Tai Chi Improves Alpha Brain State: An EEG Power Spectra And Standardized Low-resolution Tomography Analysis

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Abstract

Background

Mindfulness meditation, including the resulting alpha brain state, is gaining attention as an adjunct to health. The effect of Tai Chi on physical and mental health has gained increasingly more attention worldwide. The Bafa Wubu of Tai Chi was recently developed for this reason. To implement the national strategy of "Healthy China 2030", we suggest using Tai Chi for improving the health of Chinese and additionally recommend it to the world.

Objectives

This paper aims to explore the effect of Tai Chi (Bafa Wubu of Tai Chi) on the alpha brain state of the brain and the different positive effects between Tai Chi (TC) and brisk walking (BW)

Methods

This paper reports a pilot study using resting EEG signals. 51 college students (male : female = 3:14, 3 groups had equal ratios of males and females) were grouped into the TC, the BW, or the Control group. The individuals' resting EEG signals were assessed before and after an 8-week training period.

Results

Two-way repeated measures ANOVA with 3 levels in the group factor (Group: TC, BW, Control) and 2 levels in the time factor (Time: pre-test, post-test) found that the TC group had significantly higher alpha1 and alpha2 power in the post-test than in the pre-test, and the BW and control groups had no significant differences. There was a significant difference in the alpha1 and alpha2 power between the three groups in the post-test, with those of the TC group being the highest. The alpha1 rhythm source localization was Brodmann Area 39 in the TC group. There was no significant difference in the alpha1 rhythm source localization result between the BW and control groups.

Conclusions:

Tai Chi emphasizes harmony between mind and body. A "calm mind and relaxed body" constitutes the most basic principle of Tai Chi. Tai Chi improves the alpha brain state. Through 8 weeks of Tai Chi exercise, the participants showed positive improvements in the brain state. Brodmann Area 39 has a strong current density and neuronal oscillations. The positive effect of Tai Chi is better than that of brisk walking. Tai Chi has its own unique advantages.

Keywords

Tai Chi, EEG power spectra, sLORETA, alpha brain state

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Introduction

An alpha brain state (indicative of a relaxed mind) enhances learning as well as psychological and physical wellbeing; the novel opportunity to 'view' that state enhances the likelihood of sustainable behavioral changes(1). Mindfulness meditation, which produces the alpha brain state, is gaining attention for the promotion of health(1). This state is called mindfulness. People are trained to see reality as it truly is by inducing a state of awareness and calmness, and in doing so, they reduce negative impacts of everyday stress and associated thoughts and anxieties. An expanding field, mindfulness art therapy, increased alpha and beta activity and decreased delta and theta EEG signals compared with a resting state [1, 2].

Tai Chi and Yoga are mindfulness exercises. Over the last decade, mindfulness meditation has grown in popularity, and the concurrent observation of the changes in the alpha brain waves are an important therapeutic tool for mental health practitioners when working with people with depression and anxiety disorders in particular using techniques such as art therapy[2], tai chi, yoga [2] and positive affirmations. The body of literature demonstrating the effectiveness of these interventions for medical and psychological disorders, such as sleep, pain[3] and cancer [4,5], is increasing.

Previous research has demonstrated the beneficial effects of skills training[6] and meditation[7] on neuropsychological difficulties. However, the mechanisms by which Tai Chi benefits the brain remain unclear. A recent review of TC research[8] detailed the benefits for physical functioning, psychological well-being, and cognitive functioning [9, 10] (i.e., attention) that have been reported in research studies to date. Practicing Tai Chi has been reported to benefit memory, emotion, executive function [11-13] and attention [10, 14-16].

EEG is widely used in the field of cognitive neuroscience because of its high temporal resolution. More recently, EEG spectral power has been used to study the coherence between distributed brain regions, for example, alpha bands [17].

