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The role of cerebellar-cortical connectivity in modulating attentional abilities: insight from football athletes

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Abstract

Neuroplasticity, a phenomenon present throughout the lifespan, is thought to be influenced by physical training. However, the relationship between neuroplastic differences and attentional abilities remains unclear. This study explored the differences in brain function and attentional abilities between professional football athletes and novices, and further investigated the relationship between the two. To address this question, we included 49 football athletes and 63 novices in our study, collecting data on resting-state functional connectivity and Attention Network Test (ANT). Behavioral results from the ANT indicated that football experts had superior orienting attention but weaker alerting functions compared to novices, with no difference in executive control attention. fMRI results revealed that football experts exhibited higher fractional Amplitude of Low-Frequency Fluctuations (fALFF) values in the bilateral anterior cerebellar lobes, bilateral insula, and left superior temporal gyrus. Functional connectivity analysis showed increased connectivity between the left anterior cerebellar lobe and various cortical regions, including the right supramarginal gyrus, left precuneus, left superior frontal gyrus, bilateral posterior cerebellar lobes, and bilateral precentral gyri in experts compared to novices. More importantly, in the expert group but not in novice group, functional connectivity differences significantly predicted attentional orienting scores. Graph theoretical analysis showed that experts exhibited higher betweenness centrality and node efficiency in the right cerebellar lobule III (Cerebelum_3_R) node. Our findings demonstrate that long-term professional football training may significantly affect neuroplasticity and attentional functions. Importantly, our analysis reveals a substantive connection between these two aspects, suggesting that the integration of neuroplastic and attentional changes is likely mediated by cerebellar-cortical connectivity.

Keywords Neuroplasticity, Attention, Cerebellum, FMRI

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Introduction

Neuroplasticity is widely recognized as a phenomenon that occurs throughout the lifespan. Professional athletes represent an ideal group for investigating the neuroplastic changes prompted by sports training. Employing the expert-novice paradigm, notable distinctions in brain structure and function have been identified between elite athletes and non-athletes [40, 46, 89–91, 95, 96, 98]. However, few studies have explored the relationship between neuroplastic differences and attentional abilities in athletes versus non-athletes.

Previous studies demonstrated that motor training can induce both functional and structural plasticity in the brain, with these neural plasticity changes involving extensive areas across the brain [4, 11, 17, 28, 56, 73, 89, 94]. A recent meta-analysis suggested that extensive motor training led to potential plastic changes in athletes' brains [34]. Moreover, a systematic review by Hortobágyi et al. [29] indicated that exercise intensity was positively associated with neuroplasticity in healthy young adults, and that exercise-induced neuroplasticity gains were linked to motor changes. Similarly, enhanced functional connectivity (FC) was identified between the posterior cerebellar lobe and the fusiform gyrus in elite athletes [98]. Vahdat et al. [79] found changes in a network comprising cerebellar cortex, primary motor cortex, and dorsal premotor cortex that were linked to the motor aspects of learning. Moreover, Yan et al. [89] demonstrated alterations in functional connectivity and topological efficiency of the brain functional network among the motor cortex, visual cortex and cerebellum were significantly correlated with training intensity parameters. In summary, these studies indicate that motor training has a consistent impact on the neuroplasticity of the motor cortex and the cerebellum.

In the present study, we employed resting-state functional magnetic resonance imaging (rs-fMRI) to investigate the plasticity changes of brain function. Compared to task-based fMRI, rs-fMRI allows for the observation of intrinsic and spontaneous Blood Oxygen Level Dependent (BOLD) activity in the brain without the potential interference from cognitive strategies [41]. Moreover, rs-fMRI patterns remain relatively stable over time, making them valuable for studying individual differences and the effects of long-term training on brain networks [27]. We calculated fractional Amplitude of Low-Frequency Fluctuations (fALFF), FC, and graph theory metrics to investigate the impact of football training on brain functional plasticity. The fALFF quantifies the low-frequency oscillatory power of local neuronal populations, reflecting spontaneous neural activity [100]. Compared to the older ALFF metric, fALFF is less susceptible to physiological noise [101] and has been associated with experience-dependent plasticity, as repeated training or skill acquisition can reshape intrinsic brain function [95, 96, 98]. Therefore, fALFF serves as an important measure of neural plasticity. Functional connectivity is defined as the temporal correlation between spatially remote neurophysiological events [25]. It can capture the organization of brain networks and the interactions between specific regions or networks. Moreover, FC has demonstrated stability within a single fMRI session and reliability over longer intervals (hours, weeks, or months), suggesting it may serve as a potential biomarker of training- or experience-driven neural plasticity [12], [17]. However, approaches focusing solely on regional brain activity or FC analysis fall short in fully encapsulating the complexity of brain functional connections and lack a description of the plasticity of the global brain functional network organization [80]. Thus, we conducted a further graph theory analysis to evaluate the differences in brain network organization between football athletes and novices. Graph theory-based approaches model the brain as a complex network of nodes and edges, offering a valuable means of examining neuroplasticity at the network level. In the virtual graph, nodes indicate anatomical elements (e.g., brain regions), and edges represent the relationships between nodes (e.g., connectivity) [85]. We calculated both nodal network metrics including betweenness centrality (BC), degree centrality (DC), node efficiency and small world parameters including normalized clustering coefficient (λ), small-worldness (σ) and normalized characteristic path length (γ). Nodal network metrics quantifies how important a node is within a network. The degree of a node in a network is defined as the count of edges that are directly connected to that node. Betweenness centrality is a measure that quantifies the extent to which a node controls the information flow between different pairs of nodes within the network. It reflects the node's potential to exert influence over the communication pathways among the network's constituents. Nodal efficiency is a measure of how well a node can communicate with others in a network. It indicates the node's contribution to information propagation. A node with high centrality is often seen as a hub in the brain network [9, 68]. The small-world model is a compelling framework for characterizing intricate brain networks, as it facilitates a dual approach to information processing: it allows for both specialized and modular operations as well as integrated and distributed functions. Furthermore, this model optimizes the efficiency of information exchange while maintaining a relatively low cost in terms of network connectivity [67].

