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ORIGINAL ARTICLE

EEG Synchronizations Length During Meditation

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Abstract The dynamic structure of the EEG signal is characterized by segments of synchronization and desynchronization. In this paper, the frequency and duration of these segments were monitored during calm meditation and insight meditation in experienced and naive meditators. A newly developed methodology based on complex continuous wavelet coherence was used to estimate these parameters. The durations highly depend on frequency band and vary from 60 ms to 250 ms. A shorter duration and a lower frequency of synchronization were found for experienced meditators during both types of meditations for the real and the imaginary parts of the complex continuous wavelet coherence. The greatest duration differences were in the gamma band, which may be associated with handling attention during meditation, whereas the differences in the alpha band were most significant for frequency. Combining the two parameters resulted in the total duration of the synchronization, which has discriminative accuracy of up to 100% and appears to be a sensitive parameter of the length of training of meditators.

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Keywords Calm meditation · Continuous complex wavelet coherence · EEG synchronization · Insight meditation

Abbreviations

CWT	Continuous wavelet transform
WCS	Wavelet cross spectrum
CCWC	Complex continuous wavelet coherence
ROC	Receiver operating characteristic
EEG	Electroencephalography
FIR	Finite impulse response

1 Introduction

The EEG signal is variable and the variation has a characteristic dynamic structure [1]. The dynamics of the network is near the critical point for identical synchronization (mutual entrainment) [2]. External stimuli can thus produce synchronous firing of groups of neurons at low energy performance allowing the mutual exchange of information [3]. The segments of regular EEG activity create stationary or travelling waves at larger spatial scales [1, 4–6] whose presence can be monitored using the coherence [7]. These synchronizations, whether induced by external stimuli or variable internal states, can be observed in narrow frequency bands, or globally [8]. So in general, synchronizations are synchronous neuron firings at two different places in the brain. In this paper we consider the synchronization as areas of increased coherence. These areas are tightly constrained and last less than 500 ms. The authors consider all other areas of EEG recording as desynchronized.

The method of principal components [9], auditory steady-state response [10], filtering in very narrow bands or

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the empirical mode decomposition [11] were used to monitor synchronization in frequency bands. Because the traditional measurement of synchronization using coherences requires a stationary signal, a combination of the Hilbert transformation with the bivariate empirical mode decomposition [12] was used as well. Quantitative rates of synchronization based on the amplitude envelopes in frequency bands have been developed recently, e.g., the activation synchrony index [13]. The continuous complex wavelet coherence allows segments of EEG synchronization and desynchronization with high temporal and frequency resolution to be monitored. The real part is sensitive to synchronization without a phase shift and thus to the volume conduction of potentials. The imaginary part better reflects synchronization with a phase shift [14]. Volume conduction is generally defined as a phenomenon where the activity of one source is measurable at several channels. This is particularly apparent with the EEG recording because the electrodes are close to one another.

Our capacity to process sensory inputs is limited. Attention is used to select relevant information and suppress irrelevant information [15, 16]. Activity in the EEG gamma band is associated with attention (approximately 30–100 Hz). In addition to attention, arousal, object recognition [17] and speech perception [18, 19] are associated with this wave band. Episodic synchronization between different groups of neurons occurs in the gamma band [20]. Meditation technique training focuses on affecting attention. Vipassana meditation or insight meditation and mainly its secularized version—mindfulness meditations—are an increasingly more frequent topic of research because of their clinical application (see review studies by [21–23]). There are two attention regulation mechanisms, which are used in meditation [24–26]:

- Focused attention—deliberately and repeatedly returning attention to the same object; the objective is tranquility (samatha in the Pali language).
- Open monitoring or mindfulness—attention can freely shift to any objects that enter the field of awareness. The objective is stable moment-by-moment awareness leading to insight (vipassana in the Pali language) in the basic characteristics of experience.