Due to its valuable cultural heritage, Taijiquan (tai chi) is inextricably related to subjects such as traditional Chinese philosophy, traditional regimens, traditional medicine, classical aesthetics and common ethics. It can not only strengthen peoples' bodies and be used in self-defense, but also promote harmony between the mind-body and advance interpersonal exchanges, which makes it a major part of sports culture with Chinese characteristics[18]. Tai Chi, a multimodal mind-body exercise integrating gracefulness, mindfulness, and gentleness, is a form of traditional Chinese exercise that involves physical activity, cognitive control, and social interaction when practiced in a group. It combines the coordination of slow movements with mental focus, deep breathing, and relaxation. It can be practiced without special facilities or expensive equipment and can be performed either individually or in groups.

To achieve scientific, standardized and simplified principles, the Bafa Wubu of Tai Chi was systematically refined on the basis of the existing 24-form Tai Chi. It evolves around the most common core techniques of "Bafa Wubu of Tai Chi " and two exercise forms, "standing" and "marching", thus forming a set of Tai Chi routines that are characterized by its culture, fitness and simplicity. With simple movements, a reasonable number of postures, and philosophical roots in traditional Chinese culture and medicine, Bafa Wubu of Tai Chi has been developed into a more simplified and ideal introductory Tai Chi routine launched after the 24-form Tai Chi.

On the basis of this burgeoning interest, the pilot study detailed herein was designed as a preliminary step in evaluating Tai Chi as a potential intervention to improve neuropsychological abilities in college students' alpha brain state. Whether Tai Chi's effect on the alpha brain state is superior to an exercise regimen of brisk walking remains unclear and deserves further discussion.

This paper explores the benefits of Tai Chi (Bafa Wubu of Tai Chi) by measuring resting EEG signals for the augmentation of alpha brain states.

Materials and Methods

Participants

51 healthy undergraduate and graduate students (9 males, 42 females, male:female ratio = 3:14) participated in our experiments as paid volunteers. The ratio of males to females in the three groups were the same.

The demographic data for the participants were as follows: 1) average age of 22±2 years; 2) right-handed; 3) Han Chinese ethnic group; 4) absence of a personal or family history of neuropsychiatric disorder and are in good mental status at time of study; 5) absence of drug abuse; 6) normal vision or normal vision after correction and the absence of color blindness or color weakness; 7) the ability to participate in and complete the experiment in a timely manner.

The study protocol was approved by the Institutional Review Board of the Brain Imaging Center of the State Key Laboratory of Cognitive Neuroscience and Learning at Beijing Normal

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University. All of the participants signed an informed consent form for the EEG experiment. The written informed consent was obtained from all participants and/or their legal guardians after the experimental procedures were fully explained to them.

Exercise Intervention and Experimental Procedures

The Tai Chi (TC) group performed Bafa Wubu of Tai Chi exercises for 8 weeks. The brisk walking (BW) group performed brisk walking collective exercises for 8 weeks. The Control group was instructed to maintain their original daily routines for 8 weeks.

The Bafa Wubu of Tai Chi Intervention Program

Bafa Wubu of Tai Chi was systematically defined by the General Administration of Sports in China on the basis of the existing 24-form Tai Chi, which revolves around the most common and core techniques of "Bafa Wubu of Tai Chi", namely, 8 elements hand techniques, including PENG (warding off), LU (rolling back), JI (pressing), AN (pushing), CAI (pulling down), LIE (splitting), ZHOU (elbowing) and KAO (shouldering), and 5 steps techniques, including JIN (advancing), TUI (retreating), GU (shifting left), PAN (shifting right) and DING (central equilibrium), thus forming a set of Tai Chi routines that are characterized by culture, fitness and simplicity.

The Tai Chi intervention group performed the Bafa Wubu of Tai Chi collective exercises 3 times/week for 8 weeks.

Each training session consisted of a 5-minute warmup, a 50-minute continuous sequential practice of the Tai Chi routines, and a 5-minute cool down. It takes approximately 3 minutes to complete the whole Tai Chi routine. The whole routine was repeated 11-14 times in each training session. A polar watch (Polar Electro Oy, Kempele, Finland) was used to monitor participants' heart rates during the exercise sessions, and we found that the intensity of the 50-minute continuous TC practice reached moderate intensity in approximately 60% of the individual participants and thus could be considered moderate intensity (60% to 69% HRmax) endurance exercise according to the classification of American College of Sports Medicine.

