Functional Magnetic Resonance Imaging Reveals Taiji's Real-time Effects on Neuronal Networks of the Brain

Phillip H. Kuo, Xintuo Zhang, Carol Stuehm, Ying-hui Chou, and Nan-kuei Chen

Abstract

Background
Taiji has beneficial effects on physical and mental health. While various traditional metrics have been applied to assess physical improvement from taiji, measuring changes in the brain to ascertain the etiology of benefits to mental health is not as straightforward. Recently, functional magnetic resonance imaging (fMRI) has been applied to the study of taiji. In this study, we measure real-time changes of neuronal networks reflecting mental taiji exercise inside an MRI scanner.

Methods
On four different days, fMRI data were acquired from a healthy volunteer with expertise in taiji. During each session, four sets of 4D fMRI data were obtained alternating between the pure resting and mentally practicing taiji states. Data were analyzed to identify intrinsic connectivity networks and brain regions that demonstrated significant difference in functional connectivity between pure-resting and mental taiji-practicing conditions.

Results
Differences in functional connectivity between pure-resting and mental taiji-practicing conditions were found in the visual, sensorimotor and default mode networks. Specifically, in regard to the default mode network (DMN), the precuneus and right angular gyrus showed relatively decreased activity during the mental taiji-practicing condition.

Conclusions
fMRI signal changes in the visual, sensorimotor and default mode networks during the mental practice of taiji may have implications for uncovering the neural mechanisms underlying the benefits of taiji.

Keywords
Tai Chi; fMRI

Funding

Registration
This study protocol was approved by the local institutional review board.

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Introduction

Numerous studies have demonstrated that taiji has beneficial effects on physical and mental/psychological health. More recently, research has delved beyond just the "if" and into the "how" taiji exerts these positive effects on well-being. Prior studies utilizing magnetic resonance imaging (MRI) to study the effects of taiji on the brain have measured subjects pre and post training or comparison of practitioners with matched cohorts [1, 2]. MRI can exquisitely delineate the anatomy of the brain and thus has been used to show that taiji practitioners have increased cortical volume in specific regions of the brain compared to controls [3].

Functional MRI (fMRI) commonly refers to blood oxygenation level dependent (BOLD) imaging which takes advantage of the tight coupling between brain activity and hemodynamic responses to localize changes in brain activity. fMRI can be performed at rest or during performance of a specific task. The brain's activities are divided into various networks that span across multiple anatomical regions of the brain. fMRI has been utilized to try to decipher the specific regions of the brain responsible for the mental/psychological effects of practicing taiji [4, 5]. The default mode network (DMN) and dorsal prefrontal-angular gyri network were identified as connectivity networks that differed between taiji practitioners and healthy controls (Wei 2017). The DMN is generally most active in the awake, resting state. It is a critical network, and, for example, dysfunction of the DMN occurs with the most common neurodegenerative disease, Alzheimer's disease [6, 7].

Unlike prior published fMRI studies which acquired imaging of patients before and after training, in this study, we acquired data in two conditions, while the participant was asked to either mentally practice taiji or rest within an MRI scanner, aiming to identity changes of neuronal connectivity network that are specific to mental taiji practicing.

Methods

MRI data acquisition

Using a 3 Tesla Siemens MRI system, functional MRI (fMRI) data were acquired from a healthy adult volunteer, who has been performing taiji for > 15 years. Specifically, whole-brain fMRI data sensitive to the BOLD contrast were obtained with a single-shot gradient-echo echo-planar imaging pulse sequence with the following scan parameters: TR = 3 sec; TE = 30 msec; voxel size = 2 mm isotropic; in-plane parallel imaging acceleration factor = 2; through-plane acceleration (i.e., multi-band or simultaneous multi-slice) factor = 2; and the number of time points for each 4D data set = 100 (with scan time = 5 min). T1-weighted structural images were obtained with the MP-RAGE pulse sequence.

