Professional Chess Expertise Modulates Whole Brain Functional Connectivity Pattern Homogeneity and Couplings

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Abstract

Previous studies have revealed changed functional connectivity patterns between brain areas in chess players using resting-state functional magnetic resonance imaging (rs-fMRI). However, how to exactly characterize the voxel-wise whole brain functional connectivity pattern changes in chess players remains unclear, which could provide more convincing evidence for establishing the relationship between long-term chess practice and brain function changes. In this study, we employed newly developed whole brain functional connectivity pattern homogeneity (FcHo) method to identify the voxel-wise changes of functional connectivity patterns in 28 chess master players and 27 healthy novices. Seed-based functional connectivity analysis was used to identify the alteration of corresponding functional couplings. FcHo analysis revealed significantly increased whole brain functional connectivity pattern similarity in anterior cingulate cortex (ACC), anterior middle temporal gyrus (aMTG), primary visual cortex (V1), and decreased FcHo in thalamus and precentral gyrus in chess players. Resting-state functional connectivity analyses identified chess players showed decreased functional connections between V1 and precentral gyrus. Besides, a linear support vector machine (SVM) based classification achieved an accuracy of 85.45%, a sensitivity of 85.71% and a specificity of 85.19% to differentiate chess players from novices by leave-one-out cross-validation. Finally, correlation analyses revealed that the mean FcHo values of thalamus were significantly negatively correlated with the training time. Our findings provide new evidences for the important roles of ACC, aMTG, V1, thalamus and precentral gyrus in chess players and indicate that long-term professional chess training may enhance the semantic and episodic processing, efficiency of visual-motor transformation, and cognitive ability.

Introduction

Long-term skill acquisition and the repetitive rehearsal of skills can result in the representative neural structural and functional changes (Draganski et al. 2004, Gaser and Schlaug 2003a, Gaser and Schlaug 2003b, Maguire et al. 2000, Song, Ge, et al. 2020, Zou et al. 2012). Chess is seen as a typical example for an expertise task requiring domain-specific experience to study brain structural and functional plasticity. Resting-state functional magnetic resonance imaging (rs-fMRI) has been applied to investigate the changed intrinsically functional activities and interactions in chess players (Duan, He, et al. 2012, Duan, Liao, et al. 2012, Duan et al. 2014, Greicius et al. 2003, Song, Ge, et al. 2020, Song, Peng, et al. 2020, Wang, Zuo, et al. 2020). These findings suggested that chess experts differ from novice players in brain functional organization of local connections and global topologies.

To characterize the functional similarity, several data-driven methods have been proposed. Zang and colleagues (Zang et al. 2004) developed a regional homogeneity (ReHo) method using Kendall's coefficient concordance (KCC) (Kendall and Gibbons) to measure the similarity of the time series of a given voxel and its nearest 26 neighbors. Integrated local correlation (ILC) used for assessing the brain local coherence was introduced (Deshpande et al. 2009). Tomasi and Volkow proposed functional connectivity density (FCD) to further characterize the regionally functional homogeneity in human brains (Tomasi and Volkow 2010). Buckner and colleagues proposed the functional connectivity strength (FCS) as the average of the correlations between this voxel and all other voxels in the brain as the "degree centrality" (Buckner et al. 2009). Based on the ReHo and FCS methods, our previous studies explored the similarity of time series and identified the changed functional activities in chess players compared with novices (Song, Ge, et al. 2020, Song, Peng, et al. 2020). Although several different measurements have been proposed to characterize the similarities of time series and regionally functional activities in chess players, it remains largely unclear whether long-term and intensive practice of chess expertise can lead to the changed voxel-wise whole brain functional connectivity pattern similarity. Exploring the whole brain functional connectivity pattern similarity changes will provide more convincing evidence for localizing the exact functional modulation in chess players.

Whole brain functional connectivity homogeneity (FcHo) method is defined by measuring the similarity of whole brain functional connectivity pattern of a specific voxel with that of its nearest 26 neighborhood voxels, and is developed to better delineate the voxel-wise similarity of whole brain functional connectivity pattern (Wang, Xu, et al. 2018). This approach has been used to reveal the whole brain functional connectivity pattern abnormalities in depression and the neural mechanism of depression patients after electroconvulsive therapy (Wang, Ji, et al. 2020, Wang, Yu, et al. 2019). In this study, our goal was to reveal whether/how a large amount of chess practice alters the voxel-wise whole brain functional connectivity pattern similarity and functional couplings using FcHo and seed-based functional connectivity analysis methods. The rs-fMRI data of 28 chess players and 27 gender-, age- and education-matched novice players was acquired, and a voxel-wise FcHo map for each subject was calculated. The resting-state functional connections of the brain areas with changed FcHo were mapped to further reveal corresponding changed functional networks in chess players. Moreover, multivariate pattern analyses using linear support vector machine (SVM) was employed to test whether these altered neural indices can be served as markers for distinguishing the chess playing levels.