There remains ongoing debate regarding whether and how long-term sports training induces changes in attention. Some studies indicated that elite athletes possessed superior attentional functions compared to non-athletes. For example, one previous study indicated elite athletes that participation in strategic sports, such as football, was associated with improved attention performance [60]. Similarly, Meng et al. [49] found that volleyball players exhibited enhanced attentional alerting compared to healthy controls. Moreover, a meta-analytic review found the athletes performed better on measures of a category of varied attentional paradigms [82]. Furthermore. Hüttermann et al. [31] found 25% greater attention breadth in expert athletes than in novices and the distribution of focused attention for experts varied as a function of the type of athletic expertise. However, some studies found that athletes did not exhibit improved attentional functions compared to the general population [48], and the prevalence of attention deficit-hyperactivity disorder (ADHD) was even higher among athletes than in the general population [58]. Therefore, more research, especially studies with larger sample sizes, is needed to explore the impact of motor training on attentional functions.

Attention refers to the selective processing of information, prioritizing certain inputs over others that compete for the brain's limited cognitive resources [21]. Posner and Petersen, [57] proposed that the sources of attention constitute a specific system of anatomical areas, which can be further divided into three distinct networks. These networks are responsible for the functions of alerting, orienting, and executive control. Alerting was defined as the establishment of an enhanced state of vigilance in preparation for an imminent stimulus. Orienting was described as the ability to direct attentional resources towards a particular stimulus or spatial location, selecting this information for further processing. Executive control was deemed necessary to manage situations where the available information triggered inappropriate behavioral responses conflicting with current intentions [44]. These three functions are considered to be independent of each other [22]. The Attentional Network Test (ANT [22]) is an assessment tool designed to measure the efficiency of these three functions at a behavioral level in the same individual simultaneously. Previous study suggested engagement in strategic sports (football) was associated with enhanced performance on ANT [60]. Lu et al. [40] demonstrated that elite shooting and archery athletes on the national team are more efficient in all three attention networks. These studies indicate that professional athletic training is associated with changes in attentional functions.

An important aspect of neuroplasticity research is exploring the relationship between neural plasticity changes and cognitive abilities [50]. However, few studies directly explored the relationship between neuroplastic differences and cognitive abilities in professional athletes compared to non-athletes. In present study, we investigated the differences in brain function and attentional functions between football athletes and novices, and further explored the potential relationship between them. Based on consistent findings from previous research, we hypothesized that significant differences existed between football athletes and novices in brain regions such as the cerebellum, motor cortex, and the superior temporal gyrus (STG). Furthermore, we hypothesized that football athletes had superior attentional functions compared to novices. More importantly, we predicted that changes in brain functional plasticity were associated with alterations in attentional functions.

Materials and methods

Participants

We recruited a total of 67 active professional football athletes from the Shanghai Greenland Shenhua Football Club and 86 students without football experience from Shanghai University of Sport. All football athletes hold a Certificate of National First-Level Athlete of China and have undergone more than 5 years of professional football training (mean = 9.724 years, SD = 2.729, range = 3–16 years). Thirty participants did not complete the fMRI scan due to having personal preference, metal implants in the body or other physical reasons. Eleven participants were excluded from the analysis due to excessive head movement (Excluding Criteria: 2.0 mm and 2.0 degree in max head motion). Therefore, the current study included 49 football athletes (28 females) and 63 football novices (36 females). The football novices had no prior experience in football training, and did not have the habit of watching football matches. We matched the two groups for age(experts: $M \pm SD = 20.408 \pm 1.707$, range:18–25; novices: $M \pm SD = 19.905 \pm 1.583$, range:17–24, $t = 1.613$, $p = 0.110$, Cohen's $d = 0.307$) and level of education (expert: 6 graduate students, 43 undergraduate students; novices: 8 graduate students, 55 undergraduate students). All participants were right-handed, had normal or corrected-to-normal vision, and reported no history of neurological disorders. All experimental procedures were approved by the Ethics Committee of Shanghai University of Sport, China. Informed consent was obtained in written form from all participants prior to their involvement in the study.

Behavioral task

Prior to the MRI scan, participants were required to complete the Attention Network Test (For the task procedure, see Fig. 1.). The ANT is a psychological testing tool used to assess the functionality of an individual's attention networks [22]. Subjects viewed five horizontal lines on a 15.6-inch (39.6 cm) computer screen, each positioned above or below a central fixation cross. The middle line contained arrowheads pointing left or right. Subjects were tasked with rapidly and accurately pressing a keyboard button to indicate the direction of the central arrowhead. To evaluate the three attentional functions, three conditions were used: (1) An asterisk appeared before the target line, measuring alerting effectiveness by the decrease in response time. (2) The asterisk was shown at the target arrow's location, with improved performance indicating the orienting network's function. (3) The target line was flanked by lines with arrowheads

