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Neural correlates of basketball proficiency: An MRI study across skill levels

Manqi Zhang [a,1], Wenbiao Zhang [a,1], Yujie Yao [a], Jiabao Lin [b], Lei Mo [a,*]

[a] Center for Studies of Psychological Application, South China Normal University, Guangzhou, 510631, People's Republic of China
[b] School of Public Health and Management, Guangzhou University of Chinese Medicine, Guangzhou, 510006, People's Republic of China

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ABSTRACT

Background: Basketball is an attractive sport required both cooperative and antagonistic motor skills. However, the neural mechanism of basketball proficiency remains unclear. This study aimed to examine the brain functional and structural substrates underlying varying levels of basketball capacity.
Methods: Twenty advanced basketball athletes (AB), 20 intermediate basketball athletes (IB) and 20 age-matched non-athlete individuals without basketball experience (NI) participated in this study and underwent T1-weighted MRI and resting-state fMRI scanning. Voxel-mirrored homotopic connectivity (VMHC), amplitude of low frequency fluctuations (ALFF), and gray matter (GM) density were calculated and compared among the three groups.
Results: The VMHC in the bilateral postcentral gyrus, middle temporal gyrus, and superior temporal gyrus, as well as the GM density in the right precentral gyrus, exhibited a hierarchical structure of AB > IB > NI. Compared with NI group, AB and IB groups showed strengthened VMHC in supplementary motor area, paracentral lobule and superior frontal gyrus. Additionally, the ALFF of left middle occipital gyrus and right hippocampal and the GM density of left medial superior frontal gyrus exhibited differences in AB-IB and AB-NI comparisons.
Conclusions: By conducting the cross-sectional comparison, this study firstly identifies the varying levels of basketball proficiency related brain resting-state functional and structural plasticity. Especially, the regions associated with motor perception and control, including bilateral postcentral gyrus, middle and superior temporal gyrus and right precentral gyrus, are involved in the key neural mechanisms of basketball proficiency. Future longitudinal studies are necessary to further validate these findings.

1. Introduction

In recent years, basketball has become one of the most popular sports globally, attracting more than 200 million enthusiasts across the world.[1] Basketball athletes with excellent capability get a lot of attention as their superior performances reflect the physiological limits of human beings in this sport.[2,3] Given that basketball is teamwork played in a large arena that requires participants to utilize a more diverse set of skills, there are relatively complex physiological reflections behind changes in an individual's basketball skills level.[4] The neuroimaging techniques allow us to delve into the neurophysiological mechanisms behind sports skill acquisition.[5] Previous MRI (magnetic resonance imaging) studies have documented that there are some brain functional and structural alterations in basketball professional athletes, suggesting the shaping effect of basketball proficiency on individuals' brains.[6,7] To fully understand the neural mechanism of basketball skill development, further study on the brain plasticity underlying varying basketball capacities is necessary.

The resting-state functional magnetic resonance imaging (fMRI), the second wave of fMRI paradigm,[8] has facilitated the development of computational metrics to study the intrinsic spontaneous brain activity, such as voxel-mirrored homotopic connectivity (VMHC) and amplitude of low frequency fluctuations (ALFF). Both methods are widely used in resting-state brain function in cognitive, athletic, and clinical neuroscience.[9,10] The VMHC refers to the symmetry of resting-state connectivity between bilateral brain hemispheres and represents the bilateral brain information transfer.[11] It offers valuable insights into the executive function and the coordination between brain hemispheres during motor tasks,[12,13] and helps us better understand the regional variability of areas involved in motor function, such as the precentral gyrus (PreCG), postcentral gyrus (PoCG), and occipital lobe.[11,14] A study found that an individual's rowing performance was associated with the

* Corresponding author. No55 West Zhongshan Avenue, Tianhe District, Guangzhou, Guangdong, 510631, People's Republic of China.
E-mail address: molei@m.scnu.edu.cn (L. Mo).
[1] Manqi Zhang and Wenbiao Zhang contributed equally to this work and are considered co-first authors.

