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Detection of Meditation-Induced Brain Activity Changes Across Individuals Using EEG

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Abstract. In the field of cognitive neuroscience, meditation is receiving increasing attention and research because of its ability to regulate neural areas related to attention, emotion, and consciousness. Much evidence indicate that the meditation process is accompanied by systematic changes in neural activity, especially concentrated in the alpha (8–13 Hz), theta (4–8 Hz), and gamma (30–100 Hz) frequency bands. In this study, we analyzed electroencephalographic (EEG) data to characterize neural activity in the meditative state and evaluate the participation patterns of various areas of the cerebral cortex. Analysis of the results revealed that the meditative state is closely related to a series of measurable neuromodulation phenomena with specific frequency characteristics, and these neuromodulation mechanisms may be the key to improving individual emotional regulation ability and cognitive resilience.

Keywords: meditation, EEG, neurophysiological

1. Introduction

Meditation originates from a variety of contemplative traditions, such as Buddhism, Hinduism, and Taoism; in these cultures, meditation has historically been developed as a means of cultivating awareness and self-regulation. In recent years, evidence has accumulated that there are measurable links between meditation and cognitive function, emotion management and underlying neurophysiological activities. Meditation was once ignored in mainstream scientific research, but now its effects on mood regulation and stress management have been proven. Researchers have conducted groundbreaking work and established mindfulness meditation as an intervention with clinical application. The current study uses neuroscientific methods to elucidate the neural basis of meditation, with a particular focus on using neuroimaging and electrophysiological methods to demonstrate its effects. Among these methods, electroencephalography (EEG) is particularly valuable because it can capture neural activity related to instantaneous mental states and it adopts a non-invasive detection method, which is very suitable for capturing those subtle and time-changing neural states during meditation. And EEG can detect brain activity in real time as the meditation state changes. Long-term meditation practice has been formally associated with changes in brain structure and functional oscillatory activity. Early electroencephalogram studies showed that experienced meditators showed significant changes in neural activity during meditation compared to their resting state.

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Meditation is associated with an increase in brain electrical power in the Alpha band (8–13 Hz), Theta band (4–8 Hz), and Gamma band (>30 Hz). Related studies have shown that unique EEG characteristics appear in experienced yoga practitioners, especially the significant advantage in the spatial distribution of rhythmic Alpha band activity. These intensity and distribution characteristics depend on the proficiency of the practitioner and the group meditation technique used. Such changes not only correspond to changes in state of consciousness and proficiency, but also depend on the individual's own characteristics, including age and gender. On this basis, this study examined the brain wave characteristics of 24 meditators, and clearly considered individual differences in age, gender, and meditation experience. Previous research has shown that these factors are more than just covariate and may have substantial effects on meditation-related neurological outcomes. This study aims to further characterize how meditation modulates EEG characteristics across individuals and elucidates its related psychophysiological and psychological effects. Likewise, this study aims to provide new insights into the relationship between meditation practice and neural patterns that differ across individuals. This research helps us more fully understand how meditation induces state changes and long-term neural adaptations.

2. Method

This study aims to explore how demographic and empirical factors affect the neural activity related to meditation and is measured by electroencephalography (EEG). A total of 24 participants (12 women and 12 men) were recruited for the experiment, aged between 29 and 78. I group the participants according to gender, meditation experience (beginners and experienced practitioners) and age (under 40 years old and over 40 years old). All participants reported normal vision or normal vision after correction, and no history of neurological or mental illness. The research program has been approved by the institutional ethics committee and obtained the written informed consent of all participants before data collection.

Each participant continues to record the electroencephalogram data while doing a meditation exercise. Participants are required to do their meditation exercises in a quiet, dimly lit environment, mainly focusing on concentration or open meditation, in order to minimize external interference. During this period, we will continue to observe the fluctuations in its attention status. In this way, you can track the attention dynamics in the process of meditation in real time.