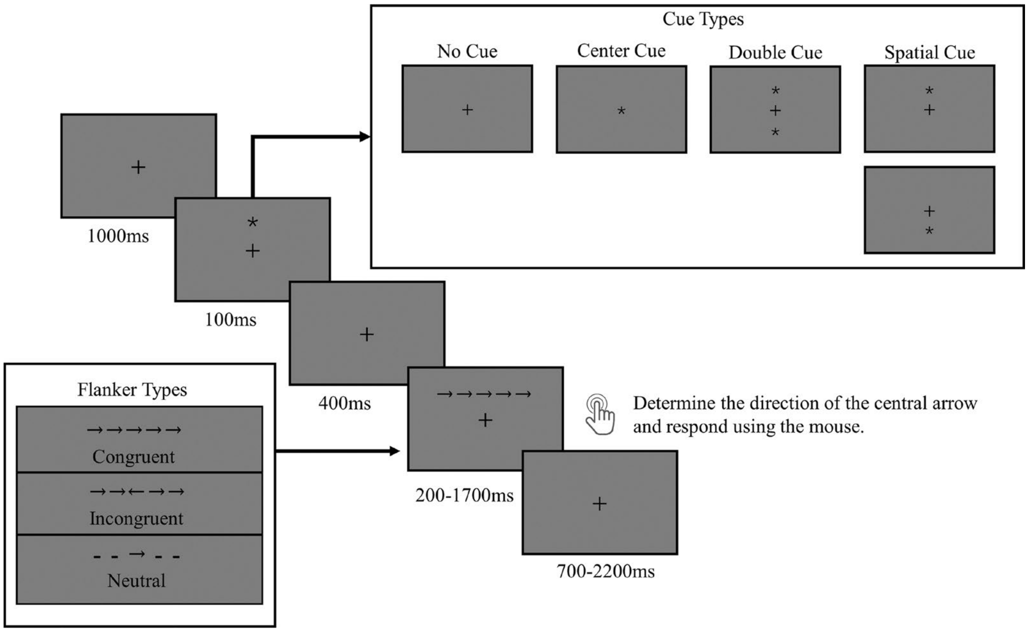

Fig. 1 Description of the Attention Network Test. Following a 1000 ms (ms) fixation point, cues (four types of cues) are presented, and after a 400 ms interval, participants need to determine the direction of the central arrow

pointing in the same (congruent) or opposite (incongruent) direction as the target, with the reaction time variance measuring executive control efficacy. Each participant completed 207 trials, including 15 practice trials with feedback. The entire session, with breaks, lasted approximately 20 min.

Functional imaging

Imaging data were acquired using a Siemens Prisma 3 T scanner with a 64-channel phase-array head coil at the Imaging Center for MRI Research, Shanghai University of Sport. Participants were positioned supine with their heads stabilized using foam pads to reduce movement during scanning. The task-based functional imaging data included 252 continuous whole-brain functional volumes (scan duration: 8.4 min). These were captured using a gradient echo-planar imaging (EPI) sequence with the following parameters: repetition time (TR) = 2000 ms; echo time (TE) = 30 ms; 58 slices; voxel size = 2 × 2 × 2.4 mm^3; flip angle = 90°. Additionally, a high-resolution T1-weighted anatomical MRI was obtained for each participant with the following specifications: TR = 2530 ms; TE = 2.98 ms; 192 slices; voxel size = 1 × 1 × 1 mm^3; flip angle = 7°.

Data analysis

Behavioral analysis

Following Fan et al. [22], the calculation of mean RT in this study excluded error trials. The alerting effect was measured by subtracting the mean RT in the double-cue conditions from the mean RT in the no-cue conditions for each group (alerting effect: $RT_{\text{no-cue}} - RT_{\text{double-cue}}$). The orienting effect was calculated by subtracting the mean RT in the spatial cue conditions from the mean RT in the center cue conditions for each group (orienting effect: $RT_{\text{center-cue}} - RT_{\text{spatial-cue}}$). The conflict effect was evaluated by subtracting the mean RT in the congruent flanking conditions from the mean RT in the incongruent flanking conditions for each group (conflict effect: $RT_{\text{incongruent}} - RT_{\text{congruent}}$). The above calculation methods are consistent with those of Fan et al. [22]. Independent samples t-tests were used to determine if there were significant differences in the performance of the attention networks between the groups.

fMRI data preprocessing

The resting-state fMRI data were preprocessed using SPM12 and the DPABI toolbox as described by Yan et al. [88]. The steps were as follows: (1) discarding the initial ten images from each participant to stabilize the magnetic field and ensure participant adaptation, (2) correcting for slice timing and head motion using the default motion correction procedures. (participants exhibiting head motion exceeding 2 mm or 2 degrees were excluded), (3) BET and T1 coregistration to the functional images, (4) regression of nuisance variables including the Friston-24 motion parameters and three other confounding signals (white matter, cerebrospinal fluid, and global signals), (5) spatial normalization to the Montreal Neurological Institute (MNI) space and resampling to $2\times2\times2$ mm^3 resolution, (6) spatial smoothing with a 4 mm full-width-at-half-maximum Gaussian kernel, (7) removal of linear trends, and (8) temporal band-pass filtering within the frequency range of 0.01–0.08 Hz.

Fractional amplitude of low-frequency fluctuations analysis In the present study, the fALFF methodology was employed as an alternative to the traditional ALFF approach due to the latter's susceptibility to signal perturbations from physiological sources unrelated to neural activity [100]. ALFF quantifies the amplitude of low-frequency oscillations in the BOLD signal, typically within the 0.01–0.08 Hz range, which is believed to reflect regional spontaneous neural activity. fALFF is defined as the ratio of ALFF within a specific frequency band (e.g., 0.01–0.08 Hz) to the ALFF calculated across the entire frequency range of the BOLD signal. This normalization process effectively reduces the impact of global signal variations and physiological noise, providing a more specific measure of spontaneous neural activity related to neuroplasticity [101]. The fALFF metric was calculated using DPABI [88]. Group-level analyses were conducted using SPM12 with independent t-tests, controlling for age and gender as covariates. Statistical significance was determined at the voxel level using a False Discovery Rate (FDR) corrected threshold of $p < 0.05$ to account for multiple comparisons. At the cluster level, significance was determined at $p < 0.05$ with FDR correction, requiring clusters to consist of at least 50 contiguous voxels.

Seed-based functional connectivity analysis The seed-based voxel-wise resting-state functional connectivity (rsFC) analysis consisted of three steps for five seed regions identified by fALFF analysis: (1) extracting and averaging the time courses of all voxels within each seed region; (2) computing Pearson correlation coefficients between the mean time courses of the seeds and those of all other voxels across the brain; (3) transforming the rsFC maps into z-maps using Fisher's z-transformation to enhance normality and improve statistical analysis quality.

For group-level analyses, SPM12 was used to conduct independent t-tests. Age and gender were included as covariates to control for irrelevant variables. The results were thresholded at $p < 0.05$, FDR-corrected, both voxel-wise and cluster-wise, with a minimum cluster size of 50 voxels.