In meditation, EEG studies usually mention higher synchronous gamma oscillations [27] in the occipital area [28]. The increased energy in the gamma band is related to focused attention [29] and memory [30]. Long term meditators show higher gamma phase synchrony during distracter-related processing than a control group [31]. Gamma band synchronization (30–70 Hz) plays an important role in the local processing of information in the cerebral cortex [32]. The increased amplitude of stimuli-evoked response in the gamma band is related to increased levels of glutamate [33]. The frequency-specific synchronization of neuronal firing is critically important for the coordination of the network of neurons involved in processing sensory information and planning motor skill activities [34]. Expected stimuli in the visual field increase the behavioral response and the synchronization of the rhythmic activity in the gamma band [35, 36]. The structure of synchronization segments, i.e. the duration of synchronization in the usual EEG frequency bands during meditation and the number of synchronizations, have not yet been the subject of study.

In this paper, we present a new methodology for estimating the duration of the temporary synchronizations between electrodes in a continuous wavelet scales. Furthermore, the authors propose a method for calculating normalized average communication time between the areas of the cerebral cortex. These new parameters based on complex continuous wavelet coherence are successfully applied to EEG records of experienced meditators (more than 1000 h of meditation practice) and a control group of non-meditators.

2 Materials and Methods

2.1 Participants

The experiment enrolled meditators practicing insight meditation (*samatha-vipassana*) as practiced in Theravada Buddhism. The conditions concerned active meditation experience and the length of meditation experience. Here, meditation experience means a formal meditation experience, i.e., in a calm environment, whilst sitting or walking.

The following meditators were enrolled in the experiment:

- at the time of the experiment they were actively formally practicing at least 2 h a week (e.g., 30 min, 4 days a week).
- the length of their meditation experience was more than 1000 h (e.g., approximately 3 years of one-hour meditation a day, or approximately 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.

The meditator group consisted of 7 males aged 20–40. The control group consisted of 6 males and 1 female aged 20–50. No further steps were taken to match the control group with the meditator group.

2.2 Procedure

The participants were divided into two groups. The first group consisted of meditators, the second group of controls. Each participant gradually underwent five phases. All phases were monitored using EEG. The phases were separated by a sound signal:

- adaptation (idle EEG without meditation), 10 min
- calm meditation (concentrated attention on breathing—raising and lowering abdominal wall while breathing in and out), 30 min
- break, 18 min. For the first 5 min of the break the EEG continued to be recorded. Then, the participant was allowed to have a slow walk, stretch, etc. During the last 3 min of the break, the participant took the position again and prepared for meditation.
- insight meditation (open observation of any objects that enter the consciousness moment by moment), 30 min.
- last 5 min of idle EEG without meditation.

In total, the experiment lasted 90 min. For detailed instructions, please see the appendix.

2.3 EEG Recording

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 kΩ. The signals were recorded with a digitization rate of 256 Hz. The stored digitized data were zero-phase digitally filtered using a bandpass FIR filter (100 coefficients, Hamming window) of 0.5–60 Hz and a band stop filter of 49–51 Hz.

2.4 Complex Continuous Wavelet Coherence

Coherence is one of the modern statistic quantities that can be used to examine relationships between two time series. Since the development of digital signal processing, especially the development of wavelet transformation, coherence can be used in ways previously impossible and has become ever more popular.

Coherence analyses the linear dependence of two signals in time–frequency space. Its values vary from 0 (independence) to 1 (linear dependence), respectively −1 (negative linear dependence). As a standard, coherence is calculated using spectra based on the Fourier transform. However, EEG recording is a non-stationary recording, i.e., its spectrum changes over time. Therefore, coherence must be regarded as a dynamic quantity, and to monitor the development of spectral density, continuous wavelet transformation is the most suitable.

2.4.1 Wavelet Spectrum

Continuous wavelet transform (CWT) is a type of transform that detects similarities between the signals. Compared to the formerly used Fourier transform, its advantage is that a time–frequency description of the signal can be obtained. For signal x(t) 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 ψ(t) is the mother wavelet, * represents the operation of a complex conjugate and t stands for time.