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VMHC of the bilateral middle temporal gyrus (MTG) and superior frontal gyrus (SFG).[9] The ALFF reflects the intensity of spontaneous brain activity in specific regions,[15] and is widely used in studies on the changes in brain resting-state function related to athletic performance.[16–18] Table tennis players showed changes in ALFF in the ventromedial prefrontal cortex.[19,20] Compared with non-contact manipulative athletes, soccer players showed weakened ALFF in the frontal lobe and cingulate cortex but strengthened ALFF in the occipital regions.[21] A study on skeleton athletes revealed alterations in the ALFF within the temporal cortex, fusiform gyrus, inferior frontal gyrus, insula, and Rolandic operculum, suggesting potential brain function adaptations associated with skeleton training and expertise.[22] The intrinsic functional characteristics of certain brain regions, which result from expertise and continuous training, may serve as indicators of expertise during the brain's resting state. Together, VMHC and ALFF are promising tools for further exploring the brain's functional representation of basketball proficiency.

Previous research has suggested that brain plasticity alters with the advancement of basketball skills also exists in brain structure.[6,23] The density or volume of gray matter (GM) has been one of the most common measures of anatomical brain change, as it reflects alterations in the number or size of neurons and glial cells.[24] The voxel-based morphometry (VBM), a main method for studying morphometric characteristic, is widely used to investigate the structural change in gray matter.[25,26] There have been some studies using VBM focus on the specialty related structural plasticity in sports field. Compared to less-skilled golfers, larger GM volumes were found in the fronto-parietal network including premotor and parietal areas in skilled golfers.[27] Compared with non-athletes, world-class gymnasts showed increased GM density in the left inferior frontal gyrus, bilateral inferior and superior parietal lobule, and bilateral superior lateral occipital cortex, suggesting alterations in inhibitory control, language control, and visual perceptual processing.[28] Increases in GM density often occur in cortical regions involved in information processing and motor control, while a lack of exercise and skill practice can lead to reduced GM density.[29] Collectively, the alteration in GM density among basketball players may reflect the brain structural plasticity related to skill improvement. However, limited existing research results in an inadequate understanding of the brain structural alteration with the basketball capability increase.

Although studies have documented functional and structural brain plasticity associated with basketball skill improvement,[7,30,31] the main method adopted in those research is a "yes/no" comparison, limiting our insight into the neural mechanism underlying the shaping role of basketball skill on the brain. The comparison between experts and novices has been the primary form of "yes/no" comparison in prior studies on basketball expertise.[23,32] However, such a binary approach raises a new question. Specifically, among the differences in brain function and structure between basketball experts and novices, it is difficult to distinguish which are the characteristics reflecting skill enhancement and which are unique features of experts. The former may be involved in the neural mechanism underlying basketball training, while the latter may be linked to innate skills in this sport. Therefore, investigations that enroll individuals with multiple levels of basketball ability would help us further explore how basketball skills development shapes an individual's brain. To our knowledge, only one study by Zhang et al. enrolled people with multiple levels of basketball proficiency. They found that compared with high-level and beginners, middle-level players had the highest activation of the left PoCG while imagining basketball shooting. During the task, the activation in the left middle frontal gyrus (MFG) increased, and that in the left supplementary motor area (SMA) decreased with increasing levels of motor expertise.[7]

The neural correlates of different levels of basketball proficiency, such as brain's resting-state functional and structural features, still warrant further exploration. To address this gap, we recruited advanced basketball athletes (AB), intermediate basketball athletes (IB), and non-athlete individuals without basketball experience (NI) and conducted resting-state and structural MRI scanning to investigate the differences among them. The comparisons on VMHC, ALFF, and GM density were performed among the three groups. The differences in VMHC and GM density among any two pairs were found in the areas mainly associated with motor and auditory function. The ALFF differences were only found in AB-IB and the AB-NI comparisons. Our findings reveal both the brain's functional and structural features linked to the varying levels of basketball skills and those especially associated with advanced skills proficiency. This work broadens our current understanding of brain plasticity related to basketball skill training, suggests neurobiomarkers that can indicate resting-state function and structure at different basketball skill levels, and provides new insights for future work in basketball training practice.