Materials And Methods

Participants

Twenty-eight chess players (female/male = 10/18, mean and standard deviation of age = 27.64 ± 9.15 years; mean and standard deviation of education = 13.43 ± 2.71 years) and 27 novice players (female/male = 15/12, mean and standard deviation of age = 26.37 ± 6.68 years; mean and standard deviation of education = 14.24 ± 3.06 years) were used in this study. This dataset was accessed from the "1000 Functional Connectomes Project" (http://fcon_1000.projects.nitrc.org/indi/pro/wchsu_li_index.html). These professional chess players had been seriously training regularly (training time: 4.17 ± 1.72h/day). The 27 gender-, age-, and education-matched novice players understand the rules and simple strategies of Chinese chess playing (gender: p = 0.14; age: p = 0.57; education: p = 0.31). No differences on observation skills or clear-thinking ability were found between these two groups (Li et al. 2015). All participants were right handed and had no history of psychiatric or neurological disorders. Written informed consent was obtained from each subject and approval was obtained through the local Institutional Review Board of the West China Hospital of

Sichuan University. The detailed information of this dataset can be found in a previous study (Li, et al. 2015).

Rs-fMRI data acquisition

The rs-fMRI data were acquired on a 3.0T Siemens Trio system at the MR Research Center of West China Hospital of Sichuan University, Chengdu, China. All MR scans were performed when subjects were relaxed with their eyes open and fixated on a cross-hair centered on the screen. A T2-weighted gradient echo planar imaging (EPI) sequence was used to collect the fMRI images. A total of 205 whole brain volumes were acquired using the following parameters: Repetition time (TR) = 2000 ms, Echo time (TE) = 30 ms, flip angle = 90°, axial slice thickness = 5 mm, with no gap, slice number = 30, voxel size = 3.75 × 3.75 × 5 mm^3.

Rs-fMRI dada preprocessing

The rs-fMRI images were preprocessed including the following steps. The first 10 volumes were removed to facilitate magnetization equilibrium effects, and the corrected time series was realigned to the first volume for head motion correction. All fMRI images were normalized to the Montreal Neurological Institute (MNI) EPI template and resampled to 3⊆3⊆3 mm^3. The fMRI images were smoothed using a Gaussian kernel of 6 mm full-width at half maximum (FWHM). Friston 24-parameter model of head motion, white matter, cerebrospinal fluid, and global mean signals were then regressed out and the functional images were filtered with a temporal band-path of 0.01–0.1 Hz. To further exclude the head motion effects on functional connectivity analyses, a scrubbing method was conducted to censor each subject's bad fMRI images to find out the mean frame displacement (FD) which was above 0.5 mm, and one volume before and two volumes after the bad volume were discarded (Power et al. 2012). Only the participants with the fMRI images more than half of the total time points were kept for the following analyses. The detailed procedures of fMRI preprocessing could be found in our previous studies (Song, Ge, et al. 2020, Song, Peng, et al. 2020). There is no significant difference in head motion between these two groups ($p = 0.33$). For resting-state functional connectivity analyses, the fMRI data were smoothed with a Gaussian kernel (FWHM of 6 mm). The global signal was not regressed to ensure that the obtained results were reliable because the whole brain signal regression will exaggerate anti-correlation (Saad et al. 2013, Wang, Wei, et al. 2018).

Whole brain voxel-wise FcHo analyses

The FcHo value measured using KCC was calculated for each voxel in each subject. FcHo of a given voxel was calculated by computing the KCC of the whole brain functional connectivity pattern of this voxel with those of its nearest 26 neighbors. The same procedures were performed for all the voxels of the whole brain, and an FcHo map for each subject was obtained. Then, all the FcHo maps were smoothed with 6 mm FWHM for statistical analyses. After obtaining the FcHo maps, the mean FcHo map for chess and novice players were separately calculated to delineate the distribution patterns. A two-tailed two sample t-test was performed to reveal the changed whole brain functional connectivity homogeneity between chess and novice players. The significance was determined using Alphasim correction method with $p < 0.05$ and voxel-level $p < 0.001$.

Functional connectivity analyses

A whole brain functional connectivity analysis was performed to identify the changed functional couplings of the identified brain regions that showed significantly different FcHo between chess and novice players. To calculate the functional connectivity, the mean time series of the identified brain regions showing changed FcHo were first extracted. Then the strength of the functional connectivity was measured by means of Pearson's correlations between the averaged time series of the brain areas showing changed FcHo and the voxels of the rest brain. Subsequently, the Fisher's Z transformation was applied to improve the normality of the original correlation maps, and a two-sample t-test was performed to determine areas with significantly different functional connectivity between chess and novice players. The significance was determined using Alphasim correction method with $p < 0.05$ and voxel-level $p < 0.001$.