The wavelet coefficients C(a,b) are obtained by convoluting shifted and scaled copies of mother wavelet ψ and signal x. These derived wavelets differ in scale *a* and translation *b*. Scale *a* is a parameter based on the stretch of the mother wavelet. Different versions of stretched wavelets detect different frequencies in the signal. The more stretched the wavelet is, the higher frequencies it detects. Scales were chosen to correspond to frequency range of 0.5–60 Hz. Translation *b* describes the shift of the wavelet along the signal. With different positions, different parts of the signal are examined. So by comparing the signal to the wavelet at various scales and positions, the function of the two variables *a* and *b* is obtained. As each scale corresponds to a different frequency, and each position corresponds to a different time point, distribution of wavelet coefficients in time–frequency plane is obtained. The obtained result is called spectrum. CWT was calculated using MATLAB (The MathWorks Inc.) signal processing toolbox.

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

To estimate the relationship between two spectra C_x and C_y in the time-scale plane, a wavelet cross spectrum (WCS) is used. The following equation can 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 behavior of the two time series in the time-scale plane [37]. It emphasizes similarities between spectra of signal x and signal y, respectively C_x and C_y.

2.4.2 Wavelet Coherence

The complex continuous wavelet coherence (CCWC) is defined as WCS normalized by the wavelet spectra of both signals. It can be interpreted as the local squared correlation coefficient in the time-scale plane [38]. For the time series *x* and *y,* represented by signals from two electrodes, it can be written as

$$CCWC_{x,y}(a,b) = \frac{S(WCS_{x,y}(a,b))}{\sqrt{S\left(|C_X(a,b)|^2\right)}\sqrt{S\left(|C_Y(a,b)|^2\right)}} \quad (3)$$

where a is scale, b is position, $C_y(a,b)$ and $C_x(a,b)$ are the coefficients of the continuous wavelet transforms. S is a smoothing operator in time and scale.

Smoothing factor S represents using a moving average filter along the wavelet scale axis and along the time axis. More information about the smoothing operation can be found in the literature [37, 39]. Their use depends on the type of wavelet and scale [40].

Because of the complexity of wavelets, it is possible to distinguish between real and imaginary parts of wavelet coherence. This split into two parts is very important for a time–frequency analysis of non-stationary signals. Although the real and imaginary parts contain the same information as the magnitude and phase of coherence, their use is preferred for studying brain interactions [14].

As the reference is used when obtaining the EEG recording, this reference can significantly contribute to coherence. The assessment of relationships between the individual sources is affected by volume conduction. One way of avoiding this problem is to assess the imaginary part. The imaginary part of the coherence is only affected by the synchronization of the two processes that are time-shifted to each other. Volume conduction does not result in a time shift. Therefore, the imaginary part of coherence is not affected by volume conduction [14]. This assumption will be adopted when carrying out calculations using CCWC. Thus, this paper assesses the real and imaginary parts separately.

2.4.3 Event Detection

Calculating wavelet coherence provides a map of the real and imaginary parts of coherence in time for individual frequencies (Fig. 1).

In this paper, rapid changes in wavelet coherence are referred to as events. The first wavelet coherence differentiation was used to detect these events (Fig. 2). The duration of the event was estimated using the local maxima and minima of the first differentiation. The events were assigned to individual frequency bands and used as a classification criterion. A positive change was chosen as the start of the event, and a negative change of the first differentiation, as the end (Fig. 3). The duration of each event (EEG microstate) is the time distance between the start and the end of the event (Fig. 4). The maximum

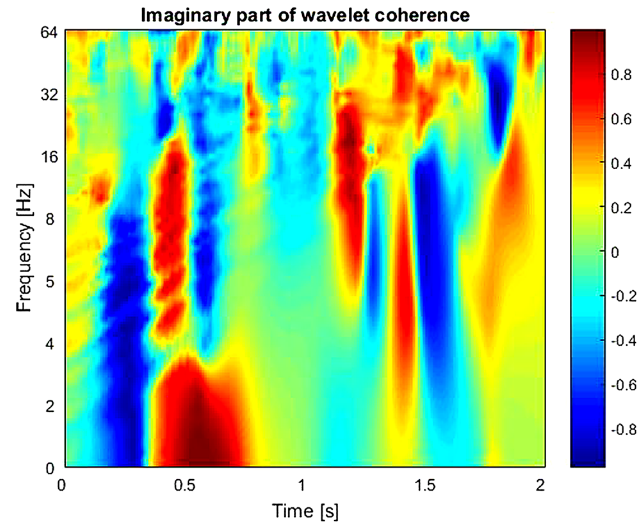

Fig. 1 Real part of the complex continuous wavelet coherence (CCWC) in a 2-s segment of the record of the 0–64 Hz frequency