2. Methods

2.1. Participants

Twenty professional players from basketball teams (advanced basketball athletes, AB), 20 undergraduates majored in basketball (intermediate basketball athlete, IB), and 20 age-matched non-athlete individuals without basketball experience (non-athlete individuals, NI) were recruited in Guangdong Province, China. The sample size was established in accordance with previous relevant studies.[19,33,34] The inclusion criteria were: (I) 18–30 years old; (II) right-handed males; (III) Han nationality; (IV) no MRI scanning contraindication; (V) no substance use disorder, chronic neurological disorders, or severe medical diseases. All participants provided their written informed consent. This study was conducted in accordance with the Declaration of Helsinki and approved by the Human Research Ethics Committee in School of Psychology, South China Normal University (protocol code: 2019-3-026).

2.2. MRI data acquisition

Scans were performed on a Siemens 3.0 T Prisma-fit system equipped with a 64-channel head coil at the South China Normal University Magnetic Resonance Research Center. Each subject underwent T1-weighted scanning and resting-state fMRI scanning for 7 min and 56 s. The Scanning parameter is provided in *Supplementary MRI scanning parameter setting.*

2.3. fMRI data preprocessing

The preprocessing steps included: (1) removal of the first 2 vol of each functional time-series; (2) slice timing and realignment; (3) two-way registration: co-registering functional images with T1 images, segmenting T1 using DARTEL,[35] and aligning GM probability maps to the MNI template; (4) linear drift correction, Friston 24 headmotion correction, and signal (from cerebrospinal fluid and WM) regression; (5) normalization to voxel dimensions of 3*3*3 mm^3; (6) to further eliminate the effect of subtle head movement artifacts, scrubbing regression was performed.[36] Specifically, signal from each "bad" frame (defined as frame-wise displacement (FD) $>$ .20 mm) and its neighbors (1 frame before and 2 frames after) were flagged for regression; (7) temporal filtering (0.01–0.08 Hz); (8) spatial smoothing with a full-width at half maximum (FWHM) of 6 mm.

2.4. VMHC and ALFF calculations

Statistical Parametric Mapping 12 (SPM12)[37] and the Data Processing Assistant for Resting-State fMRI (DPABI)[38] were used for fMRI preprocessing. Participants with excessive movement (motion between volumes in any direction >3 mm, or rotation about any axis >3°) were ruled out. A sample of 16 AB (Mean age ± S.D., 20.56 ± 1.59 years; range, 18.03–23.24 years), 18 IB (Mean age ± S.D., 20.42 ± 1.06 years;

range, 18.94–22.81 years), and 19 NI (Mean age ± S.D., 20.49 ± 2.42 years; range, 18.72–26.96 years) was obtained for the subsequent calculations.

VMHC and ALFF were calculated using the DPABI toolbox. For VMHC, we chose the Pearson correlation coefficient as the index of homotopic functional connectivity. For each voxel, the Pearson correlation coefficient between the time series of it and the time series of its symmetrical counterpart in the opposite hemisphere is computed. For ALFF, the functional images after smoothing were used for subsequent computational analysis. The extraction of power spectra from smoothed time-series was conducted using Fast Fourier Transform. Then the summation of amplitudes within predetermined low-frequency bands (0.01–0.08 Hz) was calculated. Finally, the images after Z-score transformation (zVMHC and zALFF) were included in the formal statistical test.

