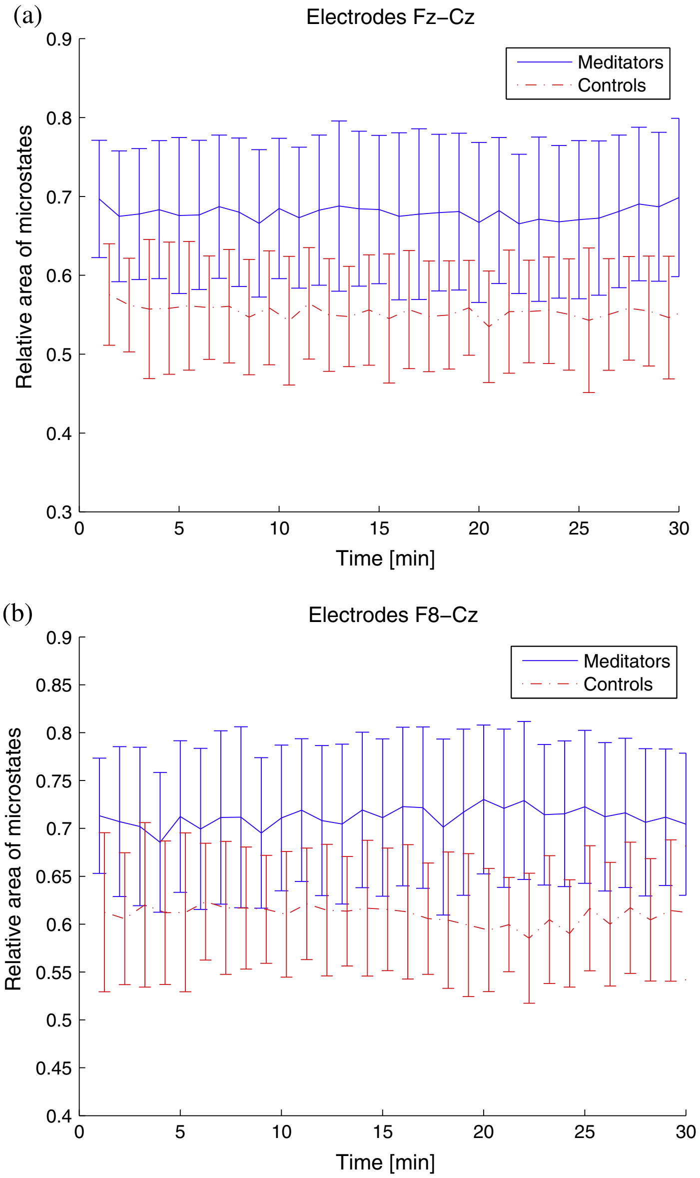


Fig. 4. The real complex wavelet coherence area development over time for the Fz-Cz pair of electrodes during calm meditation (a) and the Fz-F8 pair of electrodes under insight-focused meditation (b) show a higher coherence in the experienced meditators, without any changes in the meditation course.

areas. However, this finding is not directly comparable with our results because of different frequency ranges and different methodology.

The broadband increase of the real continuous complex wavelet coherence part areas for the neighbouring electrodes in the frontal area can be explained by volume conduction of EEG potentials when the coherent activity of the localised group of cortical neurons propagates into several neighbouring electrodes.

The imaginary continuous complex wavelet coherence parts are not as sensitive to the influence of volume conduction and suggest the activation of the occipito-frontal fasciculus connecting the parieto-occipital areas with the dorsolateral premotor and prefrontal areas. The maximum of non-linear similarities between the frontal and occipital electrodes was also detected by Lo and Chang (2013) in individuals practicing Chan meditation. This methodology is not sensitive to the time behavior of the meditation, and rather than changes induced by the current activity of the meditator, it reflects long-term changes in brain activity while learning the meditation states. Confining the meditation training to a very simple, but fundamental, mindful breathing meditation, which often constitutes the first step into a more elaborate path of meditation practices, provides assurance that the observed changes indeed stem from the meditation practice itself. The weakness of this study is that it only uses a cross-sectional approach, which does not answer the question of whether meditation practice