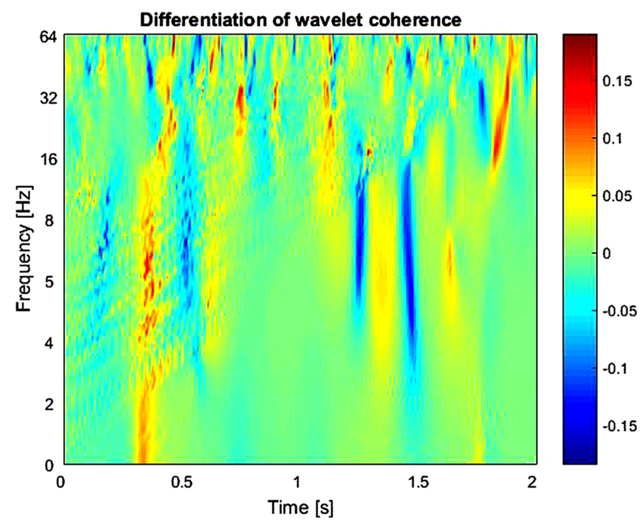

Fig. 2 First differentiation of CCWC from Fig. 1. This is used to identify the start and end of events

length of the microstate was limited to 500 ms. Longer events were not the subject of this paper. The average number of events per 1 s was calculated. The product of the number and the length of the event is the average normalized duration of communication between the areas of the cerebral cortex, under EEG electrodes in individual frequency bands.

2.5 ROC Analysis

To be able to compare experienced meditators against control group Receiver operating characteristic (ROC) analysis is used. ROC analysis is tool for the binary classification of the two data sets—in this case meditators and control group. The ROC curve depicts the relationship

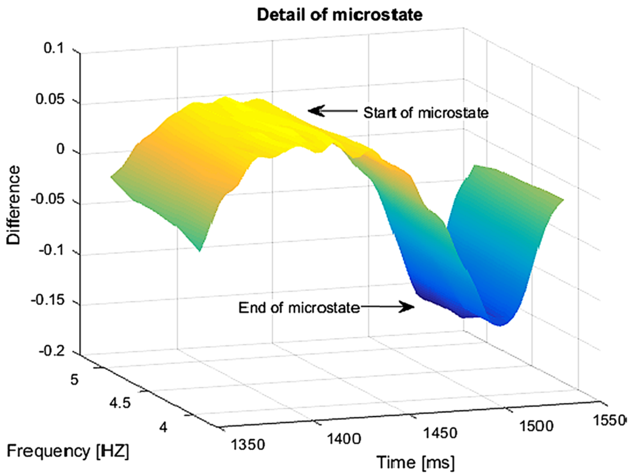

Fig. 3 Event detail from Fig. 2

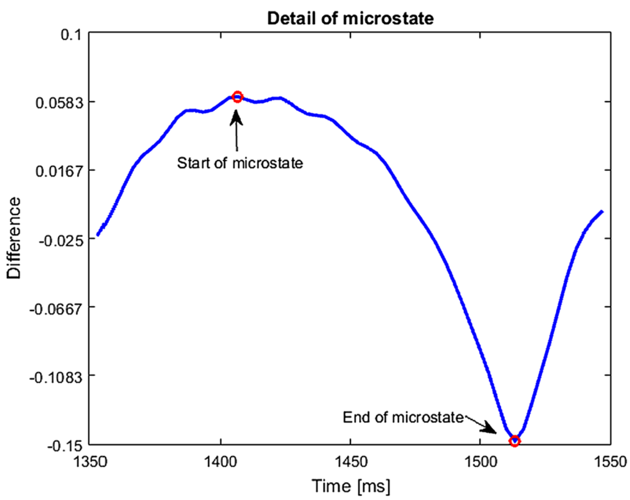

Fig. 4 Method of calculating the start and end of a microstate—detail from Fig. 3

between sensitivity (true positive rate) and specificity (true negative rate). Sensitivity relates to the test's ability to correctly detect experienced meditators.