2.5. VBM analysis

VBM analyses were conducted using the Computational Anatomy Toolbox for SPM12 (CAT12).[39] The processing pipeline consisted of manual inspection and reorientation, segmentation, spatial normalization, modulation, quality assessment, and smoothing. Details could be found in *Supplementary Material VBM processing.* After quality check, data from 19 AB (Mean age ± SD, 20.89 ± 1.66 years; range, 18.03–23.28 years), 19 IB (Mean age ± SD, 20.71 ± 1.21 years; range, 18.94–22.81 years), and 20 NI (Mean age ± SD, 20.95 ± 2.38 years; range, 18.72–26.96 years) were included in the formal statistical test.

2.6. Statistical analysis

The statistical analysis was conducted using SPM12. One-way ANOVA was performed on zVMHC, zALFF, and GM density among three groups. The results of one-way ANOVA were set as masks for two-sample *t*-test performed between any two pairs. Age and mean frame-wise displacement (FD) were set as covariates in between-group comparisons on functional data. Mean FD showed no significant differences among three groups ($Mean_{AB} = .078$ mm, $SD_{AB} = .021$, $Mean_{IB} = .083$ mm, $SD_{IB} = .037$, $Mean_{NI} = .069$ mm, $SD_{NI} = .011$, $F = 1.14$, $p = 0.33$). In the comparison on structural data among three groups, age and total intracranial volume (TIV) were set as covariates. TIV showed no significant differences among three groups ($Mean_{AB} = 1628.77$ mm^3, $SD_{AB} = 110.72$, $Mean_{IB} = 1572.24$ mm^3, $SD_{IB} = 92.95$, $Mean_{NI} = 1569.10$ mm^3, $SD_{NI} = 140.22$, $F = 1.59$, $p = 0.21$). We included age, mean FD and TIV as covariates to control the potential effect of individuals' differences in overall developmental characteristics, headmotion, and brain maturation on any observed differences between groups. The statistical significance threshold was set at voxel-wise uncorrected $p < 0.001$ and cluster-wise $p < 0.05$ for Family-Wise Error rate.

3. Results

3.1. VMHC

With age and mean FD setting as covariates, there were significant differences on zVMHC among AB, IB, and NI groups. As showed in Table 1, the VMHC of the bilateral PoCG and MTG/superior temporal gyrus (STG) exhibited a hierarchy with AB > IB > NI. Compared with NI, AB and IB showed strengthened VMHC in bilateral supramarginal gyrus (SMG), SMA, paracentral lobule (PCL), precuneus (PCUN), and SFG.

3.2. ALFF

After controlling for age and mean FD, significant differences on ALFF of AB with IB and NI were observed. As showed in Fig. 1 and Table S1 in Supplementary Materials, compared with both IB and NI groups, AB group showed increased ALFF in the left middle occipital gyrus and angular gyrus (MOG/ANG) but decreased ALFF in the right hippocampal and parahippocampal gyrus (HIP/PHG).

3.3. VBM

There were differences on GM density among the three groups, with age and TIV as covariates. The results were provided in Fig. 2 and Table S2 in Supplementary Materials. The GM density of the right PreCG exhibited a hierarchy with AB > IB > NI. Compared with IB and NI groups, AB group showed higher the left medial superior frontal gyrus

Table 1
The significant differences on VMHC among the three groups ($n_{AB} = 16$, $n_{IB} = 18$, $n_{NI} = 19$).