The EEG signal is recorded by the BioSemi ActiveTwo system equipped with a 64-channel electrode cap. The electrode cap is arranged according to the international 10-20 system, and the initial sampling rate of the data is 2048 Hz. In order to improve computing efficiency while maintaining signal fidelity, the original data is then downsampled to 256 Hz using the BioSemi BDF extraction tool. Electroencephalogram preprocessing and spectrum analysis are carried out through MNE-Python. Through band-pass filtering, the power spectrum density (PSD) is estimated by Welch method (n_fft = 2048). The average spectral power of typical frequency bands is calculated, including δ wave (1–4 Hz), θ wave (4–8 Hz) and α wave (8–13 Hz). In order to study regional brain activity, the electrodes are grouped into the frontal lobe, central and parietal lobe regions, and the power spectrum density (PSD) values of all electrodes in each region are averaged. The process follows the established process of EEG-based meditation research and uses a powerful open-source neural information framework to achieve fine and repeatable spectrum analysis.

We assume that spectrum analysis will be affected by differences in gender and age. Because gender differences in cognitive control and emotional regulation may be due to hormonal influences, neurobiological structure, and psychological tendencies.

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3. Result

One of the main purposes of our research is to explore whether gender affects the electroencephalographic (EEG) pattern during meditation. For each participant, we calculated the average power spectrum density (PSD) of all EEG channels. As shown in Figure 1, the results show that the power of female participants in the δ wave and θ wave bands is significantly higher than that of men, and the power of α waves is also slightly higher than that of men. In general, these findings suggest that women may be more likely to enter a more lasting or deeper state of meditation. Nevertheless, these results emphasize the importance of incorporating gender-specific analysis in meditation neuroscience and further confirm the neurophysiological effects of gender regulating mindfulness exercises.

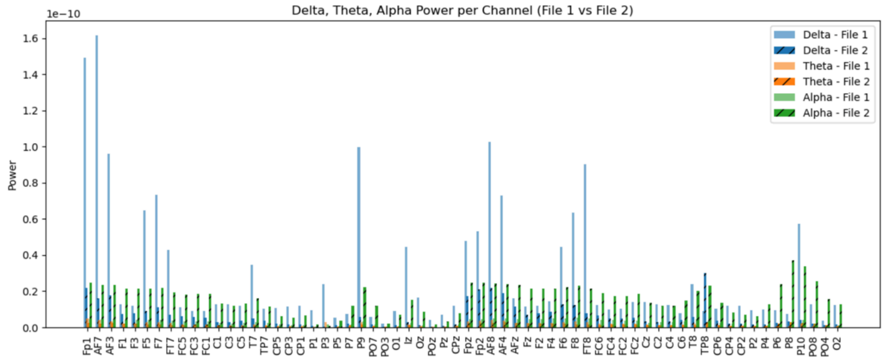
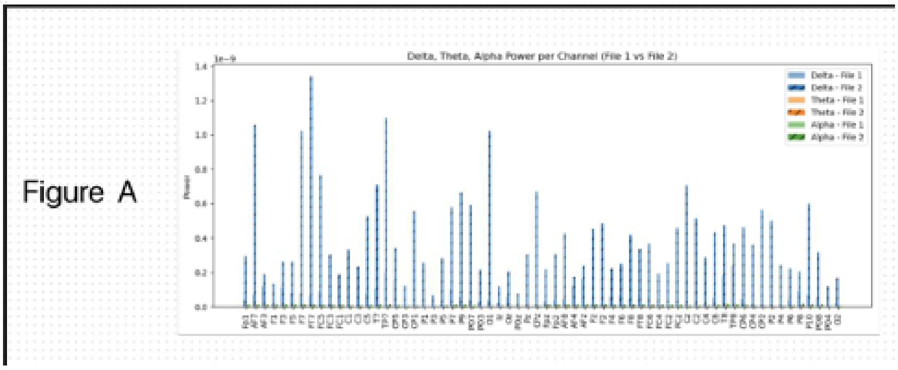


Figure 1. Difference between female and male

Note: Figure legend, x axis represents different channels, y axis represents the strength of electrical signals. Columns without oblique lines represent female data, while columns with oblique lines represent male data. Blue represents Delta wave, orange represents Theta wave, and green represents Alpha wave.

Another main purpose of this study is to determine whether the level of meditation experience (especially for novices and experienced practitioners) affects the neural oscillation pattern during meditation. The problem is based on previous research results, which show that training-related neuroplasticity can change baseline and task-related brain activity over time. Participants are divided into novice groups and experienced groups according to the frequency of self-reported practice and years of meditation experience. However, during meditation, novice and experienced practitioners did not observe significant differences in any frequency band of detection (Figure 2 (a)(b)).