The Brisk Walking Intervention Program

The Brisk Walking group (BW) performed brisk walking collective exercises 3 times/week for 8 weeks. Mirroring the TC group, each training session consisted of a 5-minute warmup, a 50-minute continuous sequential practice, and a 5-minute cool down. As in the TC group, a polar watch was used to monitor the participants' heart rate during the exercise sessions, and we found that the intensity of the 50-minute continuous BW practice reached moderate intensity in approximately 62% of the individual participants and thus could be considered moderate intensity (60% to 69% HRmax) endurance exercise.

The Control group

The control group was instructed to maintain their original daily routines and physical activity habits and to not perform any new or additional exercise interventions.

EEG recording and preprocessing

The electroencephalography (EEG) signals were recorded continuously from 64 active Ag/AgCl scalp electrodes that were mounted in a preconfigured elastic cap (NeuroScan, Inc.) and labeled according to the extended 10–20 system. 5 minutes of eyes-closed resting-state EEG was recorded at a sampling rate of 1000 Hz. The EEG recordings of all the participants were monitored throughout the sessions to ensure that they followed the instructions and did not show signs of drowsiness. The participants were instructed to relax, avoid movements, not think about anything and remain awake. All participants underwent the resting-state EEG recordings in a noiseless, dimly lit laboratory room at Beijing Normal University.

To detect eye movements and blinks, the EOG was recorded from electrodes placed at the outer canthi of each eye and above and below the right eye. All electrodes, except those used for monitoring eye movements, were physically referenced to the left mastoid and were then off-line re-referenced to the average of the left and right mastoids. Electrode impedance was kept below 5 kΩ. The EEG signals were amplified with AC-200 Hz, digitized online at a sampling interval of 1 ms and then offline filtered with a digital bandpass filter between 0.1 and 30 Hz.

EEG Data analysis

The acquired EEG signals were preprocessed using MATLAB and the EEGLAB toolbox.

First, the data were re-referenced to the mastoid channels and then low-pass-filtered and bandpass-filtered between 0.1 and 30 Hz to exclude very low-frequency artifacts and line noise. Data portions contaminated by eye movements, electromyography, or any other non-physiological artifacts were corrected using the independent component analysis algorithm [19,20]. Then, the pre-processed continuous EEG data were segmented into dozens of epochs, with an epoch length of 2000 ms. All further analyses were conducted for the alpha1

(10-13 Hz) and alpha2 (13-19 Hz) frequencies.

Standardized low-resolution tomography analysis
Based on the scalp-recorded electrical potential distribution, standardized low resolution tomographic analysis (sLORETA) (http://www.uzh.ch/keyinst/loreta.htm) was used to compute the cortical 3D distribution of the current density for the early and late CNV between the participant groups (TC, BW and Control). The sLORETA method provides a solution for the EEG inverse problem with the assumption that neighboring neuronal sources are similarly activated. This method is followed by a standardization of the current density to produce images of the electric neuronal activity [21]. Specifically, sLORETA was used to compute the intracerebral current density distribution based on voxel-by-voxel paired sample t tests of the 3D sLORETA images. To identify the possible differences in the brain, built-in voxel-wise randomization tests (5000 permutations) that were based on statistical nonparametric mapping and corrected for multiple comparisons were performed [22].

Statistical Analysis
Two-way repeated measures ANOVA was performed with 3 levels in the group factor (Group: TC, BW, Control) and 2 levels in the time factor (Time: pre-test, post-test) to assess: 1) homogeneity; 2) differences in exercise intensity; 3) differences in alpha1 rhythm power pre- and post-test; 4) differences in alpha2 rhythm power pre- and post-test; 5) alpha1 rhythm source localization. $p<0.05$ was considered statistically significant. Statistical analyses were performed using MATLAB 2017b (MathWorks, Natick, MA, USA), EEGLAB(https://sccn.ucsd.edu/wiki/EEGLAB), FILEDTRIP, and sLORETA software.

