Increased Entropy of Gamma Oscillations in the Frontal Region during Meditation

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***Abstract*— Meditation practices are considered mental training and have increasingly received attention from the scientific community due to their potential psychological and physical health benefits. We compared the EEG data recorded from long-term rajayoga practitioners during different meditative and non-meditative periods. Minimum variance modified fuzzy entropy (MVMFE) is computed for each EEG band for all channels of a given lobe. The means across all the channel entropy values were obtained and compared during meditative and non-meditative states. Meditators showed higher frontal entropy in the lower gamma band (25-45Hz) during the meditative states. Independent component analysis was applied to ensure that muscle or eye artifacts did not contribute to the gamma activity. Our results extend previous findings on the changes in entropy observed in long-term meditators during rajayoga practice. Gamma band in EEG is implicated in cognitive processes requiring high-level processing such as attention, learning, memory control, and retrieval. Gamma activity is also suggested as a potential biomarker for therapeutic progress in patients with clinical depression. Based on our findings, there is an excellent possibility to utilize the practice of meditation as a training tool to strengthen the neural circuits, where age-related degeneration is making its pathological impact.**

I. Introduction

Over the last decade, the volume of scientific publications on studies related to meditation has dramatically increased [1]. Neuroscientists are investigating the changes in emotion regulation and cognition due to mental practices like meditation. Psychotherapists are also interested in improvements in interpersonal relationships, and personal development [2]. The entropic brain hypothesis proposes that the level of conscious states can be indexed with entropy, with increased entropy of brain activity relating to the psychedelic state [3]. High entropy is associated with uncertainty leading to low predictability, which is a result of subjective experiences during meditation, which is beyond the scope of ordinary conscious wakefulness [4], [5]. The hypothesis supports the increase in the entropy during meditation that the long-term practice of meditation is associated with an increased repertoire of experiences which are subjective [6], [7].

Consistent differences were found in the prefrontal cortex and regions involved in body awareness in meditators as compared to controls [8]. Permutation entropy and fractal dimension were used to analyze two types of meditation, and it was found that permutation entropy was advantageous over fractal dimension [9]. Decrease of non-linear dimensional complexity in midline frontal and central regions was observed during Sahaja yoga meditation as compared to rest condition [10]. Neuroimaging study on rajayoga practitioners has shown enhanced white matter integrity in corpus callosum segments as compared to controls [11].

Frequency components around '40 Hz' termed as gamma band are considered to be a vital characteristic of the brain activation during meditation [12]. It has been hypothesized that the role of gamma-band is prominent in the 'binding problem' defined as the binding of independent neural assemblies resulting in the integration of information processing for unified conscious experience [13]. A study of advanced meditators on four different meditations revealed that the source of gamma-band activity was in the anterior regions of the brain during meditation [14]. Another study of advanced practitioners has indicated an increase in the gamma band activity supporting the higher attentional capacities [15].

The objective of this study is to examine whether there exists a consistent difference in entropy in the EEG activity of rajayoga practitioners between meditative and non-meditative states. It has been observed that the increase in entropy during meditation was significant in frontal and centroparietal regions [16]. This analysis is now extended to bandwise computation in the present work.

A. *Rajayoga practice and present study*

Rajayoga meditation is a practice reported to be based on contemplation on the supreme soul and thus may involve more metaphysical components. The present study investigates entropy changes during the following two types of rajayoga practices: peaceful soul consciousness meditation(PM) and angelic meditation (AM).

II. Experimental Procedure

This work is a continuation of the analysis reported in our previous publication [16].

A. *Participants*

Fourteen long-term meditators (one female) with mean age and standard deviation of 42 ± 5 years, with an average experience and standard deviation of 23 ± 5 years, were recruited for the study. The experiments were carried out at the Brahma Kumaris headquarters, Mount Abu, India.