Multivariate pattern analyses using SVM

To explore whether the identified neural indices might serve as markers for distinguishing the chess playing levels, a linear SVM approach was performed (Chang and Lin∗). The FcHo and functional connectivity values of the brain regions that showed significant differences between chess and novice players were used as the features for classification. Because of the small number of samples, a leave-one-out cross-validation strategy was used to estimate the generalization ability. The performance of a classifier was assessed using the classification accuracy, sensitivity and specificity based on the results of the cross-validation.

Correlation analyses

To explore the relationship between the rs-fMRI indices and the amount of time chess players spent on professional training, correlation analyses were performed between the mean FcHo and functional connectivity values and the professional training time. The significance was set at $p < 0.05$.

Results

FcHo pattern in chess and novice players

Spatial distribution of mean FcHo maps for chess and novice players were shown in Fig. 1. High FcHo was mainly observed in association cortical areas, such as parietal cortex, frontal cortex, lateral temporal cortex, dorsal insula, cuneus, posterior cingulate cortex, and dorsomedial prefrontal cortex.

Changed FcHo in chess players

Statistical analyses identified significant differences in FcHo maps between chess and novice players. Significantly increased FcHo in anterior cingulated cortex (ACC), anterior middle temporal gyrus (aMTG) and primary visual cortex (V1) was found in chess players compared with novices. A significant decrease of FcHo in chess players was found in thalamus and precentral gyrus (Fig. 2).

Changed functional connectivity in chess players

To reveal the changed functional connectivities to the brain areas showing changed FcHo, whole brain functional connectivity analyses were performed and identified decreased functional connections between precentral gyrus and V1, and decreased functional connections between V1 and precentral gyrus, parietal opercula/ posterior insula in chess players compared with novices (Fig. 3).

Classification results

Using the combined features of the mean FcHo and functional connectivity values in the brain regions showing differences between chess and novice players for classification, the linear SVM classifier achieved an accuracy of 85.45% [85.71% for chess players (sensitivity), 85.19% for novice players (specificity)] (Fig. 4).

Correlation analyses

Correlation analyses revealed that the mean FcHo values of thalamus were significantly negatively correlated with the amount of time chess players spent on professional training ($r = -0.45$, $p = 0.02$) (Fig. 5), which suggested a direct association between the alterations of FcHo and the chess training frequency.

Discussion

In the present study, FcHo and functional connectivity analysis methods were used to identify the changed whole brain functional connectivity pattern similarity and functional couplings to delineate how the long-term professional training modulates brain functional connectivity patterns. FcHo analyses identified significantly increased whole brain functional connectivity pattern similarity in ACC, aMTG and V1, and decreased whole brain functional connectivity pattern similarity in thalamus and precentral gyrus in chess players. Resting-state functional connectivity analyses further identified chess players showed decreased functional connections between V1 and precentral gyrus. Correlation analyses revealed that the mean FcHo values of thalamus were significantly correlated with the amount of time chess players spent on professional training. Our findings provide new evidences for the important roles of ACC, aMTG, V1, thalamus and precentral gyrus in chess players.

aMTG in chess players

In our study, increased FcHo in aMTG was found in professional chess players compared with novices. This finding was supported by a previous study which used the same participants and found significant deactivation in this area in professional Chinese chess players (Duan, et al. 2012). Previous resting-state functional connectivity analyses revealed aMTG was dominantly connected with DMN related regions, which indicates that aMTG is an important part of DMN (Buckner et al. 2008, Xu et al. 2019, Xu et al. 2015) and plays an important role in episodic memory (Buckner, et al. 2008). Additionally, the spatial and functional convergence of the DMN and semantic memory system has been explored (Binder et al. 2009, Wirth et al. 2011) demonstrating aMTG is also important for semantic retrieval (Cho et al. 2012). When encountering the chess playing situations that commonly appear in games, the 'chunks' held in long-time memory are activated and chess players produce ideas for the best following move to advance better performances (Wan et al. 2011). Thus, we speculated that higher FcHo in aMTG found in professional chess players may be related to higher efficiency and less effort for semantic and episodic processing related to chess games.