$$sensitivity = \frac{true\ positives}{true\ positives\ +\ false\ negatives} \tag{4}$$

Specificity relates to the test's ability to correctly detect members of a control group.

$$specificity = \frac{true\ negatives}{true\ negatives + false\ positives} \tag{5}$$

This tool is mostly used in medicine because the results describe statistical accuracy. 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. One threshold was found for the duration of microstates; second one for relative number of microstates.

Statistical accuracy is defined as

$$accuracy = \frac{true\ positives + true\ negatives}{true\ positives + false\ negatives + true\ negatives + false\ positives} \tag{6}$$

In our case, the two classes are represented by the meditators and control group. The optimal threshold for differentiating between these two states is that which has the highest accuracy (Table 3).

True positive stands for correctly identified experienced meditators, false positive for incorrectly identified, true negative for correctly rejected and false negative for incorrectly rejected.

Thus the accuracy predicts the possibility of correct classification of random patient based on calculated parameters.

All the computations were carried out by MATLAB Statistics toolbox and Signal processing toolbox.

3 Results

Although both the number and duration of events differ for both the real and imaginary parts of complex continuous wavelet coherence, they have comparable discriminatory values to distinguish experienced meditators from inexperienced meditators (Tables 1, 2; Figs. 5, 6, 7, 8). The contribution of volume conducted potentials in the real part of CCWC does not apply significantly here [14]. However, in terms of the number of events, the most significant changes are in the alpha band (Tables 1, 2; Figs. 5, 6, 7, 8). There is the lowest frequency of events but this band has the highest discriminative accuracy—75%. The highest frequency of events was in gamma band with statistical accuracy 70%. In terms of duration, the most significant differences (accuracy 70%) are in the gamma band for both types of meditation. Duration of events in gamma band is 230 ms. Both number of events and their duration highly depends on frequency band. Results during both meditations are comparable.

As there is lower number of events and they are of shorter duration in experienced meditators, it is preferable to monitor the total duration of synchronization. Total duration is a product of the number of microstates and their duration. This combined parameter has the highest discriminative value for both the real and imaginary parts of CCWC (Table 3). It shows significant differences between each meditator and each member of the control group. Figures 9 and 10 show dependency of length of microstates on their duration for each participant. The dashed line proves that the two groups are linearly separable, which is also reflected in the high accuracy (Table 3).

Table 1 Average length and number of microstates 30 min after the start of the meditation estimated by the real part of the CCWC in inexperienced and experienced meditators for both types of meditation

Calm meditation				Insight meditation			
Band	Inexperienced	Experienced	Accuracy (%)	Band	Inexperienced	Experienced	Accuracy (%)
Real part							
Duration of microstates (ms)							
Delta	74	58	63	Delta	70	59	62
Theta	153	135	65	Theta	156	147	62
Alpha	226	208	66	Alpha	224	209	66
Beta	227	195	63	Beta	227	214	58
Gamma	232	221	73	Gamma	242	226	70
Relative number of microstates							
Delta	265	192	68	Delta	258	181	66
Theta	115	66	65	Theta	130	79	66
Alpha	113	58	75	Alpha	121	60	75
Beta	228	151	70	Beta	155	114	63
Gamma	492	374	70	Gamma	583	426	73

Table 2 Average length and number of microstates 30 min after the start of the meditation estimated by the imaginary part of the CCWC in inexperienced and experienced meditators for both types of meditation