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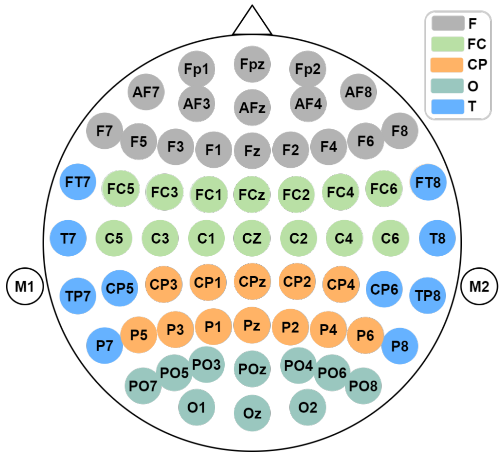

Fig. 1: Grouping of the 64 EEG electrodes recorded according to the 10-10 system into different lobes considered in the study. F: frontal; FC: fronto-central; CP: centro-parietal; O: occipital; and T: temporal.

B. *Experimental Design*

All the participants were instructed about the protocol, and a written consent form was collected. The experiment consisted of two different rajayoga meditation types for 10 minutes each in the protocol. Initial (BL) before PM, intermediate (IBL) after PM, and final baseline (FBL) segment after AM with a duration of five minutes were recorded [16]. The present study analyzes the changes in entropy in different frequency bands during the various segments of the protocol. The meditation segments AM and PM were not randomized in the protocol of the proposed study.

C. *EEG data acquisition and pre-processing*

EEG data were recorded using 64 + 8 channels ANTNeuro amplifier system with a 10-10 standard Waveguard head cap. Data were recorded at a sampling frequency of 1024 Hz, and all the electrodes were kept within 20 kΩ impedance. Data were preprocessed with EEGLAB version 13. A highpass filter with a 0.5 Hz cutoff and an order of six was applied to the EEG time series. Independent components due to muscle artifacts, eye movements, and electrode popping were removed using independent component analysis (ICA) and other procedures described in detail in a previous publication [16]. The 64 channels considered for the study were grouped into broader regions of the brain, as illustrated in Fig. 1.

D. *Minimum variance modified fuzzy entropy (MVMFE)*

EEG time series were filtered using EEGLAB to obtain the canonical frequency bands listed in Table 1.

The fuzzy entropy used in the study is based on the estimated complexity of a time series derived from the concept of membership function defined by De Luca and Termini [17] [18]. In the proposed study, a relative energy function is used as the membership function termed as MVMFE [19] to extract the entropy values from epochs of 0.5 seconds (512 samples) length. Given a time series $X = \{x_1, x_2, ..., x_N\}$,

TABLE I: Frequency bands considered in the study.

Sl. No.	Band name	Frequency range
1	Delta	0.25 - 4 Hz
2	Theta	4 - 8 Hz
3	Alpha	8 - 13 Hz
4	Beta	13 - 25 Hz
5	Gamma	25 - 45 Hz

the key computations are

$$FE = -K \sum_{i=1}^{N} [\mu_i log(\mu_i) + (1 - \mu_i) log(1 - \mu_i)] \quad (1)$$

where K is a constant $(= 1/N)$ and μ_i is obtained using the relative power membership function given by,

$$\mu_i = \frac{|x_i|^2}{\sum_{i=1}^{N} |x_i|^2} \quad (2)$$

III. Results

Multiple comparisons are shown in Fig 2, with the increase in entropy observed in all brain regions. However, the increase is statistically significant only in the frontal region in the gamma band.

A. *Statistical Analysis*

Wilcoxon signed-rank test, a non-parametric two-sample test, is applied to assess the difference between two conditions/states of the protocol, and Cohen's d test is used to find the effect size. Results of the Wilcoxon test are graphically represented in Fig. 3. MVMFE of narrow-band EEG signal is computed for each channel of a given lobe, and the means across all the channel entropy values are obtained. The results are significant only for the gamma band (25 - 45 Hz) in the frontal lobe. As shown in Fig. 3, the changes in other frequency bands and lobes are not significant.

The topographic distribution of electrodes of overall MVMFE increase in the gamma band, predominantly in the brain's frontal and temporal regions, is as shown in Fig 4.