Taiji protocol

Our adult volunteer participated in the imaging study on 4 different days within 6 weeks. On day 1 and day 3 of the experiments, 4 sets of 4D fMRI data (scan time = 5 min for each data set) were obtained with the following order: 1) pure resting; 2) mentally practicing taiji; 3) pure resting; 4) mentally practicing taiji. On day 2 and day 4, the order was changed to 1) mentally practicing taiji; 2) pure resting; 3) mentally practicing taiji; 4) pure resting. By staggering starting with rest or taiji, a potential ordering bias was eliminated. During rest, the subject was instructed specifically not to meditate. During rest and the mental practice of taiji, the volunteer was instructed to stay motionless with eyes closed.

Data Processing

The acquired 16 data sets were pre-processed with the standard resting-state fMRI analysis pipelines. First, the acquired fMRI data were aligned to the first image in the time-series, to correct for subtle movement. Second, the aligned time-series data were low-pass filtered (cutoff: 0.1 Hz). The linear drift of time-series signals was also corrected on a pixel-by-pixel basis. Third, the filtered images were smoothed (with a 4 mm x 4 mm x 4 mm full-width-at-half-maximum Gaussian kernel) and normalized to the Montreal Neurological Institute (MNI) coordinates. The pre-processed data were then jointly analyzed with independent component analysis (ICA) using the FSL-Melodic software package, to identify major intrinsic connectivity networks across 16 data sets (comprising both pure-resting and mental taiji-practicing conditions). Afterward, a dual-regression analysis was further performed to identify brain regions that demonstrated statistically significant difference in functional connectivity between pure-resting and mental taiji-practicing conditions. Differences were identified (corrected at $p < 0.05$) with multiple comparisons corrected by FSL-Melodic's threshold free cluster enhancement (TFCE). To further examine more subtle difference in fMRI signals between pure-resting and mental taiji practicing conditions, we ran an exploratory analysis with a less rigorous statistical threshold (at one-tailed uncorrected $p < 0.005$).

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Results

Independent component analysis

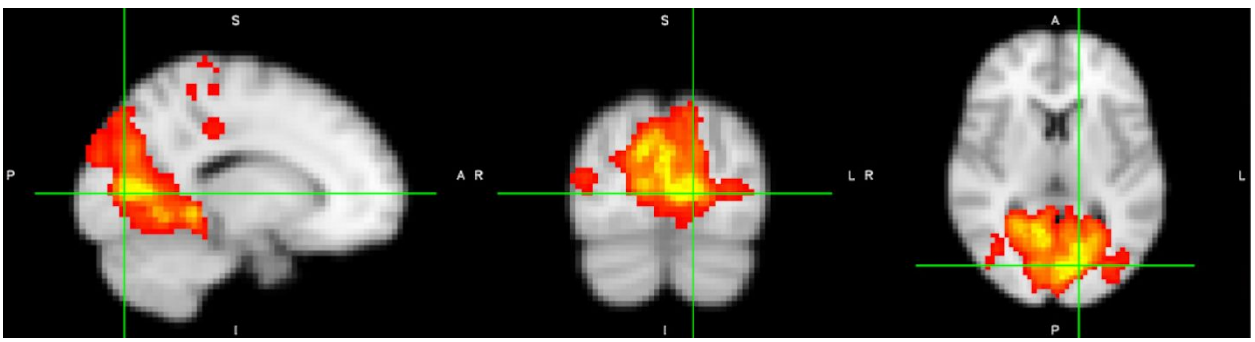
The analyses of the fMRI data from all 16 data sets (8 resting and 8 mentally practicing taiji) using ICA identified major intrinsic connectivity networks. The identified ICA components, including the occipital region (Fig. 1A), pre- and post-central gyri (Fig. 2A), as well as precuneus, medial prefrontal cortex, and angular gyrus (Fig. 3A), correspond to the visual, sensorimotor and default mode networks, respectively.

Dual-regression analysis

Dual-regression analysis was then used to identify brain regions with statically significant differences (corrected $p < 0.05$) between pure-resting and mental taiji-practicing conditions. As shown with blue color in Fig. 1B, clusters within the visual network showed a statically significant difference between pure-resting and mental taiji-practicing conditions (i.e., pure-resting > taiji).