Calm meditation				Insight meditation			
Band	Inexperienced	Experienced	Accuracy (%)	Band	Inexperienced	Experienced	Accuracy (%)
Imaginary part							
Duration of microstates (ms)							
Delta	79	66	63	Delta	80	70	63
Theta	129	119	64	Theta	133	127	62
Alpha	183	174	64	Alpha	185	174	64
Beta	175	166	63	Beta	180	166	58
Gamma	190	181	74	Gamma	190	175	70
Relative number of microstates							
Delta	301	265	58	Delta	323	257	62
Theta	183	106	66	Theta	147	95	69
Alpha	224	129	75	Alpha	216	117	74
Beta	236	150	61	Beta	298	202	60
Gamma	464	309	69	Gamma	454	425	69

4 Discussion

Both duration and relative amount of microstates are suitable tools for discrimination between experienced and inexperienced meditators. These parameters reflect differences between the two groups regardless of whether the imaginary or real part of CCWC is used (Figs. 9, 10). Highest accuracies found are around 70%. High differences in gamma band and also large number of events in gamma band correspond to findings by other researchers [27, 28]. By combining these discriminative parameters, total duration of synchronization is introduced. The total duration of synchronization during meditation is the most promising marker of the advancement of the meditators. It can with 100% accuracy distinguish experienced meditators from the beginners in calm meditation as well as insight meditation (Table 3). Since the group of subjects was small these results must be confirmed on larger group of subjects. Despite this fact the accuracy shows that there are clear differences between the two groups and they are detectable using CCWC. Specificity and sensitivity values shows that experienced meditators will be correctly classified but there is a risk of misclassifying inexperienced meditators, although the chance is low (Table 3). In

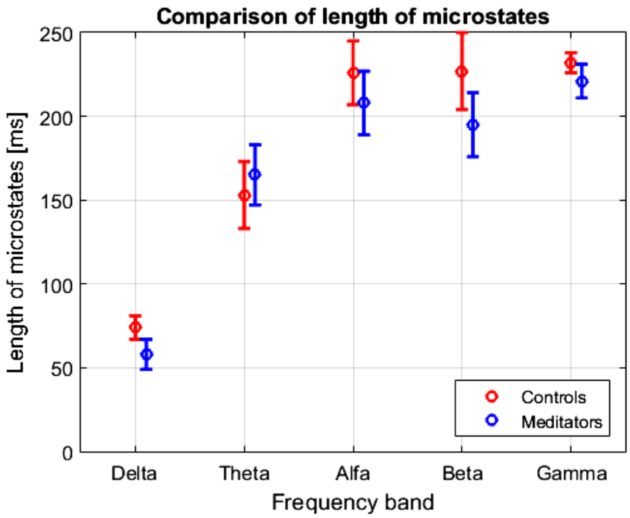

Fig. 5 Estimate of the average length of microstates using the real part of CCWC in calm meditation

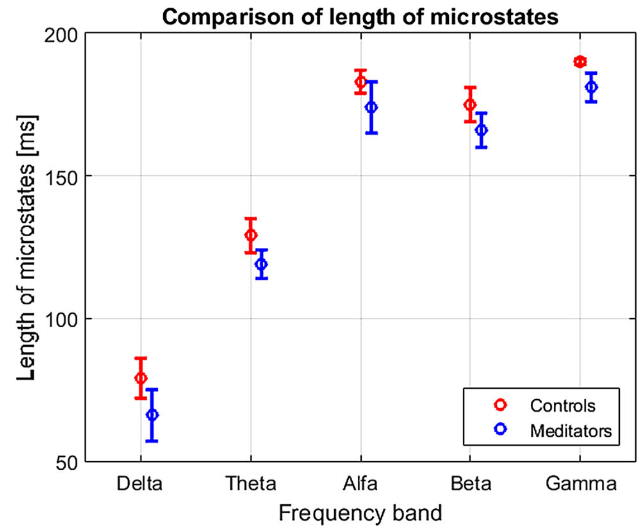

Fig. 7 Estimate of the average length of microstates using the imaginary part of CCWC in calm meditation