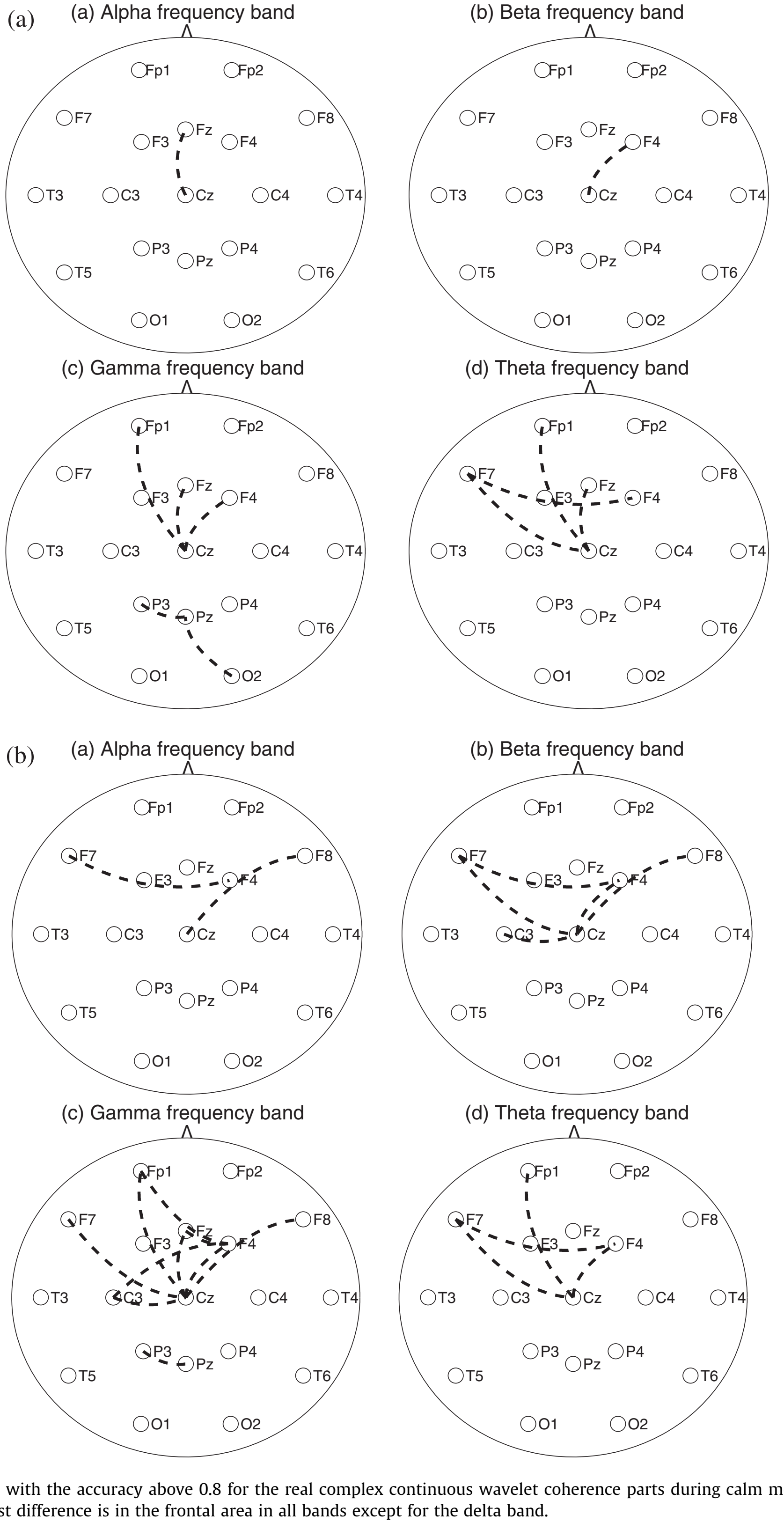


Fig. 5. Pairs of electrodes with the accuracy above 0.8 for the real complex continuous wavelet coherence parts during calm meditation (a) and insight meditation (b). The biggest difference is in the frontal area in all bands except for the delta band.