IV. Discussion

Our analysis has extended our previous findings by showing how rajayoga practice can increase signal complexity in the brain's frontal region as indexed by MVMFE. Our findings are consistent with increased gamma synchronization during meditative states [15] and increased sample entropy in the alpha and gamma bands during meditation [6]. Increased EEG gamma activity in the parieto-occipital lobe has been observed in other studies during non-rapid eye movement (NREM) sleep in experienced mindfulness meditators [20]. A study on long-term Vipassana meditators reported increased occipital gamma power compared to controls and was hypothesized to be the effect of imagined visualization of body parts during meditation. Vipassana meditation is considered to be of the open-monitoring type, which may

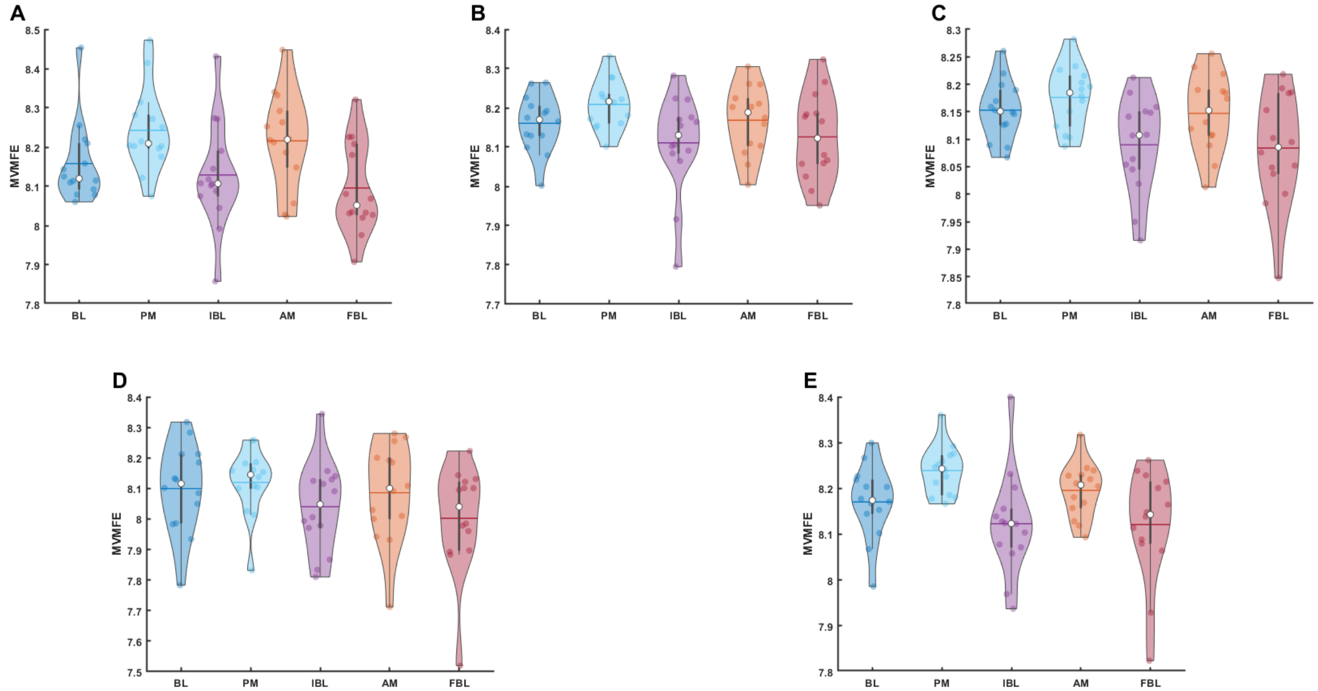

Fig. 2: Effect of meditation on the entropy of gamma oscillations of all the subjects (14 points in each state). The meditative state changes the entropy of gamma oscillations in frontal **(panel A)**, frontocentral **(panel B)**, centroparietal **(panel C)**, occipital **(panel D)** and temporal **(panel E)** lobes. Colored circles represent the number of subjects; white circles, the median values; respective dark color horizontal lines in the violin plots represent the mean values; thick grey color bars denote the interquartile range. (BL: Baseline, PM: Peaceful soul consciousness meditation, IBL: Inter-mediate baseline, AM: Angelic meditation, FBL: Final baseline)

be interpreted as the state of enhanced wakefulness [21]. Cognitive processes such as learning, working memory, and attention are implicated by gamma-band oscillations [22]. Gamma activity observed in the frontal area can be related to the redirection of attention towards the meditation task, which can be a top-down control of attention [1].