When lowering the statistical threshold to one-tailed uncorrected $p < 0.005$ in an exploratory analysis, subtler differences between pure-resting and mental taiji practicing conditions were revealed in two networks. First, the pre- and post-central gyri of the sensorimotor network showed difference (green color in Fig. 2B: pure-resting > taiji). Second, the precuneus of the default mode network showed greater activity at rest compared with mental practice of taiji (green color in Fig. 3B). A reduction of activity with taiji is also seen in a gyrus in the right angular gyrus (yellow arrow in Fig. 3B).

1A



1B

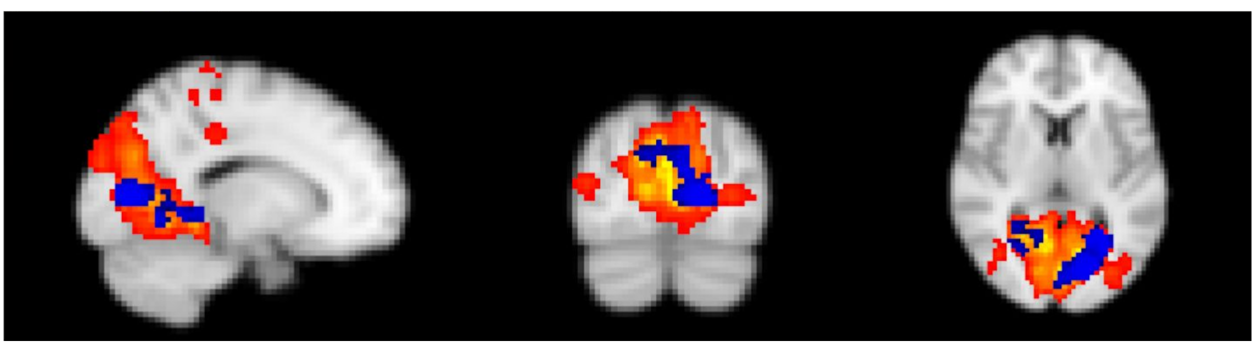


Figure 1: A) ICA identified the visual network in the occipital region (shown in orange-red and marked by crosshairs). B) In the occipital region, dual-regression analysis shows a statically significant difference between pure-resting and mental taiji-practicing conditions, shown in blue (corrected $p < 0.05$ for pure-resting> taiji, with multiple comparisons corrected by FSL's threshold free cluster enhancement).

2A

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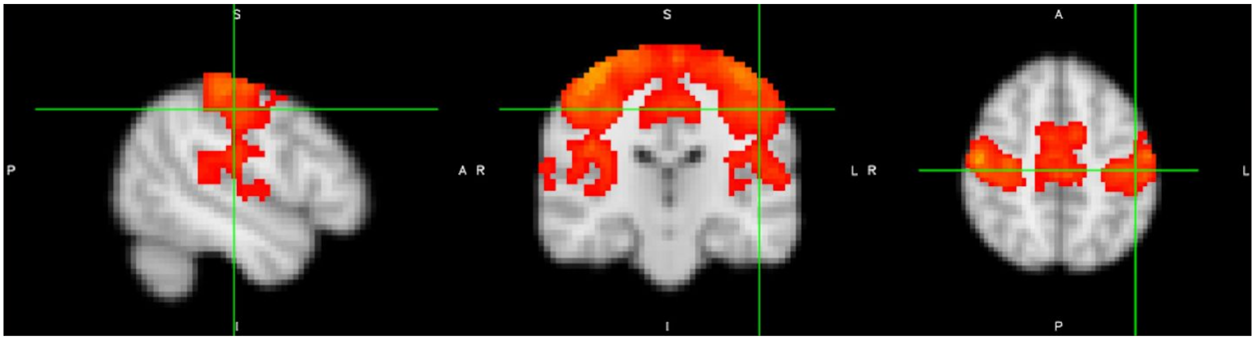