Results

Homogeneity Test
There were no significant differences between the three groups in terms of the participants' sex, age, handedness, average years of education, and body mass index (BMI) (Table 1). We observed homogeneity in the three groups in terms of the age [$F_{(2,48)}$=0.112, P=0.894>0.05], average years of education [$F_{(2,48)}$=0.173, P=0.841>0.05], and body mass index (BMI) [$F_{(2,48)}$=0.979, P=0.383>0.05]. The three groups (TC, BW, Control) were homogeneous before the exercise intervention.

Table 1 Sample Characteristics

Items	**TC**	**BW**	**Control**	**F**	**P**
	M(SD)	M(SD)	M(SD)		
Sex (Male/Female)	3/14	3/14	3/14	–	–
Age (years)	20(2)	22(3)	22(2)	0.112	0.894
Handedness (Left/Right)	0/17	0/17	0/17	–	–
Education (years)	16(1)	16(1)	16(1)	0.173	0.841
BMI (kg/m^2)	22.32(1.41)	23.01(2.09)	22.23(1.75)	0.979	0.383

Exercise Intensity Monitoring
The average heart rate of the Tai Chi (TC) group was controlled at - 118 beats per min (bpm) during the 8-week exercise intervention. The average heart rate of the Brisk Walking (BW) group was controlled 119 bpm during the 8-week exercise intervention. A chart of the average monitored heart rate of each group is shown in Fig. 1.

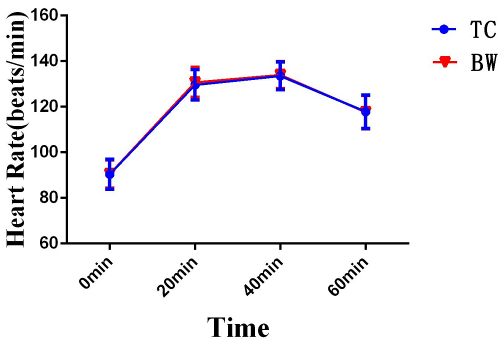

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Fig. 1 Average heart rates of the Tai Chi (TC) group and the BW group

The difference in alpha1 rhythm power pre- and post-test

The frequency domain of the alpha1 rhythm ranges from 10 Hz to 13 Hz. The occipital lobe and the posterior region of the head produce alpha waves.

In terms of the Oz measures, repeated measures analysis of variance revealed that the main effect of time was significant [$F_{(1,49)}=9.38, \eta_p^2=0.095, P=0.028<0.05$], indicating that the alpha1 wave power was greater in the post-test than in the pre-test. The main effect of group was significant [$F_{(2,49)}= 9.778, \eta_p^2=0.095, P=0.0000<0.01$], indicating that the alpha1 wave power was different in the three groups. The interaction between time and group was significant [$F_{(2,49)}=12.837$, $\eta_p^2=0.344$, $P=0.000<0.001$].

From an additional simple effect analysis, we found that there was a significant difference between the three groups under the post-test [$F_{(2,49)}=20.51$, $P=0.000<0.001$]. There was no significant difference between the three groups under the pre-test [$F_{(2,49)}=0.08$, $P=0.928>0.05$]. These data further demonstrate that the alpha1 wave power of the Tai chi group was greater in the post-test than in the pre-test [$F_{(1,49)}=29.89$, $P=0.000<0.001$]. No other effects were significant in the BW [$F_{(1,49)}=0.04$, $P=0.835>0.05$] and control groups [$F_{(1,49)}=1.49$, $P=0.228>0.05$] (Fig. 2).

In terms of the POz measures, repeated measures analyses of variance revealed that the main effect of time was significant [$F_{(1,49)}=4.972, \eta_p^2=0.092, P=0.03<0.05$], indicating that the alpha1 wave power was greater in the post-test than in the pre-test. The main effect of group was significant [$F_{(2,49)}= 10.462, \eta_p^2=0.299, P=0.0000<0.01$], indicating that the alpha1 wave power was different in the three groups. The interaction between time and group was significant [$F_{(2,49)}=12.935$, $\eta_p^2=0.346$, $P=0.000<0.001$].