ACC in chess players

The ACC, a limbic structure, has connections with a set of other limbic and related areas involved in emotion and reward-related processing (Zhang et al. 2016, Zhang et al. 2014). The ACC performs goal-directed (top-down) cognitive processing which is critical for identifying and responding to stimuli relating to reward in a largely irrelevant sensory world (Chelazzi et al. 1998, Chelazzi et al. 1993, Desimone 1998, Fuster and Jervey 1982, Miller et al. 1993). During the chess playing, a chess expert needs to active the 'chunks' held in long-time memory, takes into account the outcomes received after actions, and will not select an action if the goal has been devalued (Kolling et al. 2016, Rushworth et al. 2012) for the best following move. In our study, significantly increased FcHo value in ACC was found in chess experts compared with novice players. Our findings provide critical functional evidence supporting that the ACC functions as part of top-down executive networks.

Thalamus in chess players

Many studies on skill acquisition have reported significant changes in the brain areas according to the development of specific skills (Duan, et al. 2012, Gaser and Schlaug 2003a, Maguire, et al. 2000, Munte et al. 2002, Schlaug 2001). The human thalamus was a comprehensive hub for functional brain networks and information integrating across cortical networks (Hwang et al. 2017). Spatial visual processing, attention, memory and expression of goal-directed behaviors are thought to be mediated by the thalamus (Browning et al. 2015, Haber and Calzavara 2009, Sommer and Wurtz 2006). Previous studies have found an important role of the thalamus in chess playing (Duan, et al. 2014, Wang, Zuo, et al. 2020, Zhou et al. 2018). In our study, the chess experts showed significantly decreased FcHo value in thalamus in comparison with novice players. Moreover, the mean FcHo values of thalamus were negatively correlated with the professional training time, which consistent with a previous study finding a strong relationship between the thalamic radiation and cognitive ability and training frequency (Zhou et al., 2018). All the converging evidences suggest that the thalamus is important in the processes of board-pattern spatial perception, attention, and next-move generation, as well as the long-term input from the motivational and learning processes involved in the problem solving of chess (Weng et al. 2017).

Functional connectivity between V1 and precentral gyrus

Decreased functional connectivity between V1 and precentral gyrus, parietal opercula and posterior insula was found in chess players compared to novice players. V1 is the main cortical area of the visual system that receives visual information from the external world. The precentral gyrus and parietal opercula/posterior insula are the important parts of the sensorimotor network that is involved in motor planning, execution and control (Eickhoff et al. 2010, Wang, Ji, et al. 2020, Wang, Wei, et al. 2019). The decreased functional connections between V1 and precentral gyrus indicate the higher efficiency in vision-motor transition in chess experts than novices.

There are several limitations in our study. First, the current study is a cross-sectional study, and the longitudinal study is required to better reveal the changes of whole brain functional connectivity pattern similarity in chess players. Second, the sample size was small, and the conclusion required further validation with data from a large sample. Third, our study focused only on resting-state functional connectivities and future studies are needed to integrate multimodal connectivity information.

Conclusion

The present study assessed the changes of voxel-wise whole brain FcHo and resting-state functional connectivities in chess experts. The increased FcHo in ACC, aMTG and V1, decreased whole brain functional connectivity pattern similarity in thalamus and precentral gyrus and decreased functional couplings between V1 and precentral gyrus, parietal opercula and posterior insula were identified in chess experts. These findings suggest enhanced semantic and episodic processing ability, top-down cognitive regulation, and efficiency in vision-motor transition in chess experts.

Declarations

Acknowledgments Not applicable.

Author Contributions LS and PD designed the study. LS, HY, MY, DL, YG, JL performed the research. LS and HY analyzed the data. LS, MY, and PD wrote the manuscript. All authors contributed to the article and approved the submitted version.

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Ethical Approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed Consent Informed consent was obtained from all individual participants included in the study.

Conflict of Interest and Disclosure The authors declare no conflict of interest.