Area	MNI coordinate						cluster size (L)	cluster size (R)	T-value	Hedges' g
	x	y	z	x	y	z				
AB v.s. IB										
PoCG.L-PoCG.R	−63	−9	27	63	−9	27	338	316	4.39	1.47
MTG.L-MTG.R	−69	−36	6	69	−36	6	20	20	3.02	1.01
AB v.s. NI										
MTG.L-STG.R	−69	−30	6	69	−30	6	71	60	6.53	2.16
PoCG.L-PoCG.R	−66	−9	27	66	−9	27	445	422	6.37	2.11
	−30	−30	66	30	−30	66	25	26	5.16	1.71
SMG.L-SMG.R	−63	−48	36	63	−48	36	11	11	4.16	1.38
SMA.L-SMA.R	−3	0	48	3	0	48	14	14	4.29	1.42
PCUN.L-PCUN.R	−3	−57	69	3	−57	69	11	12	5.70	1.89
PCL.L-PCL.R	−3	−36	66	3	−36	66	12	12	4.86	1.61
SFG.L-SFG.R	−12	−9	78	12	−9	78	11	11	4.73	1.57
IB v.s. NI										
STG.L-STG.R	−66	−36	18	66	−36	18	54	45	5.49	1.77
PoCG.L-PoCG.R	−63	0	24	63	0	24	64	58	3.92	1.26
	−27	−30	66	27	−30	66	19	19	4.21	1.35
SMG.L-SMG.R	−63	−48	36	63	−48	36	11	11	4.13	1.33
PoCG.L-MFG.R	−54	−9	51	54	−9	51	20	16	5.37	1.73
SMA.L-SMA.R	−3	−15	54	3	−15	54	14	14	3.90	1.26
PCUN.L-PCUN.R	−3	−60	66	3	−60	66	11	12	4.81	1.55
PCL.L-PCL.R	−3	−36	69	3	−36	69	12	12	4.64	1.49
SFG.L-SFG.R	−18	−12	78	18	−12	78	11	11	4.87	1.57

AB: Advanced basketball athletes; IB: Intermediate basketball athletes; NI: Non-athlete individuals; MFG: middle frontal gyrus; MTG: middle temporal gyrus; PCL: paracentral lobule; PCUN: precuneus; PoCG: postcentral gyrus; SFG: superior frontal gyrus; SMA: supplementary motor area; SMG: supramarginal gyrus; STG: superior temporal gyrus; L: left; R: right. The threshold of statistical significance was set at voxel-wise $p < 0.001$ (uncorrected) and cluster-wise $p < 0.05$ (FWE-corrected).