From an additional simple effect analysis, we found that there was a significant difference between the three groups under the post-test [$F_{(2,49)}=21.85$, $P=0.000<0.001$]. There was no significant difference between the three groups under the pre-test [$F_{(2,49)}=0.02$, $P=0.977>0.05$]. These data further demonstrate that the alpha1 wave power of the Tai chi group was greater in the post-test than in the pre-test [$F_{(1,49)}=29.44$, $P=0.000<0.001$]. No other effects were significant in the BW [$F_{(1,49)}=0.00$, $P=0.982>0.05$] and control groups [$F_{(1,49)}=2.03$, $P=0.161>0.05$] (Fig. 2).

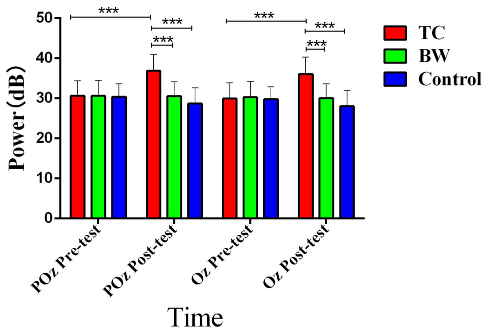

Fig. 2 Changes in alpha1 rhythm power from the pre-test to the post-tes

Table 2 Repeated measures ANOVA of the **alpha1** rhythm power

	Interaction	Type III Sum of Squares	df	mean square	F	P	η_p^2
Oz	Time	65.506	1	65.506	5.116	0.028*	0.095
	Group	323.501	2	161.750	9.778	0.000***	0.285
	Time* Group	328.693	2	164.347	12.837	0.000***	0.344
POz	Time	59.395	1	59.395	4.972	0.030*	0.092
	Group	337.708	2	168.854	10.462	0.000***	0.299
	Time* Group	309.038	2	154.519	12.935	0.000***	0.346

NOTE: 95% CI corresponds to the lower and upper 95% confidence limits. *Significant at $p < .05$. **Significant at $p \le .01$. ***Significant at $p \le .001$.

Table 3 Repeated measures ANOVA of **alpha2** rhythm power

	Interaction	Type III Sum of Squares	df	mean square	F	P	η_p^2
Oz	Time	62.145	1	62.145	4.289	.044*	.080
	Group	377.256	2	188.628	11.562	.000***	.321

	Time* Group	268.189	2	134.094	9.254	.000***	.274
	Time	55.273	1	55.273	4.141	.047*	.078
POz	Group	397.555	2	198.777	12.419	.000***	.336
	Time* Group	251.335	2	125.667	9.415	.000***	.278

NOTE: 95% CI corresponds to the lower and upper 95% confidence limits. *Significant at $p < .05$. **Significant at $p \leq .01$. ***Significant at $p \leq .001$.

The difference in alpha2 rhythm power pre- and post-test

The frequency domain of the alpha2 rhythm ranges from 13 Hz to 19 Hz. In terms of the Oz measures, repeated measures analyses of variance revealed that the main effect of time was significant [$F_{(1,49)}$=4.289,η_p^2=0.08,P=0.044<0.05], indicating that the alpha1 wave power was greater in the post-test than in the pre-test. The main effect of group was significant [$F_{(2,49)}$= 11.562,η_p^2=0.321,P=0.0000<0.01], indicating that the alpha1 wave power was different in the three groups. There was a significant time×group interaction [$F_{(2,49)}$=9.254, η_p^2=0.274, P=0.000<0.001].

From an additional simple effect analysis, we found that there was a significant difference between the three groups under the post-test [$F_{(2,49)}$=19.46, P=0.000<0.001]. There was no significant difference between the three groups under the pre-test [$F_{(2,49)}$=0.27, P=0.763>0.05]. These data further demonstrate that the alpha1 wave power of the Tai chi group was greater in the post-test than in the pre-test [$F_{(1,\ 49)}$=22.51, P=0.000<0.001]. No other effects were significant in the BW [$F_{(1,49)}$=0.04, P=0.845>0.05] and control groups [$F_{(1,49)}$=0.74, P=0.394>0.05] (Fig. 3).