2B

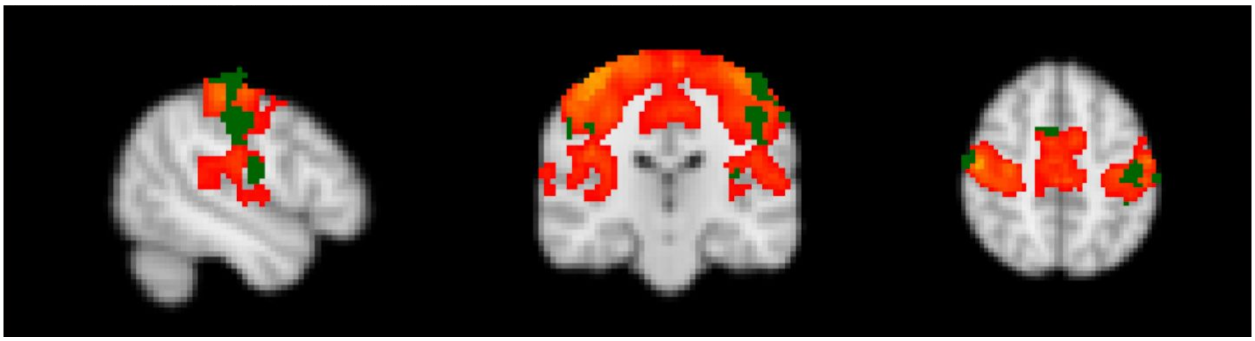
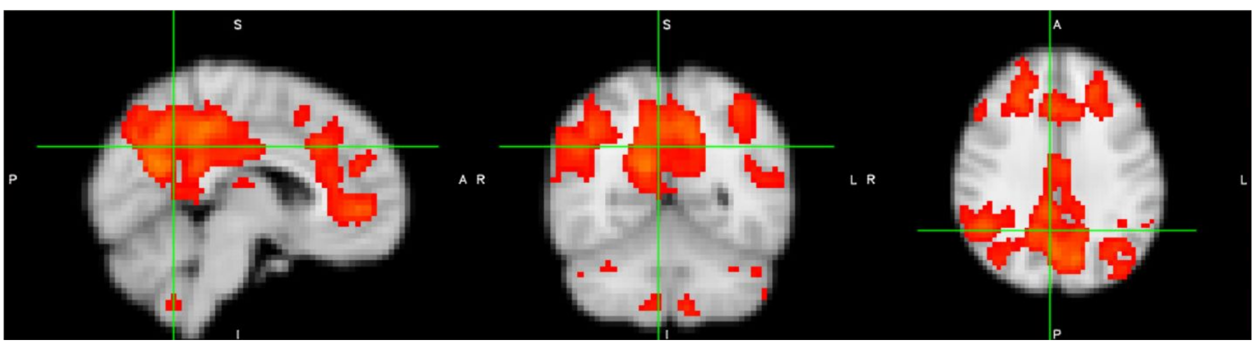


Figure 2: A) ICA identified the sensorimotor network in the pre- and post-central gyri (shown in orange-red and marked by crosshairs). B) In the pre- and post-central gyri, dual-regression analysis showed a difference between pure-resting and mental taiji-practicing conditions, shown in green (one-tailed uncorrected $p < 0.005$; for pure-resting> taiji).