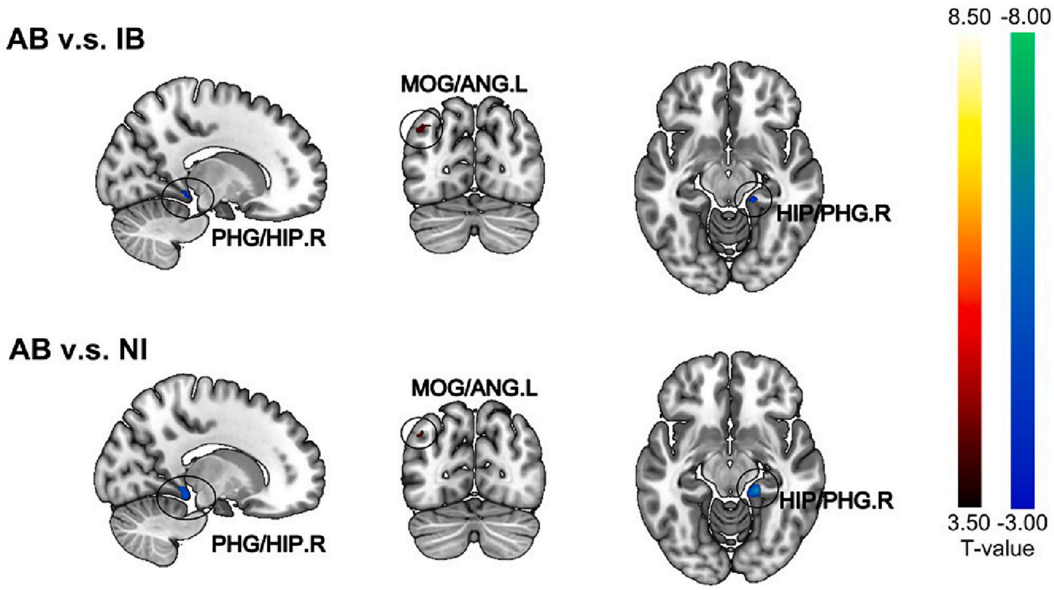

Fig. 1. Between-group Differences in ALFF. Warm color bars indicate regions with increased ALFF values, whereas cool color bars indicate regions with decreased ALFF values. AB: Advanced basketball athletes; IB: Intermediate basketball athletes; NI: Non-athlete individuals; ANG: angular gyrus; HIP: hippocampal gyrus; MOG: middle occipital gyrus; PHG: parahippocampal gyrus; L: left; R: right. The threshold of statistical significance was set at voxel-wise $p < 0.001$ (uncorrected) and cluster-wise $p < 0.05$ (FWE-corrected).