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Figures

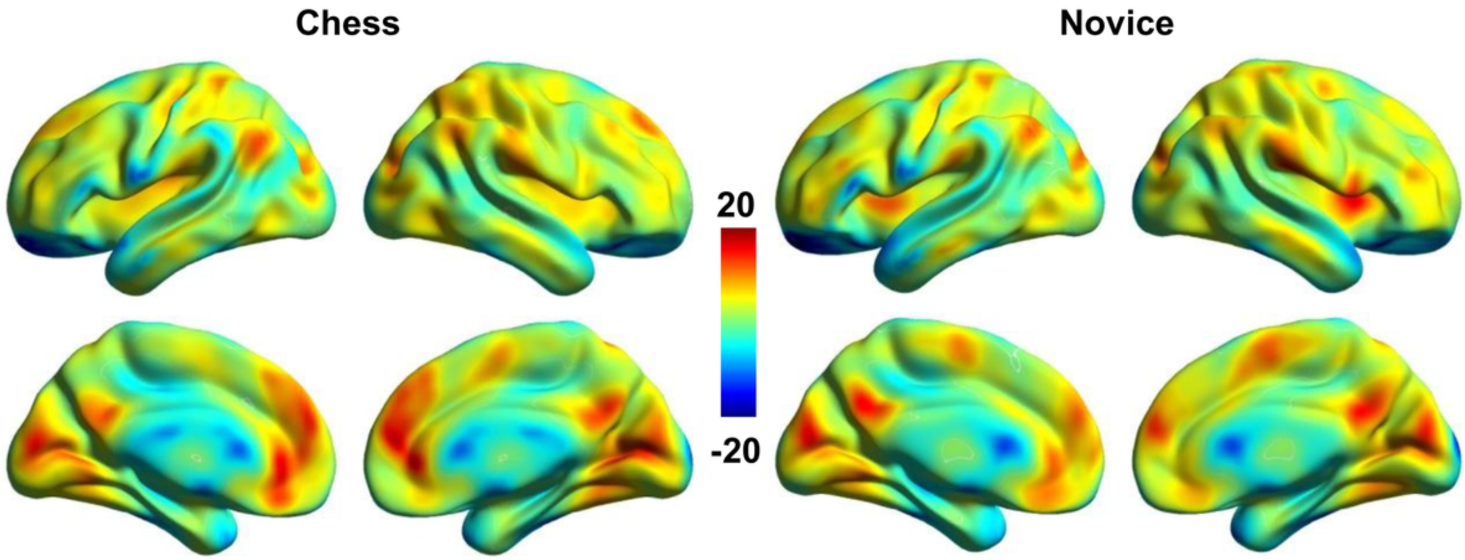

Figure 1

Distribution patterns of functional connectivity pattern homogeneity (FcHo). One- sample t-tests were used to identify the whole brain FcHo distribution pattern in chess and novice players. The high FcHo is mainly distributed in the association cortex such as parietal, frontal, lateral temporal and occipital lobes.