Multiple linear regression analysis Seed-based rsFC analysis indicated that the anterior lobe of the cerebellum might play an important role in higher cognitive functions through its connections with cortical areas. To further verify this hypothesis, we extracted and averaged rsFC values across the brain regions that exhibited differential connectivity with the left anterior lobe of the cerebellum (as determined by an independent-samples t-test with voxel-based FDR correction at $\alpha = 0.05$ and a minimum cluster size of 50 voxels) in the seed-based FC analysis, and then used these aggregated measures for a multiple linear regression analysis comparing experts and novices. Multiple linear regression analyses were then conducted to ascertain whether the differentially active regions could predict the executive control, orienting, and alerting scores for both expert and novice groups, as well as to evaluate the distinct contributions of rsFC in explaining individual variability. Specifically, each region's average rsFC value served as a separate predictor in the multiple regression models, with a total of eight predictors. The dependent variables included the executive control, orienting, and alerting scores. To further evaluate the relationship between cerebellar cortical connectivity and professional football training, we conducted a multiple linear regression analysis using training years as the dependent variable and the same rsFC values as independent variables, consistent with the methodology described above.

Our multiple linear regression analyses were performed using OriginLab (OriginLab Corporation, Northampton, MA, USA).

Graph theory analysis Graph theory provides the ideal framework for the precise mathematical depiction of complex networks. In formal terms, a complex network can be depicted as a graph, represented by G(N, K), where N indicates the total nodes and K represents the edges within the graph G. In present study, nodes (N) representing the brain regions in the Automated Anatomical Labeling (AAL) template which divided the gray matter cortex. Edges (K) representing the functional connectivity strength between nodes. Functional network analysis was conducted across the whole brain, using 116 regions defined by the AAL atlas as network nodes [89]. The BOLD time series of all voxels within each region were extracted and averaged. Subsequently, functional connectivity among all ROI pairs was measured using Pearson correlation coefficients. The correlation coefficients were subsequently standardized to z-scores via Fisher's r-to-z transformation. These matrices represent the strength of the functional connectivity within the whole brain and served as edges for the graph analysis.

For the graph analysis, two types of brain network metrics were calculated using Gretna [86]: (1). The nodal network metrics including betweenness centrality, degree centrality and node efficiency within the whole brain, respectively; (2). The small world parameters including normalized clustering coefficient (λ), small-worldness (σ) and normalized characteristic path length (γ). Network sparsity was used as thresholding method, sparsity is calculated as the fraction of the actual number of edges over the highest possible number of edges within a network. In networks that share an equal number of nodes, a sparsity threshold is applied to maintain an identical edge count across all networks, achieved by setting a threshold based on the unique connectivity strength for each subject. This method permits the assessment of the comparative organizational structure of networks [30]. Threshold sequence was calculated based on the existing literature [39, 87]. Network type was set to binary, and the negative correlation coefficients were set to zero.

Then, independent samples T-tests were used to compare brain network indices between experts and novices. The results of the nodal network indices were corrected using FDR correction (α = 0.05).

Results

Behavioral results

The results of independent samples T-test (Fig. 2) showed there were no significant differences for executive control scores($t_{(110)}=0.594$, $p=0.123$, Cohen's $d=0.296$). The orienting scores of experts were significantly higher than those of novices. ($t_{(110)}=2.022$, $p=0.046$, Cohen's $d=0.385$). However, the alerting scores of experts were significantly lower than those of novices. ($t_{(110)}=-2.132$, $p=0.043$, Cohen's $d=-0.405$).

Fractional amplitude of low-frequency fluctuations analysis

The independent samples T-test on the fALFF z-score maps revealed significantly higher fALFF values in experts within the bilateral anterior cerebellar lobes, bilateral insula, and left superior temporal gyrus (FDR-corrected α = 0.05, cluster size > 50; see Fig. 3 and Table 1 for details).

Seed-based functional connectivity analysis

Seed-based rsFC analysis, utilizing regions identified in the fALFF analysis, was conducted to examine the differences in intrinsic connectivity between experts and novices. Figures and Tables depict the T maps from the seed-based rsFC analysis. For the left anterior cerebellar lobe seed (Fig. 4), experts demonstrated enhanced correlations with clusters in the right supramarginal gyrus, left precuneus, right posterior cerebellar lobe, left middle temporal gyrus, superior temporal gyrus, supramarginal gyrus, angular gyrus, left superior frontal gyrus, left posterior cerebellar lobe, and bilateral precentral gyrus. For the left superior temporal gyrus seed (Fig. 5), experts showed increased correlation with clusters in the left anterior cerebellar lobe and left inferior frontal gyrus (FDR-corrected α = 0.05, cluster size > 50; see Table 2 for details). For the right cerebellum anterior lobe, left insula, and right insula seed regions, no significantly different clusters were identified between experts and novices.

Multiple linear regression analysis

The results of the multiple linear regression analysis, summarized in the Table 3, revealed that the differences in rsFC between the groups exhibit strong predictive power for orienting scores in the expert group (adjusted $R^2=0.178$, $F=2.303$, $p=0.039$). However, such predictive power was not observed in the novice group (adjusted $R^2=-0.001$, $F=0.995$, $p=0.451$). As shown in Fig. 6, the cerebellar-cortical connectivity can predict the attention orientation scores in the expert group but cannot predict the attention orientation scores in the novice group. No severe multicollinearity was observed in either group, with tolerance values

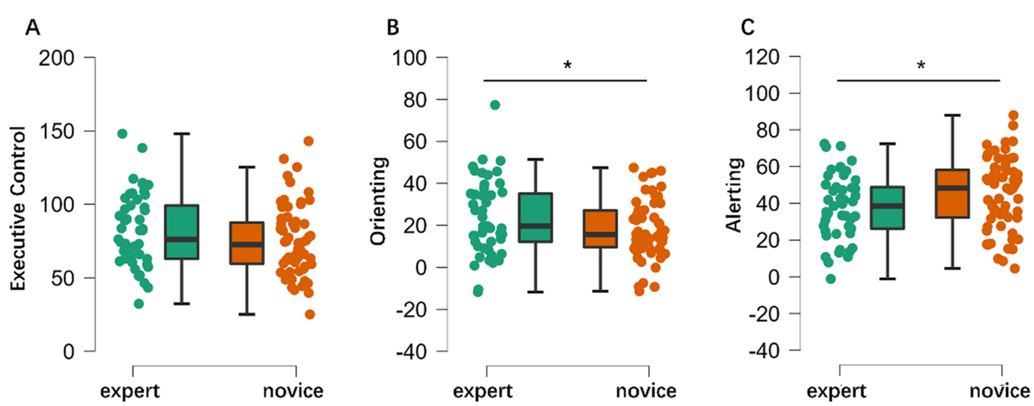

Fig. 2 Behavioral results of ANT. The efficiency of attention networks, calculated using the subtraction method by Fan et al. [22]. **A** Executive control score; **B** orienting score; **C** alerting score. *$p < 0.05$