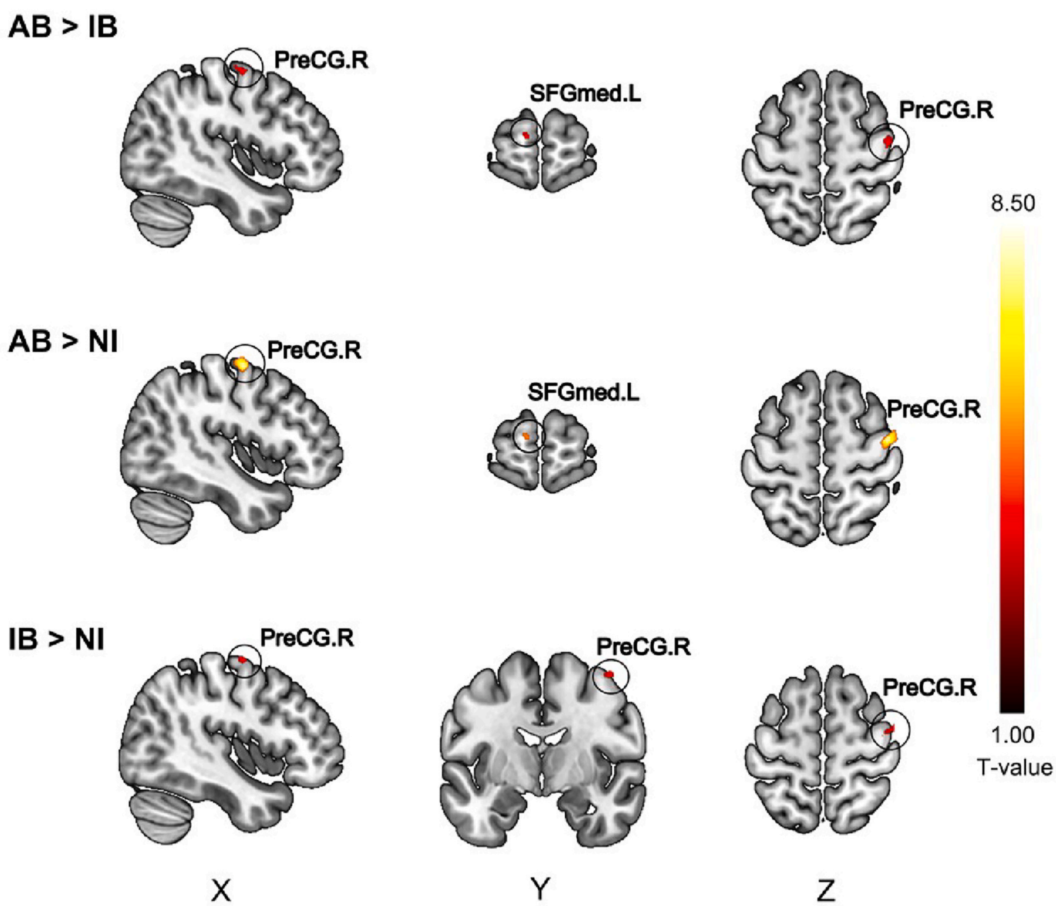

Fig. 2. Brain regions with increased GM density in pairwise comparisons among AB, IB, and NI. The color bar scale indicates lower values trending towards black, and higher values trending towards the opposite end. AB: Advanced basketball athletes; IB: Intermediate basketball athletes; NI: Non-athlete individuals; SFGmed: medial superior frontal gyrus; PreCG: precentral gyrus; L: left; R: right. The threshold of statistical significance was set at voxel-wise $p < 0.001$ (uncorrected) and cluster-wise $p < 0.05$ (FWE-corrected).

(SFGmed).

4. Discussion

The current study firstly investigated the brain resting-state functional and structural plasticity associated with levels of basketball expertise. There are three main findings: 1) the VMHC of the bilateral PoCG and STG/MTG, as well as the GM density of the right PreCG, showed significant differences among three groups, representing key features that can reflect varying levels of basketball capacities; 2) the VMHC of other motion areas (e.g. SMA, PCL, and SFG) exhibited significance in AB-NI and IB-NI comparisons, which may be characteristics to distinguish whether individuals have basketball training experience; 3) the ALFF of left MOG and right HIP and the GM density of left SFGmed could be key features distinguishing individuals with advanced basketball skills.

The PoCG, as a core area of sensorimotor regions, is involved in somatosensory processing and muscle regulation.[40] During a shooting imagery task, intermediate players were found to have higher activation in the left PoCG than elite players and novices. This suggests that neural engagement in the PoCG reflects an individual's refinement in sensory processing and the associated cognitive effort during motor imagery.[7] Woods et al. found that when listening to sport-related sounds, athletes had higher activation in brain regions such as the PoCG than novices.[41] Both STG and MTG function in processing environmental sounds, but MTG may have more to do with higher-level aspects of sound recognition.[42] A study found that the MTG involved in motor planning and processing.[41] In a visual-spatial task, table tennis athletes showed less activation in the left MTG than non-athletes.[43] Similarly, athlete group exhibited less activation in the left MTG than novices during motor decision.[44] Therefore, in our analysis, the VMHC of bilateral PoCG and bilateral STG/MTG were the strongest in the AB, the second in the IB, and the lowest in the NI, suggesting that information communication of the bilateral PoCG and temporal cortex are enhanced with the improvement of basketball skills.

The PreCG also plays an important role in motor control.[45] The right PreCG is crucial in the visual awareness of biological motion.[40] Similar to our finding, Kim et al. reported that basketball players had greater PreCG WM volume than normal people.[30] The endurance runners showed greater GM volume and cortical surface area in the left PreCG.[46] Compared to strength-endurance training program, dance training was found to induce an increase GM volume in the left PreCG, suggesting the significance of the PreCG in complex motor coordination.[47] We observed a decreasing trend in the GM density of the right PreCG across AB, IB, and NI groups. Collectively, the stepwise changes of the bilateral PoCG and STG/MTG information exchange and right PreCG GM density across three groups indicate varying patterns of motor perception and control among individuals with distinct levels of basketball skills. We proposed that the neural development mechanism of basketball capability is primarily synchronized with changes in motor perception and control areas.

We found that AB and IB showed strengthened VMHC in the SMA, PCL, and SFG than NI. These areas are involved in motor control and coordination, particularly for complex and voluntary movements and movements involving the lower extremities.[48] Decreased activation of the left SMA with increased basketball expertise, suggesting that the SMA stores motion-related information and participates in the automatic extraction of such information.[7] In a machine learning model for predicting ping-pong experts versus non-experts, the decision function's top-ranking regions included the SMA and PCL.[49] The VMHC of SFG was positively correlated with measures of rowing performance in high-stimulation group, suggesting that SFG may be involved in the enhancement of athletic performance.[9] Therefore, changes in SMA, PCL and SFG may be key index of professional basketball training.