(a) Difference between Expert and Novice

Note: Figure legend, x axis represents different channels, y axis represents the strength of electrical signals. Columns without oblique lines represent expert, while columns with oblique lines represent novice. Blue represents Delta wave, orange represents Theta wave, and green represents Alpha wave.

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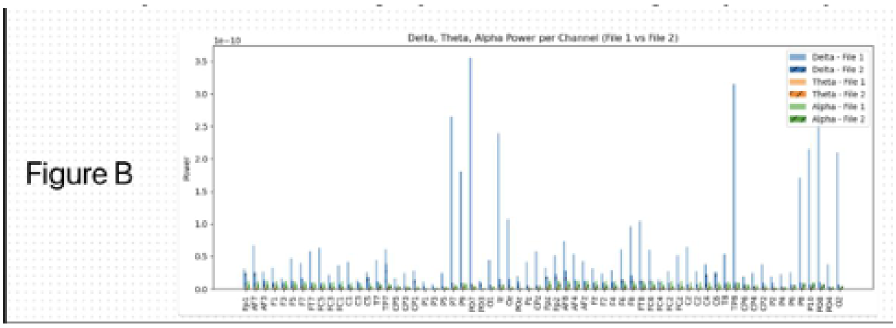

(b) Difference between Expert and Novice

Figure 2. (a) (b): Difference between expert and novice

Note: Figure legend, x axis represents different channels, y axis represents the strength of electrical signals. Columns without oblique lines represent expert, while columns with oblique lines represent novice. Blue represents Delta wave, orange represents Theta wave, and green represents Alpha wave.

Finally, this study examines age as a key factor affecting EG activity during meditation. Participants are divided into two age groups: the group under 40 and the group over 40. The electroencephalogram data is segmented and analyzed using band-pass filtering and power spectrum density estimation. The results revealed a complex age-related pattern: compared with young participants, older participants showed lower θ wave power during meditation, but higher δ wave and α wave power (Figure 3).

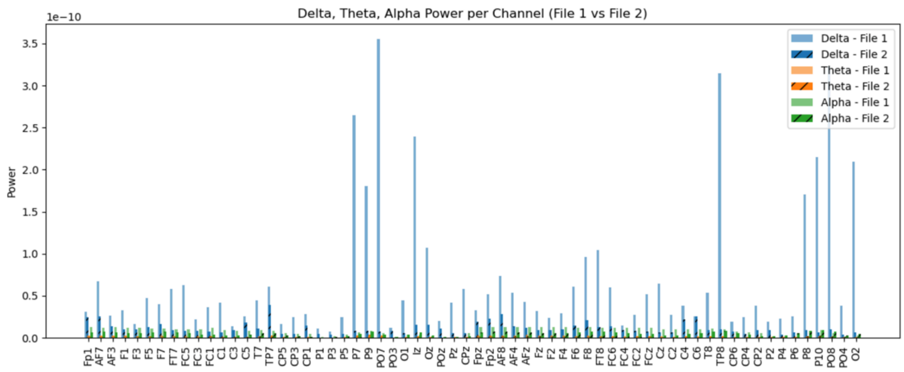

Figure 3. Difference between people over the age of 40 and people under the age of 40

Note: Figure legend, x axis represents different channels, y axis represents the strength of electrical signals. Columns without oblique lines represent people under the age of 40, while columns with oblique lines represent people over the age of 40. Blue represents Delta wave, orange represents Theta wave, and green represents Alpha wave.

4. Discussion

EEG results show that there are significant gender differences in meditation-related neurodynamic between men and women, especially in the δ wave and θ wave bands. Compared with male participants, female meditators showed higher power in these frequency bands, a pattern consistent with the early observations of Banquet, which reported that experienced female meditators had increased alpha-wave activity [1]. These results show that female practitioners may reach a higher level of inner awareness and inner peace during meditation. At the same time, Barnhofer also further proved that meditation can regulate alpha wave asymmetry and emotional regulation, which is particularly effective in individuals with a history of depression [2]. In addition, David J. Creswell