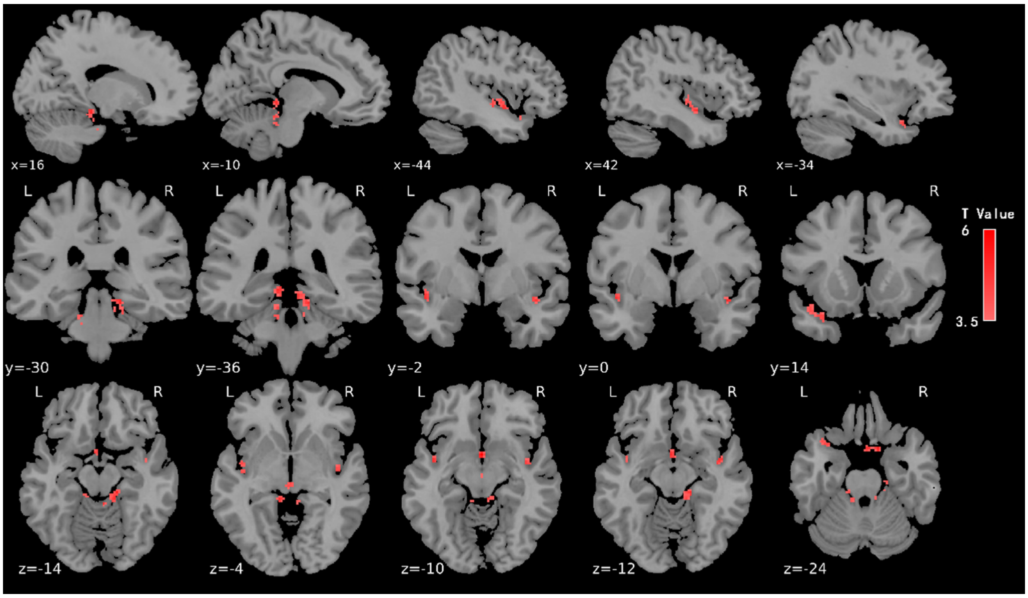

Fig. 3 Differences in fALFF between football athletes and non-athletes. The red area indicates that football experts have significantly higher fALFF values in this brain region compared to football novices (FDR-corrected α = 0.05)

Table 1 fALFF differences between football athletes and non-athletes

Predominant regions in cluster	Cluster size	Peak T-value	Voxel-level	MNI coordinates		
			$P_{FDR\text{-}corr}$	x	y	z
Contrast: Experts > Novices						
Right cerebellum anterior lobe	219	5.017	0.029	16	− 30	− 14
Left cerebellum anterior lobe	124	4.806	0.029	− 10	− 36	− 4
Left insula	74	4.823	0.029	− 44	− 2	− 10
Right insula	59	4.838	0.029	42	0	− 12
Left superior temporal gyrus	86	4.341	0.045	− 34	14	− 24

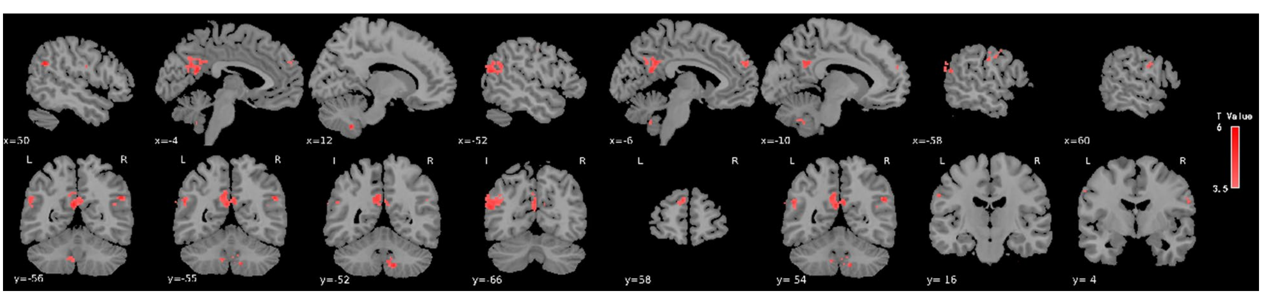

Fig. 4 Functional connectivity differences between experts and novices using the left anterior cerebellar lobe as the seed region

above 0.2 and VIFs below 5 for all eight covariates [37]. Additionally, no significant predictors were identified for either the expert or novice groups (Supplementary Tables S2 and S3 for detailed information).

As shown in Fig. 7, the multiple linear regression analysis revealed that rsFC values significantly predicted training years (adjusted $R^2 = 0.279$, $F = 3.327$, $p = 0.005$). The coefficients of the predictive factors are presented in the

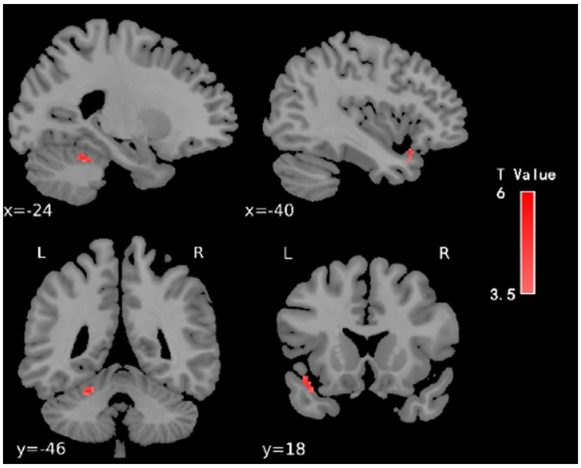

Fig. 5 Functional connectivity differences between experts and novices using the left superior temporal gyrus as the seed region

supplementary materials. The cerebellum-precuneus connectivity ($\beta = -0.438$, $p = 0.011$) and cerebellum-MTG connectivity ($\beta = 0.468$, $p = 0.024$) identified as significant predictors.