During a soccer goal-predicting task, the left MOG and ANG were found to play a key role in visual innovative prediction.[50] The MOG is one of the areas involved in visual perception.[51] The enhanced activation of the ANG contributes to situational memory, potentially representing a spatiotemporal integration of multisensory information.[52] The SFGmed brain region is key in visual awareness and attention to biological movements.[40] During action anticipation, the left SFGmed of badminton players exhibited significant activation and stronger connectivity with other regions.[53] The correlation between faster adaptation capacity and SFGmed activity was found in pilot populations.[54] When viewing sports scenes, there was a lateralization advantage in SFGmed in sports experts compared to controls, suggesting the role of the left SFGmed in experts' attentional advantage.[55] In this study, AB showed increased left MOG/ANG ALFF and SFGmed GM density than IB and NI groups. As basketball required high anti-disturbance ability, the findings on the MOG/ANG and SFGmed may reflect an excellent ability of attention control, especially to movement-related visual stimuli, among professional basketball athletes.

Intriguingly, we found AB group exhibited decreased right HIP/PHG ALFF than IB and NI groups. Diminished spontaneous activation in HIP and PHG is associated with decreased memory and related cognition, which is also involved in emotion regulation.[56,57] Previous studies have suggested that the reduced volume and weakened function of the HIP were induced by chronic stress.[58] It has been proven that ALFF is reliable and sensitive for detecting abnormal neural activity in the HIP.[59] Professional basketball players are often exposed to high-intensity training and competition pressures, which may lead to chronic stress responses. Therefore, the reduced ALFF of HIP/PHG in AB group in the present study may reflect the effects of chronic stress from long-term competitive basketball experience on brain function. However, direct evidence linking reduced spontaneous activity in the hippocampus (HIP) to chronic stress is currently lacking. To address this gap, future studies should incorporate comprehensive psychological stress measurements and HIP/PHG spontaneous activity to elucidate the relationship between stress levels and HIP/PHG function in basketball athletes.

In the present study, there are several limitations that should be noted. First, this study is a cross-sectional study, where individual differences could be one of major confounding variables. Although age, mean FD, and TIV were set as covariates to control their potential effect in between-group comparisons, some other factors (e.g. education level, lifestyle, and other sports experiences) could potentially impact an individual's brain structure and function, which should be taken into consideration in future cross-sectional studies. Longitudinal studies are also needed to further validate the brain functional and structural features related to different levels of basketball capacity. Second, the relatively small sample size may affect the statistical power of results. To substantiate the validity of our findings, we calculated the statistical test power indicator Hedges'g. The absolute values of Hedges'g were all over 0.8, indicating good validity of the statistical results. Finally, we did not collect data on the subjects' actual basketball performance. Future studies should incorporate such data to more accurately explore the quantitative relationship between brain function/structure and on-court performance.

5. Conclusion

Through the comparisons of brain resting-state function and structure among individuals with different levels of basketball skills, we identified some key features constituting the neural mechanism of basketball capacity. Primarily, the VMHC of bilateral PoCG and STG/MTG and the right PreCG GM density showed a decreasing trend among AB, IB, and NI groups. These results reveal the effects of basketball skills on both resting-state functional and structural plasticity, indicating that areas associated with motor perception and controls involve in the neural basis of basketball proficiency.

CRediT authorship contribution statement

Manqi Zhang: Conceptualization, Investigation, Formal analysis, Visualization, and, Writing – original draft. **Wenbiao Zhang:** Investigation, Formal analysis, Visualization, and, Writing – original draft. **Yujie Yao:** Conceptualization, Investigation. **Jiabao Lin:** Investigation. **Lei Mo:** Conceptualization, Supervision, and, Writing – review & editing.

Data availability

The data are available from the corresponding author upon reasonable request.

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Conflicts of interest

All authors have reported no financial interests or potential conflicts of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jesf.2024.12.001.

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