3A



3B

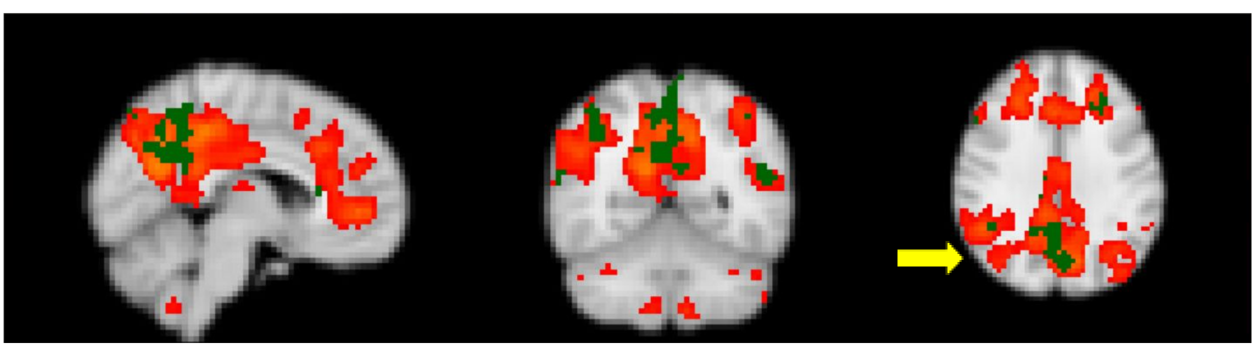


Figure 3: A) ICA identified the precuneus, medial prefrontal cortex, and angular gyrus (shown in orange-red and the precuneus is marked by crosshairs) of the default mode network. B) In the precuneus, dual-regression analysis showed a

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difference with greater activity at rest compared to taiji (one-tailed uncorrected $p < 0.005$, shown in green). A difference is also seen in a gyrus in the right angular gyrus (yellow arrow).

Discussion

At first glance, it would seem that taiji with its complex movements would be incompatible with studying in real-time using fMRI which requires the subject to remain as still as possible. This study demonstrates the feasibility of using fMRI to study the real-time effects on the brain of mentally practicing taiji simulating true practice. In this study, the robust signals allowing ready identification of important brain networks likely relied at least to some degree on the subject's discipline and mastery of taiji. To address this limitation, a future project would be to perform fMRI on multiple taiji masters to assess the inter-subject variation. Then, their activation patterns could be used to generate a template to compare against taiji practitioners at different levels; therefore, the evolving changes in the brain with increasing mastery of taiji could be identified. It would also be very interesting to examine if different styles of taiji have different brain activation patterns.

Our fMRI data and whole-brain network analyses strongly suggested that the DMN is likely key in the mental engagement during taiji and potentially other types of internal martial art styles. A logical hypothesis is that the regular "exercise" of the brain through taiji contributes to the sustained changes in the DMN shown in taiji practitioners versus healthy controls [8]. Emotional awareness and meditative techniques such as mindfulness have also demonstrated a connection to the default-mode network [9, 10]. The importance of the DMN in brain health and disease (e.g., Alzheimer's dementia) suggests that fMRI may be a valuable research tool for understanding the effects of taiji, for example, on the aging brain. A significant change from rest to mental practice of taiji was also seen in a right superior parietal gyrus which interestingly appears to be in the region of the right superior parietal lobule which was found to be affected by mindfulness meditation [9].

The activation of the visual network (occipital region) is particularly interesting given the important context that the subject's eyes were closed the entire time (both at the pure resting state and while mentally practicing taiji). The fMRI analysis suggests that visualization during taiji practice is critical. The ability to internally visualize practice of taiji may be a critical milestone in mastery of taiji and thus an important network to monitor in practitioners of differing levels and/or as practitioners improve.

While activation of the sensorimotor network by the mental practice of taiji was likely to be expected for a taiji master, this network will also be critical for studying the progression to higher levels of taiji practice. Additionally, examining the engagement of the sensorimotor network during taiji will likely be important for distinguishing the effects on the brain from taiji versus mindfulness or yoga. Future work can also explore how taiji enhances the connection between the brain and body, not only the external but also the internal such as the immune system and sympathetic/parasympathetic nervous systems.

Conclusion

Functional MRI of the brain during the mental practice of taiji reveals the real-time activation of the visual, sensorimotor and default mode networks and thus provides insight into potential neural mechanisms underlying the benefits of taiji.

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Appendix

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Authors' contributions

Abbreviations

ACSM: American College of Sports Medicine
RPE: rating of perceived exertion.

Ethics approval and consent to participate

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 on reasonable request.

Competing interests

The authors declare that they have no competing interest.

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