Graph theoretical analysis

For the nodal network metrics, independent samples t-tests were conducted for each attribute, followed by FDR multiple comparison correction ($\alpha = 0.05$). The results showed that three nodal regions differed significantly between experts and novices. For the right cerebellar lobule III (Cerebelum_3_R) node, experts showed higher BC ($t = 4.283$, $p < 0.001$) and node efficiency ($t = 3.363$, p = 0.001) compared to novices. For the left dorsal cingulate gyrus (DCG.L) node, experts showed lower DC ($t = -3.644$, $p < 0.001$) and node efficiency ($t = -3.645$, $p < 0.001$) compared to novices. For the left supplementary motor area (SMA.L) node, experts showed lower node efficiency ($t = -3.332$, $p = 0.001$) compared to novices.

For the small-world parameters, both athletes and non-athletes exhibited economic "small-world" properties ($\lambda \approx 1$, $\gamma > > 1$). This indicates that their networks achieve global information processing efficiency comparable to a matched random network, while also demonstrating enhanced local information integration efficiency and fault tolerance [87]. The results of two-sample t-tests showed no differences between experts and novices in the three small-world parameters.

Table 3 Model summary of linear regression models with rsFC

Models	R^2	Adjusted R^2	F	Sig
Experts				
Executive control scores	0.089	− 0.093	0.488	0.857
Orienting scores	0.315	0.178	2.303	0.039
Alerting scores	0.135	− 0.038	0.782	0.621
Training years	0.400	0.279	3.327	0.005
Novices				
Executive control scores	0.112	− 0.019	0.853	0.561
Orienting scores	0.128	− 0.001	0.995	0.451
Alerting scores	0.105	− 0.028	0.792	0.612

Table 2 Functional connectivity differences between experts and novices

Predominant regions in cluster	Cluster size	Peak T-value	Voxel-level	MNI coordinates		
			$P_{FDR\text{-}corr}$	x	y	z
Seed Region: Left Cerebellum Anterior Lobe, Experts vs. Novices						
Right supramarginal gyrus	96	5.087	0.036	50	− 56	28
Left precuneus	585	5.066	0.036	− 4	− 56	20
Right cerebellum posterior lobe	69	4.829	0.036	12	− 52	− 48
Left Middle Temporal Gyrus	506	4.788	0.036	− 52	− 66	20
Superior Temporal Gyrus						
Supramarginal Gyrus						
Angular Gyrus						
Left superior frontal gyrus	61	4.242	0.038	− 6	58	28
Left cerebellum posterior lobe	59	4.120	0.039	− 10	− 54	− 42
Left precentral gyrus	104	4.055	0.041	− 58	− 16	32
Right precentral gyrus	55	3.977	0.043	60	− 4	26
Seed Region: Left Superior Temporal Gyrus, Experts vs. Novices						
Left cerebellum anterior lobe	53	5.138	0.036	− 24	− 46	− 24
Left inferior frontal gyrus	59	4.994	0.036	− 40	18	− 20

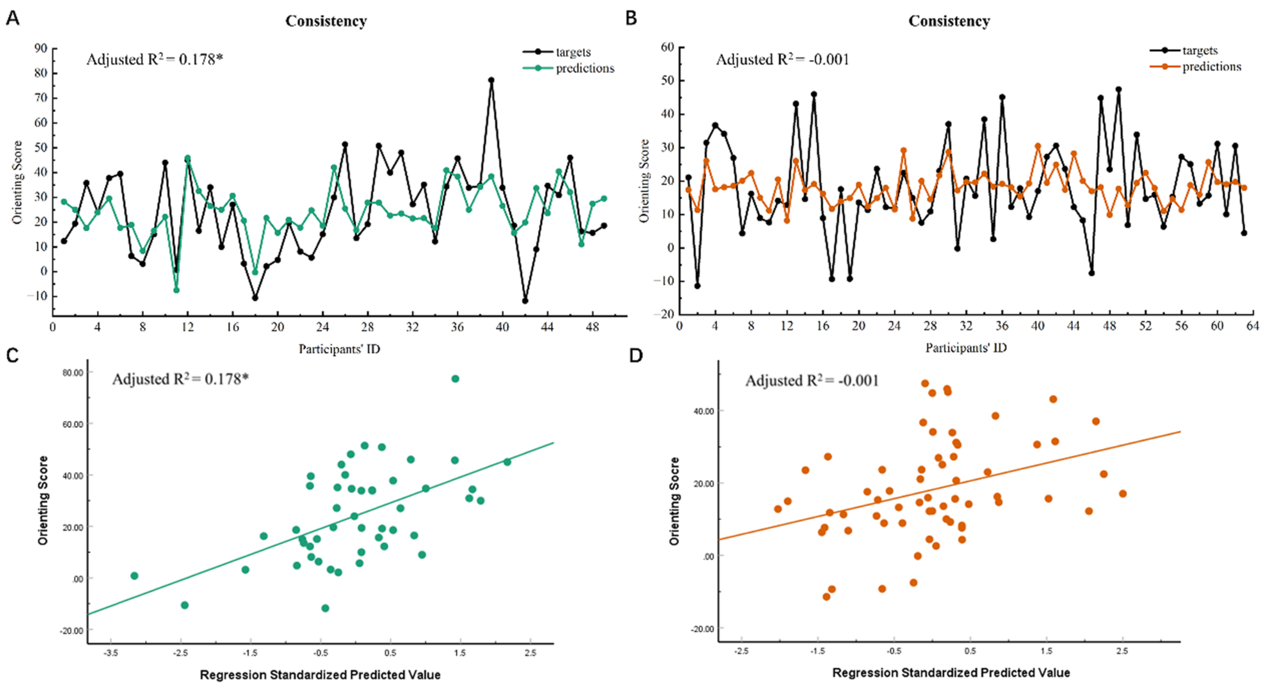

Fig. 6 Performance of the multiple linear regression model from the rsFC maps on orienting scores. **A** Multiple linear regression using rsFC significantly predicted experts' orienting scores (adjusted $R^2 = 0.178$, $p = 0.039$). **B** Multiple linear regression using rsFC did not significantly predict novices' orienting scores (adjusted $R^2 = -0.001$, $p = 0.451$). **C** The scatter plot displaying the relationship between the regression standardized predicted values and the orienting scores for experts **D** and for novices