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proved that the more common self-reference awareness enhancement in women is related to a variety of physiological processes, which affect emotional labels and emotion-related cognitive tasks [3]. These gender differences in neuroactivity may reflect the common influence of different hormonal regulations and socio-cultural backgrounds between men and women. Similarly, Creswell [3] and Farb [4] reported that characteristic mindfulness is associated with changes in neural circuits involved in emotional labeling and self-reference processing, and these effects may vary by gender. Therefore, consistent with early literature, female meditators showed higher theta band and delta band activity, as well as slightly higher alpha band power than male participants. And it was found that it was consistent with the observation results of Banquet. Banquet recorded the enhancement of the alpha rhythm of experienced female meditators and observed that the alpha band synchronization of female meditators was higher [1]. Overall, these findings show that the neural association of meditation is not completely consistent but will change with gender-related cognitive-emotional characteristics, hormonal influences and sociocultural background.

Contrary to original expectations, there is less difference between novice and experienced meditators. Although previous studies have shown that long-term meditation exercises can enhance gamma band activity and neural synchrony [4, 5], the current findings contradict some studies that show significant experience-dependent neuroadaptation. For example, Brefczynski-Lewis reported that long-term meditators showed higher attention stability and higher neural efficiency [6]. However, no similar effect was observed in this study, which may be due to the low duration or intensity of the practice, or the fact that the meditation techniques used are different from those used in other studies or are not universal in all meditation states. Cahn and Polich [7] remind that state-dependent regulation may lead to instantaneous changes in EEG activity instead of continuing to reflect stable, characteristic-level neural adaptation. Therefore, the difference in EEG results we observed may not be stable trait level characteristics. In addition, Frederick Travis and R. Keith Wallace proved that different meditation exercises are related to different autonomic neuroregulation levels and electro encephalic activity [8]. So, the zero results observed in this study may also be attributed to task-specific effects or insufficient training duration and intensity. In a word, since we cannot determine whether the electroencephalogram is a stable characteristic level feature, and the duration and skills of practice may also be different from other related experiments, these may lead to the results of the experiment to contradict other relevant research results.

Finally, age is also an important factor affecting the characteristics of EEG related to meditation. Our study found that compared with young people, participants over the age of 40 showed increased δ wave and α wave activity, while the power of θ wave was reduced. These findings are consistent with the results of van Leeuwen's research. Van Leeuwen's research shows that the age difference in distraction is associated with the corresponding changes in the dynamics of EEG during meditation [9]. These studies show that short-term meditation exercises can enhance the self-regulation ability and attention control ability of people of all ages. Studies by Pagnoni and Cekic [10] show that older meditators show better attention performance and more complete gray matter than non-meditators of the same age. At the same time, aging will affect the distribution of attention, resulting in corresponding changes in the neurological oscillation pattern [11]. Unlike young people, older people may rely on compensatory adjustment strategies that emphasize calmness and continuous attention, rather than effortful centralized monitoring. This difference may indicate that there may be some additional nerve regulation mechanisms in the process of meditation. The enhancement of δ band activity may be due to the increase in the volume of the hippocampus in elderly meditators, which is associated with internal attention and deep relaxation [12]. The enhancement of α-band activity may be due to the elderly showing higher cortex activation in the process of integrated

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attention processing [13]. These mind-based interventions can enhance the attention and physical perception of the elderly, and they can also change their characteristic spectrum power patterns through attention compensation strategies. These findings show that adaptive neural reorganization may be a continuous process that runs through the entire life cycle, rather than the static result of meditation practice.

To comprehensively explain the neural effects of meditation, it is necessary to consider the dynamics of large-scale brain networks, rather than isolated regional or frequency-specific changes. In this study, we still have many limitations, such as limited meditation skills and practice time, and the actual spectrum of EG is not stable characteristic level characteristics. These will affect the final experimental data. In future research, we will still improve this problem and strive to make the experimental results more stable. At the same time, we will still explore the time evolution of these effects and their transformation significance in clinical intervention and neurorehabilitation in future studies.

5. Conclusion

This study explored meditation-related brain activity using EEG data from participants with different genders, ages, and levels of meditation experience. The results showed that gender and age were associated with differences in EEG power across several frequency bands, while no significant differences were observed between novice and experienced meditators. These findings suggest that meditation is linked to measurable neural activity changes, but the effects may vary across individuals. Future research with larger samples and more controlled meditation protocols is needed to further clarify the neural mechanisms underlying meditation and its potential benefits for cognitive and emotional functioning.

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