In terms of the Oz measures, repeated measures analyses of variance revealed that the main effect of time was significant [$F_{(1,49)}$=4.141,η_p^2=0.078, P=0.047 < 0.05], indicating that the alpha1 wave power was greater in the post-test than in the pre-test. The main effect of group was significant [$F_{(2,49)}$=12.419, η_p^2=0.336, P=0.000 <0.001], indicating that the alpha1 wave power was different in the three groups. The interaction between time and group was significant [$F_{(2,49)}$=9.415, η_p^2=0.278, P=0.000<0.001].

From an additional simple effect analysis, we found that there was a significant difference between the three groups under the post-test [$F_{(2,49)}$=20.91, P=0.000<0.001]. There was no significant difference between the three groups under the pre-test [$F_{(2,49)}$=0.33, P=0.724>0.05]. These data further demonstrate that the alpha1 wave power of the TC group was greater in the post-test than in the pre-test [$F_{(1,49)}$=22.30, P=0.000<0.001]. No other effects were significant in the BW [$F_{(1,49)}$=0.00, P=0.983>0.05] and control groups [$F_{(1,49)}$=1.16, P=0.288>0.05] (Fig. 3).

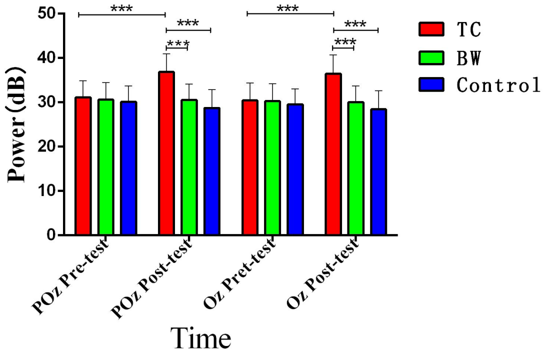

Fig. 3 Changes in the alpha2 rhythm power pre- and post-test

Table 4 Alpha1 rhythms Source Localization list

	Anatomy(Brodmann area)	Cerebral hemisphere	MNI X	MNI Y	MNI Z	t	P
Temporal lobe	39	left	-30	-60	25	2.258	0.0238*

The result of Alpha1 rhythm Source Localization

We used sLORETA for the source localization analysis. Due to the lack of MRI structural images of the subjects, we adopted the default MNI template as the template for the brain structural images.

The TC group showed significant differences, while the BW and control groups showed no significant differences. Compared to the BW and control groups, the TC group showed a widespread increase in alpha 1 rhythm sources (Fig. 4).

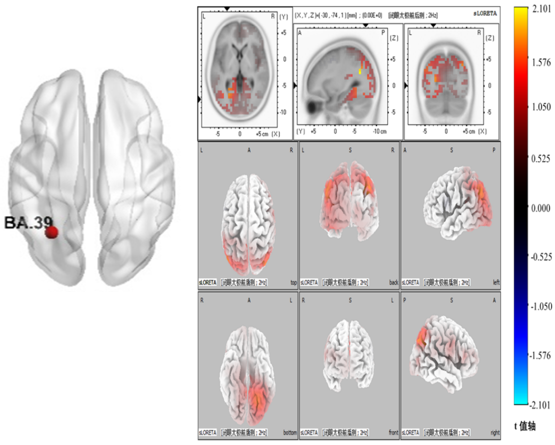

Fig. 4 The anatomy map of alpha1 rhythm source localization with statistically significant differences. The corresponding t value of the blue section is negative, indicating that the post-test current density is smaller than the pre-test current density. The red section corresponds to a positive t value, indicating that the post-test current density is higher than the pre-test current density.

The alpha1 rhythm source localization result indicated that the probe increased the ampere density of alpha1 rhythm in the left hemisphere and was located in MNI (X=-30, Y=-60, Z=25) (Fig. 3). The alpha1 rhythm ampere density in the post-test was significantly stronger than that in the pre-test ($t=2.258$, $P=0.0238<0.05$, corrected for multiple comparisons). This finding indicates that this brain area has a stronger current density and neuronal oscillations.

This brain area is Brodmann Area 39. The angular gyrus is a cortical area involved in cross-model association among somatosensory (body knowledge) information, auditory information, and visual information. In addition, area 39 seems to also participate in an executive function brain circuitry, and it activates during tasks such as those involving verbal creativity, inferential reasoning and processing sequences.