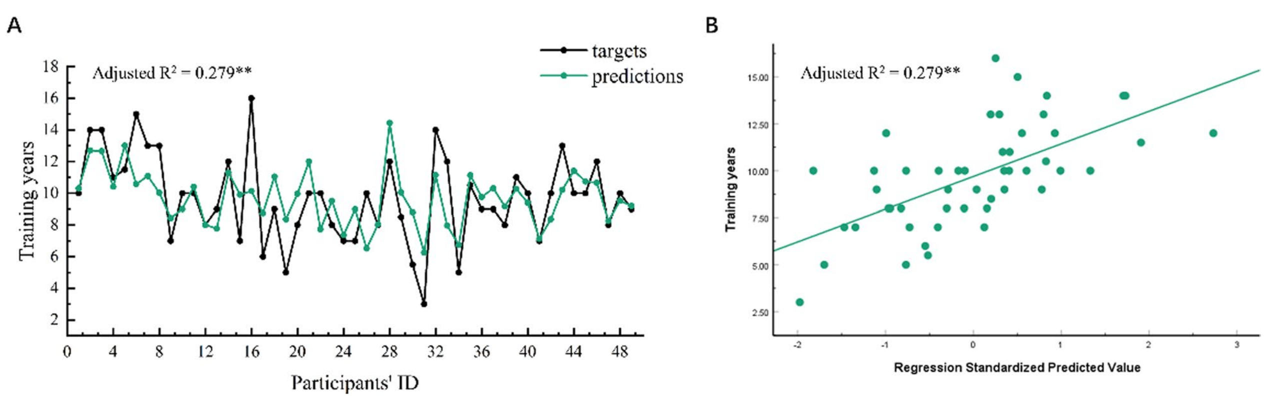

Fig. 7 Performance of the multiple linear regression model derived from rsFC maps on experts' training years. **A** Multiple linear regression using rsFC significantly predicted experts' training years (adjusted $R^2 = 0.178$, $p = 0.005$). **B** The scatter plot displaying the relationship between the regression standardized predicted values and the training years for experts

Discussion

In this study, we investigated the differences in brain function and attentional abilities between professional football athletes and novices using resting-state functional magnetic resonance imaging and the Attention Network Test. We found that football experts and novices exhibited differences in fALFF, intrinsic functional connectivity, and topological properties of brain networks. Furthermore, significant differences were observed between football experts and novices in aspects of attentional orienting and alerting. More importantly, functional connectivity differences observed in the connectivity analysis significantly predicted attentional orienting scores and training years in the expert group. Taken together, our results indicated significant neuroplastic changes and attentional alterations in athletes, suggesting that the cerebellum might play a crucial role in orienting attention functions.

The behavioral results from the ANT revealed that football experts exhibited superior orienting attention but weaker alerting functions compared to novices, with no difference in executive control attention. These three ANT components represent distinct attentional processes. The alerting attention represents the efficiency of achieving and maintaining a vigilant state in response to an impending stimulus. The orienting attention indicates the ability to shift attentional focus toward relevant spatial or sensory cues. The executive control attention measures the capacity to resolve conflicts between competing responses [44]. Previous meta-analyses have indicated that football training may enhance attentional abilities in children and adolescents [43]. For example, Rahimi et al. [60] reported that soccer players demonstrated faster response times in the alerting and valid orienting cue conditions of the ANT. Consistent with these findings, the present study showed that football experts exhibited superior orienting attention. However, we did not find that football experts possessed enhanced executive control attention, which is inconsistent with some previous studies [1, 52, 84]. For example, Moratal et al. [52] found that, compared to non-athletes, soccer players exhibited overall faster responses and better executive control attention on the ANT. Moreover. our finding diverges from some previous studies that reported enhanced alerting functions in athletes [60, 81]. One possible reason for the lower alerting scores in experts is that their training emphasizes quick, automatic responses to familiar stimuli, potentially reducing the need for heightened alertness. The enhanced orienting function in experts may be attributed to the specific demands of football, which requires rapid and precise attention shifts to dynamic and spatially distributed stimuli [40]. In summary, our study suggests that the relationship between motor training and attentional functions is multifaceted. While football training appears to enhance orienting attention, it does not uniformly improve all components of the attentional functions. Therefore, further research is needed to elucidate the underlying mechanisms and to explore how different types of training may differentially impact various aspects of attention.

Our findings were consistent with previous research showing that long-term motor training induces both structural and functional plasticity in the brain [40, 46, 89, 91, 95, 96, 98]. Specifically, we observed higher fALFF values in football experts within the bilateral anterior cerebellar lobes, bilateral insula, and left superior temporal gyrus. The anterior cerebellum, traditionally known for its role in motor control and coordination, has gained attention for its involvement in cognitive performance and attentional processes [5, 66]. The insula, located deep within the lateral sulcus, is an important node of the fronto-parietal attention network [24, 74], and is closely related to attentional function [77]. Increased neural activity in the insula might facilitate the integration of sensory information and the allocation of attentional resources to salient stimuli. The superior temporal gyrus is known for its role in auditory processing and language comprehension [51, 92]. fALFF reflects the amplitude of low-frequency oscillations (0.01–0.08 Hz) within a specific frequency range, which are believed to reflect the intensity of regional spontaneous brain activity [100]. The enhanced fALFF observed in football athletes indicates increased spontaneous neuronal activity in these regions, suggesting that sports training may induce adaptive neural changes, which is consistent with previous studies [32, 59, 97]. Moreover, the present study reveals that the effects of sports training on the brain are widespread, influencing not only motor control related regions but also areas linked to higher cognitive functions, such as the insula. These findings provide valuable insights into the mechanisms underlying neuroplastic changes induced by physical training.