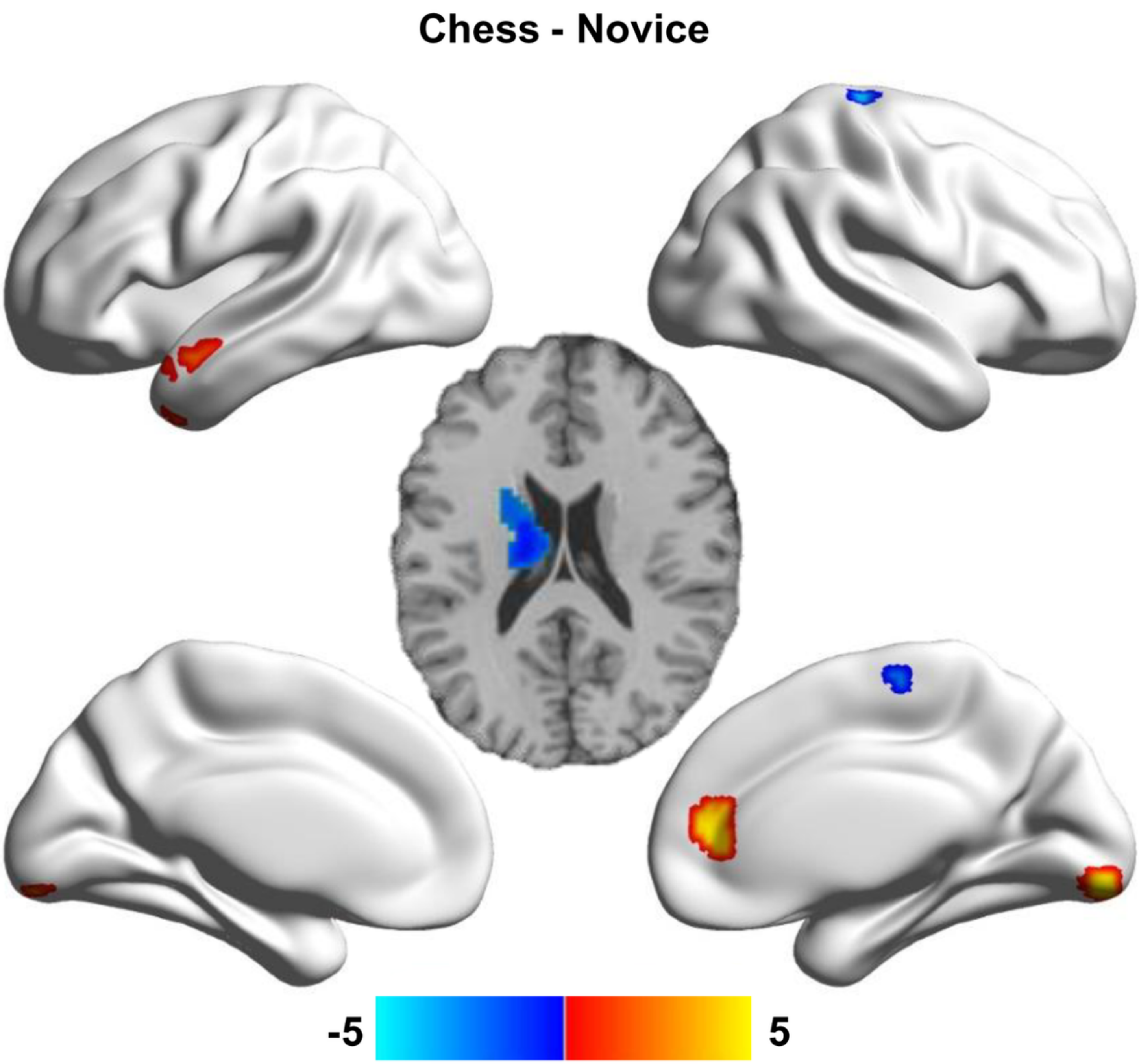

Figure 2

FcHo differences between chess players and novices. A two-sample t-test was used to compare the FcHo maps between chess and novice players. FcHo analyses identified significantly increased whole brain FcHo in anterior cingulated cortex (ACC), anterior middle temporal gyrus (aMTG) and primary visual cortex (V1), and decreased whole brain FcHo of the thalamus and precentral gyrus in chess players compared with novices.