A. *Gamma and associated artifacts*

ICA methods are utilized to remove the artifacts from the muscles of the scalp, eye blinks, and movements. Hence, an increase in the gamma entropy values in the brain's frontal region during the meditative states is not due to eye movements.

V. Conclusion

In summary, peaceful soul consciousness and angelic meditations under rajayoga practice result in increased gamma-band entropy of EEG in the frontal brain region. The changes in other regions of the brain and frequency bands vary across subjects. Future research should address whether these reported results are related to the long-term meditation as a trait effect relative to control subjects.

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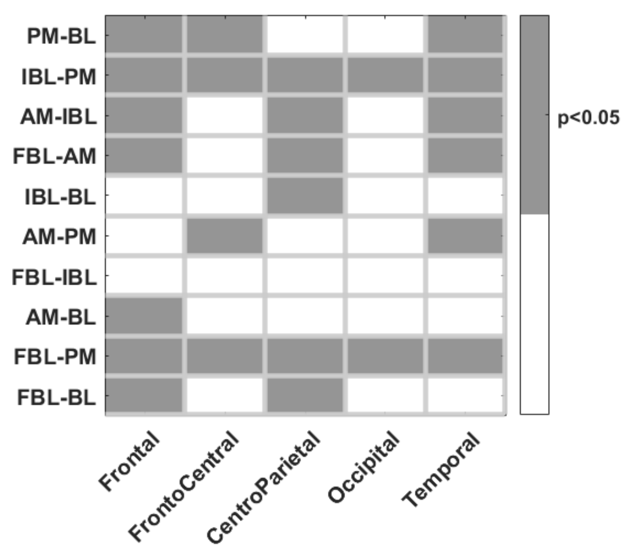

Fig. 3: Statistical significance of entropy changes in gamma band between different meditative and non-meditative states in different brain regions considered in the study. x-axis is the lobe considered, and the y-axis is the combination of states for which the statistical significance was calculated. Grey color denotes significant entropy changes with p-value ≤ 0.05.

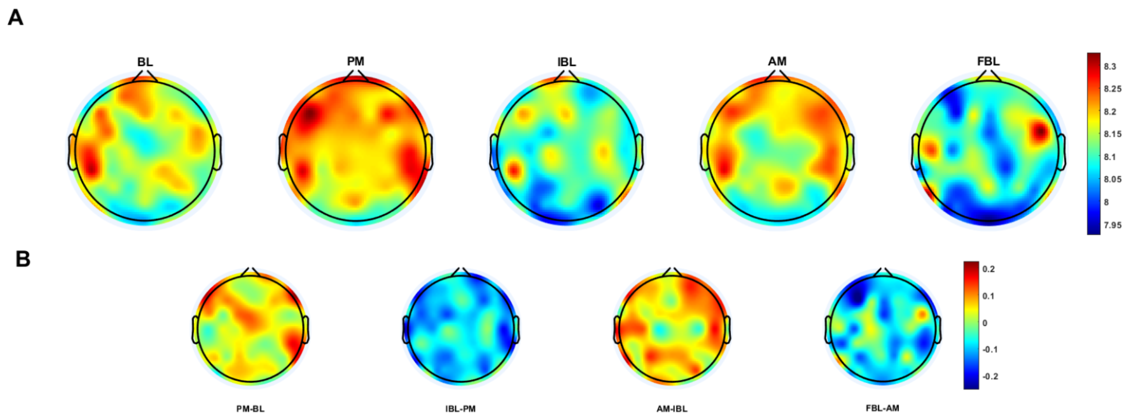

Fig. 4: Localization of entropy changes in gamma band averaged across all the 14 subjects. Topographic distribution of higher MVMFE values in meditative states relative to non-meditative states for the gamma band **(panel A)**: From left to right, BL, PM, IBL, AM, and FBL. **Panel B** is the difference entropy plot with successive states. From left to right, PM-BL, IBL-PM, AM-IBL, and FBL-AM.

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