There was no significant difference in the alpha2 rhythm source localization results.

Discussion

Tai Chi's improvements in body-mind health remain poorly understood and are still controversial. Here, by recording resting EEG signals from human adults, we revealed how Tai Chi improves the alpha brain state. We explored the differences in the alpha brain state of the Tai Chi, BW and control groups. Our results indicate that alpha rhythm power increases in the post-test compared with the pre-test. The TC group's alpha1 rhythm source localization result is Brodmann Area 39.

Tai Chi stems from the Taoist principle called the unity of people and nature, in which people are trained to see reality as it truly is by inducing a state of awareness and calmness, and in doing so, they can reduce the negative impacts of everyday stress anxieties. "Relaxed" and "calm" are the basic rules by which Tai Chi practitioners must abide.

"Relaxed" concerns the body externally, while "calm" emphasizes the body internally and psychologically, developing the requirements for a "calm mind and relaxed body" in Tai Chi. The "relaxed" state refers to a state without tension inside and outside of the body. It is the basis and guarantee for correct postures, coordination of the whole body, stretching in movements and flexible transformation. Therefore, the "relaxed body" state in Tai Chi cannot be simply understood as a "loose", "limp" or a feeble state. Creating the "calm mind" means eliminating any distractions and concentrating one's attention, being completely absorbed in the Tai Chi practice, so Tai Chi practitioners are in an exceedingly tranquil, relaxed and comfortable state. In this way, each action can be guided by yi (mind) with focused attention to complete a movement in the correct and full manner. Thus, it can be seen that the "calm mind and relaxed body" constitutes the most basic principle of Tai Chi [18].

Brain oscillations are closely associated with a range of cognitive tasks [23]. EEG alpha oscillations are the single most salient feature of the waking electroencephalography signals [24]. Alpha rhythms are a biomarker [1] for a relaxed mind, which plays an important role in the "calm mind and relaxed body" state. Among all the EEG spectral components, the delta and alpha rhythms are the reliable indices of cortical inhibition not only during sleep but also in an awake state in adult individuals who are not engaged in specific cognitive tasks [25-29]. Additional studies that explore the effect of Tai Chi exercise on mental health should be conducted on the research of the alpha brain state.

Brodmann Area 39 has a strong current density and neuronal oscillations. Compared to general Brisk Walking, Tai Chi is a multimodal mind-body exercise that emphasizes the importance of the "relaxed" state. The mind-body interaction is emphasized during Tai Chi performance. Brisk Walking is a cyclical movement that involves changes: emptiness and fullness, strength and softness, movements forward and backward, and action and serenity [30]. This alpha brain state can introduce positive effects for sustainable subconscious-driven behavior changes[1].

Conclusion

Our experiment provides novel, strong, and converging neurophysiologic evidences that Tai Chi can improve the alpha brain state. In other words, Tai Chi promises to be a useful adjunct for the development of alpha brain states in people desiring to change behaviors, such as their diet or exercise, or their level of stress, anxiety or depression. The positive effect of Tai Chi is better than that of Brisk Walking. Tai Chi has its own unique event advantages.

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Declaration of Interests

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Appendix

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Authors' contributions

H.C.Y. conceived the experiment and wrote the manuscript;
X.J.L. designed the experiment, participated in exercise intervention, collected the data, analysed the data and wrote the manuscript; L.C. participated in exercise intervention, collected the data; Y.W. participated in exercise intervention, and collected the data; J.L., Y.F.L., Q.Q.S., J.Y.Z. and D.L.W. participated in exercise intervention and collected the data. All authors reviewed the manuscript.

Abbreviations

EEG: Electroencephalogram

Ethics approval and consent to participate

The study protocol was approved by the Institutional Review Board of the Brain Imaging Center of the State Key Laboratory of Cognitive Neuroscience and Learning at Beijing Normal University. All of the participants signed an informed consent form for the EEG experiment. The written informed consent was obtained from all participants and/or their legal guardians after the experimental procedures were fully explained to them.

Consent for publication

Not applicable.

Availability of data and materials

The datasets used and analysed during the current study are available from the corresponding author upon reasonable request.

Competing interests

The authors declare that they have no competing interest.

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