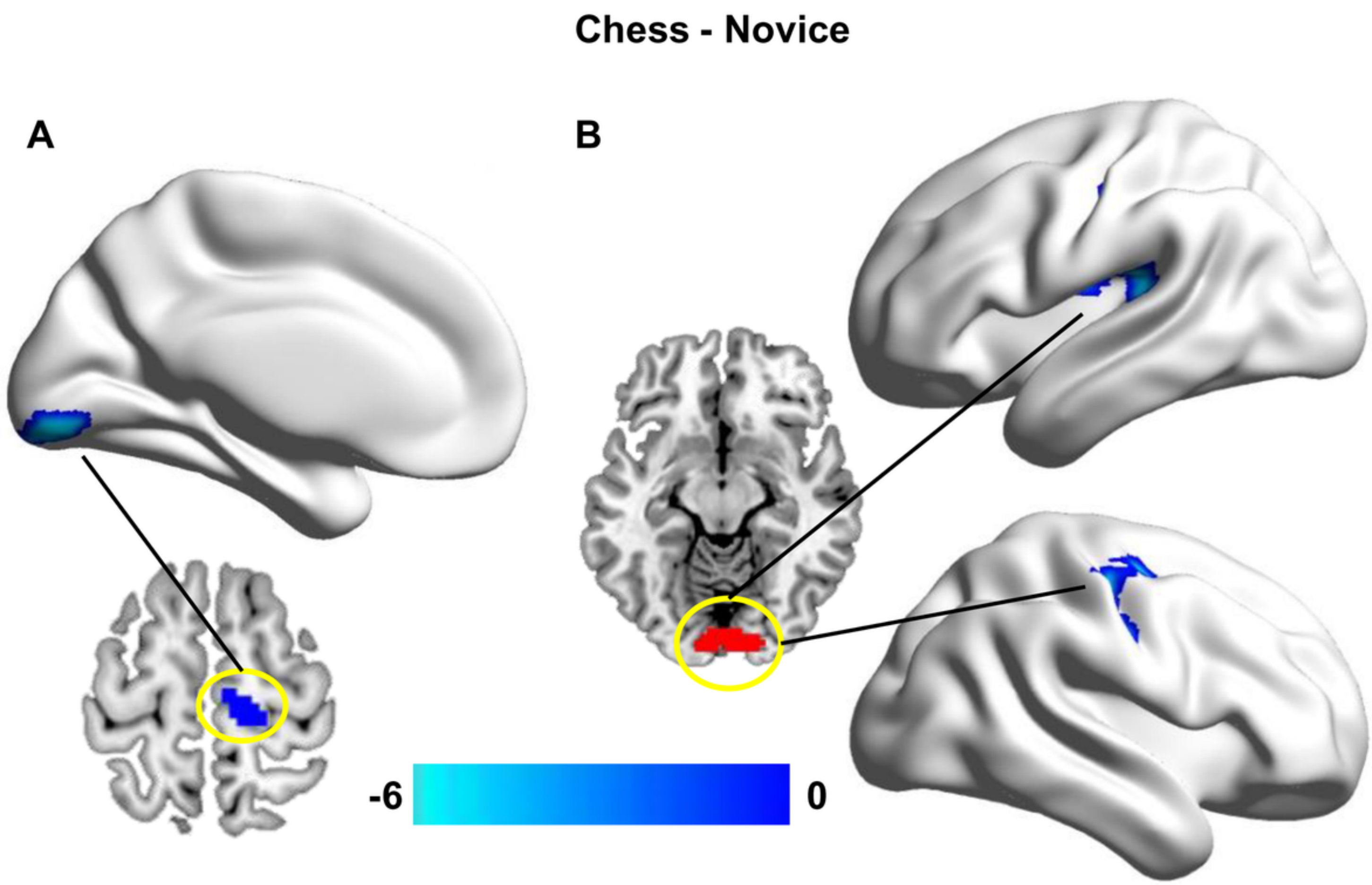

Figure 3

Different functional couplings between chess and novice players. A two-sample t-test was used to identify the significantly different functional interactions to the changed FcHo regions in chess players compared with novices. The functional connectivity analyses identified decreased functional connections between precentral gyrus and V1, and decreased functional connections between V1 and precentral gyrus, parietal opercula and posterior insula in chess players.

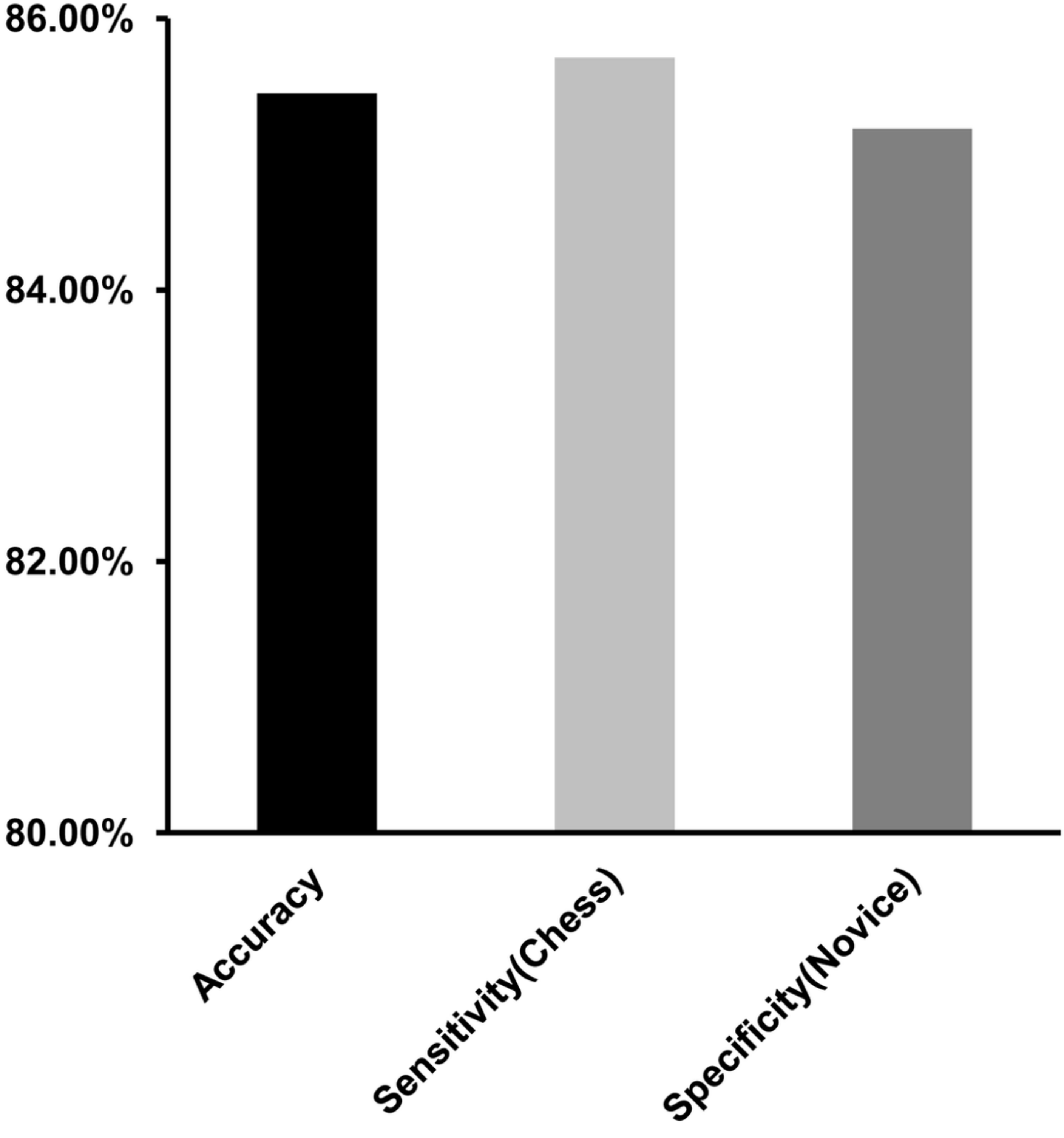

Figure 4

Classifying chess from novice players. Multivariate pattern analyses using support vector machine (SVM) was applied to determine whether identified neural indices might serve as markers for distinguishing the chess playing level. The regions with changed FcHo and functional connections were used as the features for classification. A leave-one-out cross-validation strategy was used to estimate the generalization ability of our classifier. The classification accuracy, sensitivity and specificity were showed.