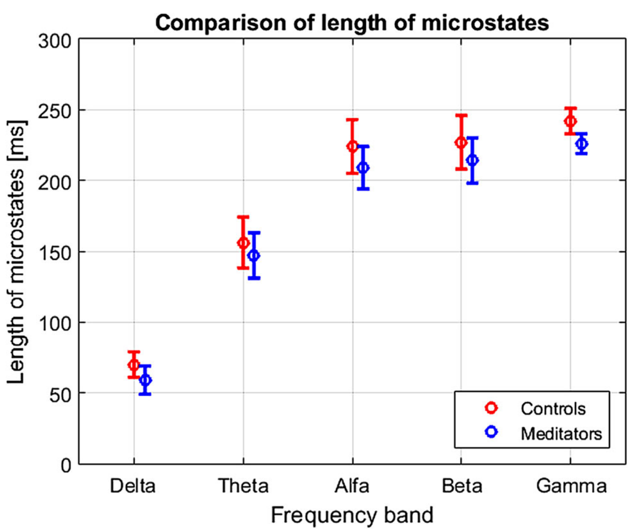

Fig. 6 Estimate of the average length of microstates using the real part of CCWC in insight meditation

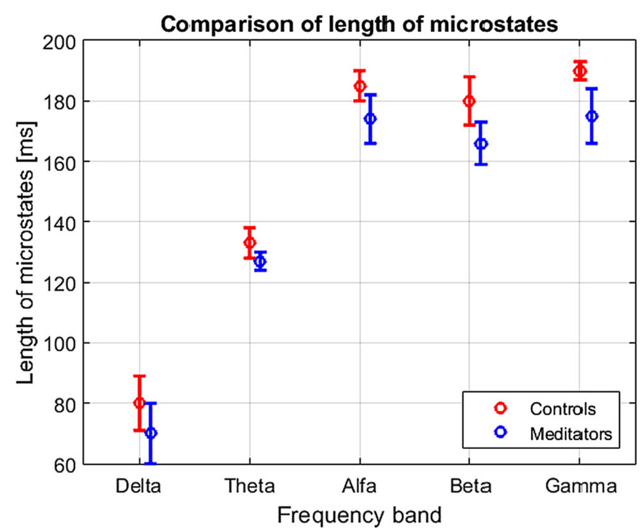

Fig. 8 Estimate of the average length of microstates using the imaginary part of CCWC in insight meditation

general, experienced meditators have lower number of EEG synchronizations with lower duration. All of the participants can be correctly classified based only on calculated parameters.

As the measured segments of synchronization have a spindle rather than a rectangular shape in two dimensions. The measured durations have the same events in nearby frequency bands of higher variance. This problem could be resolved by identifying events in 2D through nearby frequencies with the identification of the maximum duration of the event and potentially the width of the frequency band. A similar approach would also allow a better identification of the spreading of the events between brain regions. The detected 50-250 ms values of synchronization duration in all bands correspond approximately to the estimated synchronization duration using other methods: 50–200 ms [7], 100–900 ms [41] and 100 ms [42]. The estimate of the number of events in individual frequency bands using the relevant method reflects not only the quantity of the events but also the width of the frequency band in which the event occurs. Here, the identification of events in 2D could substantially increase the predictive value of this parameter.

Meditation technique training changes the synchronization time dynamics of spontaneous oscillations during meditation, depending on the length of the training. For synchronization durations, the changes with the highest discriminative value are in the gamma band for both

Table 3 Total duration of microstates estimated by the real and imaginary parts of the complex continuous wavelet coherence in inexperienced and experienced meditators; thresholds are optimal values of total length of microstates (min) based on which the two group are separated

	Calm meditation				Insight meditation			
	Threshold	Specificity	Sensitivity	Accuracy (%)	Threshold	Specificity	Sensitivity	Accuracy (%)
Real part	13.4	0.71	1	86	13.2	0.71	1	86
Imaginary part	11.7	0.86	1	93	14.5	1	1	100