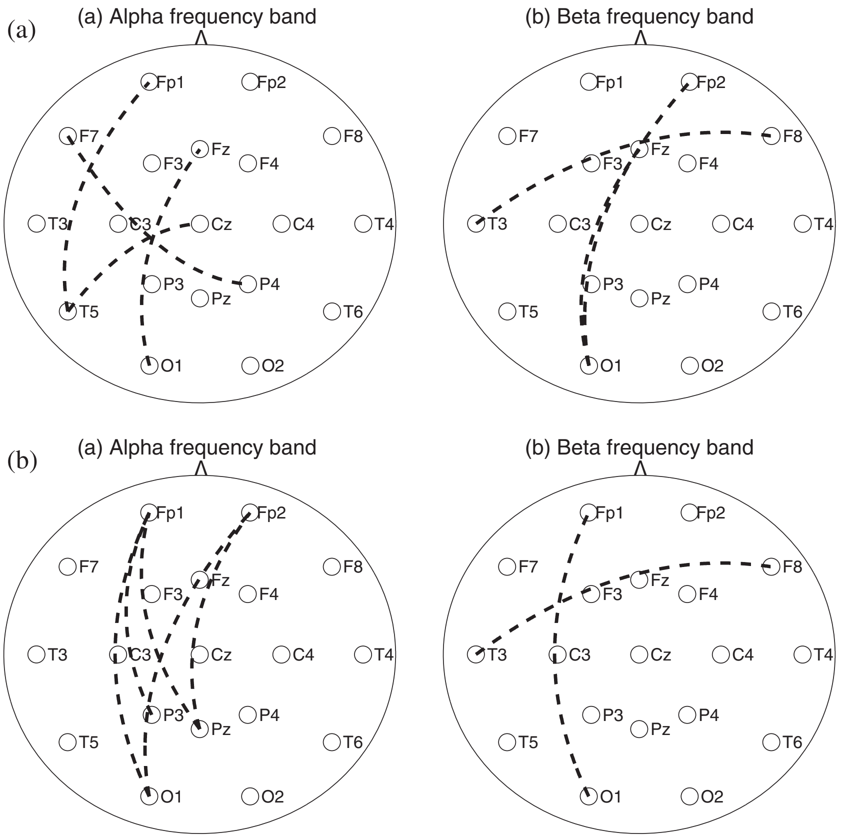


Fig. 6. For the imaginary part, the most significant differences in the complex continuous wavelet coherence under calm meditation (a) and insight meditation (b) are in the alpha- and beta- bands between the frontal occipital and frontal parietal electrodes.

is causally involved in observed differences between meditators and non-meditators. In this study, the participants were required to record the frequency and amount of meditation practice themselves.

As the experimenters appeared to have a good rapport with the participants and they emphasised to the subjects that it is more important to provide accurate information than to fulfil a specific regime, we have no specific reason to doubt the honesty and accuracy of these records. We are, however, in no position to objectively confirm this. These data will allow us to investigate brain dynamics during rest and meditation practice, in which we are particularly interested in global brain states, indexed by oscillating neural activity. Several recent studies suggest that there might be differences between meditators and non-meditators (e.g., Cahn & Polich, 2009; Lutz et al., 2004; Tei et al., 2009) and between different types of meditation (Travis & Shear, 2010) in this respect. Our analysis is exploratory, and the results still need to be confirmed with a subsequent hypothesis-driven experiment.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.concog.2014.07.015.

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