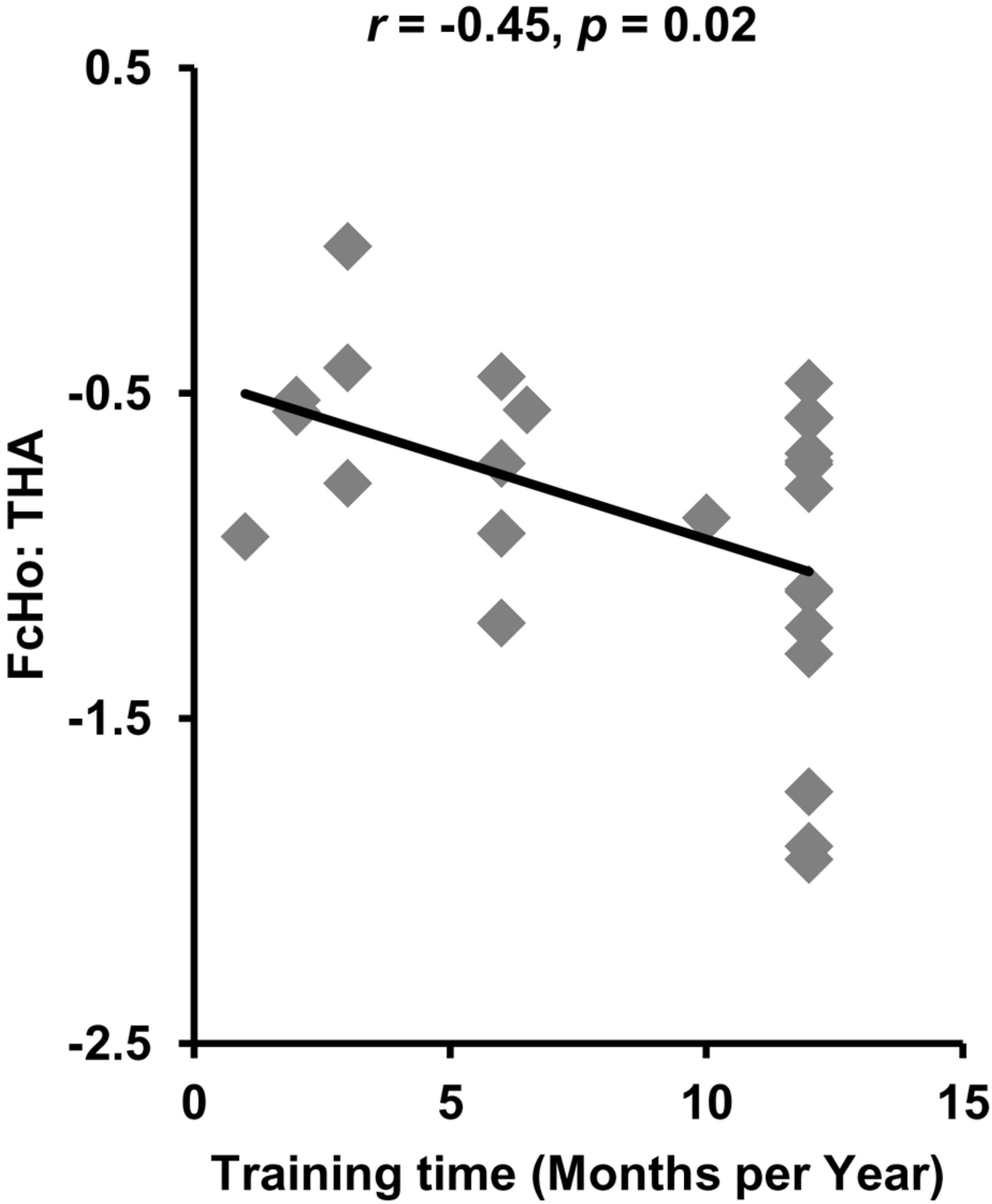

Figure 5

Correlation analyses between the altered neural indices and the training time. The significantly negative correlation between the mean FcHo values in thalamus and the training time was identified.

Supplementary Files

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