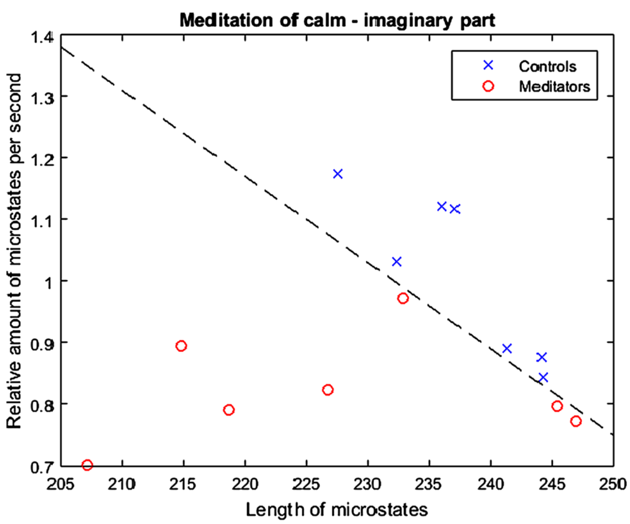

Fig. 9 Dependence of the average duration of microstates on their number in 30 min of calm meditation for all frequency bands for the imaginary part of CCWC

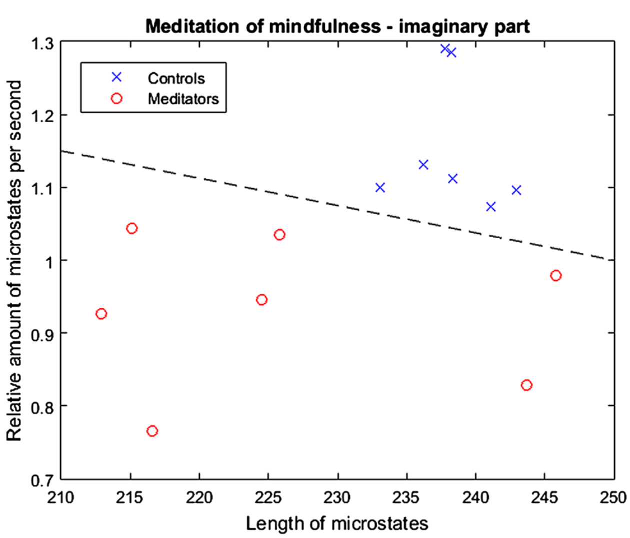

Fig. 10 Dependence of the average duration of microstates on their number in 30 min of insight meditation for all frequency bands for the imaginary part of CCWC

meditation techniques, whereas for the number of synchronizations, the most significant changes are in the alpha band. This finding cannot be directly related to experiments with evoked and induced gamma oscillations outside of the state of meditation [29]. The average duration of EEG synchronization, estimated using CCWC, is a sensitive parameter of the length of training of the meditators. The greatest differences in the synchronization duration found in the gamma band show a connection between this parameter and the handling of attention in meditation techniques, regardless of the type of meditation.

We reported a general increase in coherence during meditation [43]. But using CCWC to detect synchronizations and to measure their duration has not been reported in literature. The methods described by the authors were used for the first time and therefore the results still need to be confirmed with a subsequent hypothesis-driven experiment.

5 Conclusion

We found significant differences between experienced meditators and control group both in number and duration of synchronization. By combining these parameters we show that the two groups are linearly separable. Every subject can be classified with 100% accuracy based on calculated parameters. To summarize these findings, experienced meditators exhibit lower number of temporary synchronizations of shorter duration than the inexperienced one across all frequency bands. This occurred for all examined participants. Results show that complex continuous wavelet coherence is the ideal tool for monitoring such synchronizations due to its high temporal and frequency resolution. The presented method is ideal for monitoring the achieved level of meditation. It can be applied for an objective comparison of effectiveness of different methods of neuropsychological rehabilitation through meditation techniques. It could be also be used as feedback while practicing meditation. Our results support the theory that intensive meditation can cause long-term neural changes but they need to be confirmed with future analyzes based on a much larger group of subjects.

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Compliance with Ethical Standard

Competing interests The authors declare that they have no competing interests.

Authors' contributions JK, OV, AP participated in the design of the study and performed the statistical analysis. Data were collected and analyzed by the investigators JK, JB, OV. OV, AP, MV conceived of the study, and participated in its design and helped to draft the manuscript. All authors read and approved the final manuscript.

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