Seed-based functional connectivity analysis further clarified the neural underpinnings of these differences. Football experts showed increased connectivity between the left anterior cerebellar lobe and various cortical regions, including the right supramarginal gyrus, left precuneus, left superior frontal gyrus, bilateral posterior cerebellar lobe, and bilateral precentral gyrus. Additionally, the functional connectivity between the left STG and the left anterior cerebellum was stronger in experts than in novices. The supramarginal gyrus is considered to be associated with word processing [55, 65, 69]. The precuneus is a core node of the Default Mode Network and is associated with higher cognitive functions, including attention [13, 16, 42, 78]. Furthermore, previous studies showed that the precuneus was activated during the execution of attentional orienting tasks [26, 54, 93]. The superior frontal gyrus contributes to higher cognitive functions, particularly working memory [7, 38, 45]. The posterior parts of the cerebellum are involved in higher cognitive modulation [5, 63]. The precentral gyrus is widely recognized for its crucial role in movement execution [33, 62]. The precentral gyrus is also thought to play a key role in higher cognitive processes, such as attention, motor learning, movement imagery and language [6, 83, 99]. Previous research utilizing transfer techniques and neuroimaging has revealed extensive connections between the cerebellum and the cerebral cortex [19, 35, 36, 70, 71]. These connections are functionally implicated in the coordination of motor and cognitive behaviors [10, 23, 61]. Furthermore, previous studies have found that motor training can modulate the connectivity between the cerebellum and motor-related cortical regions [47, 75, 76]. For example, Mehrkanoon et al. [47] found enhanced connectivity within the cerebellum and between the cerebellum and motor cortex following motor training, as revealed by source-reconstructed electroencephalography. Consistent with previous studies, the current study found that football athletes exhibited stronger functional connectivity within the cerebellum and between the cerebellum and motor-related cortex (bilateral precentral gyrus) compared to novices. Furthermore, we found that long-term sports training also enhanced connectivity between the cerebellum and broader brain regions, including the precuneus and supramarginal gyrus. The findings suggest that long-term motor training may induce plastic changes in cerebellar-cortical connectivity, and these adaptive changes could potentially regulate cognitive abilities such as attention and language. Furthermore, the multiple linear regression analysis examining the relationship between rsFC and years of football training revealed that enhanced rsFC significantly predicted athletes' training years, with cerebellum-precuneus connectivity and cerebellum-MTG connectivity identified as significant predictors. These findings provide additional evidence that motor training induces plastic changes in cerebellar-cortical connectivity.

More importantly, we found the enhanced functional connectivity can significantly predicted attentional orienting scores of experts, a phenomenon not observed in the novices. Previous studies have emphasized the crucial role of the cerebellum in attentional functions [2, 3, 5, 15, 63, 66]. For example, Brissenden et al. [8] found that visual attention tasks strongly engage the cerebellum, and cerebellum-to-cortex functional connectivity significantly predicted cortical activation patterns during task performance. The current study further demonstrated that the cerebellum may participate in attentional orienting functions through extensive crossed cerebrocerebellar connections. Additionally, this involvement was modulated by long-term professional football training. Furthermore, previous studies primarily linked the posterior lobe of the cerebellum to attentional processes [2, 5], [64]. However, our findings suggest that the anterior cerebellum may also contribute to attentional processes. This observation may be understood within the broader context of the relationship between attention and motor control. Attention and motor control are closely intertwined, as rely on shared neural resources and overlapping networks [14, 20]. Effective motor control often demands precise allocation of attentional resources to guide movements and adapt to dynamic environments ([18]; [53]. Given the anterior cerebellum's established role in motor coordination [72], [66] and its connectivity with cortical areas implicated in attention, it is plausible that this region supports attentional processes indirectly through its involvement in motor-cognitive integration. Long-term professional football training may further enhance this integration, facilitating the adaptation of attentional functions to task-specific demands. Our finding highlights the need for a more nuanced understanding of how the cerebellum contributes to the interplay between motor and cognitive processes.

Graph theoretical analysis emphasized the impact of athletic training on neural plasticity, suggesting that football training could reorganize functional connectivity patterns within the brain. Experts exhibited higher betweenness centrality and node efficiency in the Cerebellum_3_R node, a part of the anterior lobe of the cerebellum, indicating enhanced integration and coordination of neural information within this region. The results of graph theoretical analysis, consistent with fALFF and functional connectivity analyses, indicate the impact of physical training on cerebellar function. Conversely, lower degree centrality and node efficiency in the DCG.L node, a part of the dorsal cingulate gyrus, may reflect a reorganization prioritizing essential connections, enhancing processing efficiency for rapid attentional shifts and decision-making in football. Additionally, both athletes and non-athletes displayed economic "small-world" properties without significant differences between groups. This suggests that while soccer training enhances specific nodal efficiencies, it does not alter the fundamental small-world architecture of brain networks. Overall, these findings suggest that long-term professional football training leads to significant neuroplastic changes, particularly in regions associated with motor and cognitive functions.

Conclusion

In summary, this study highlights the significant impact of long-term professional football training on neuroplasticity and attentional functions. Our findings demonstrated that football athletes exhibit enhanced functional connectivity between the cerebellum and various brain regions involved in higher cognitive processes, compared to novices. Specifically, the cerebellum's involvement in attentional orienting functions appears to be modulated by extensive crossed cerebrocerebellar connections. Moreover, graph theoretical analysis indicated that football training enhances integration and coordination of neural information, particularly in the cerebellum. These findings reveal a neurobiological basis for the correlation between neuroplasticity and attentional plasticity, highlighting how professional football training leads to significant neuroplastic changes and enhanced attentional functions.

Limitation

This study selected professional football athletes and used university students without football experience as a control group. Despite balancing for age and educational background between the groups, we must acknowledge that this study cannot determine whether changes in brain function and attentional abilities in football players are due to innate factors, environmental influences, or a combination of both. Future research could incorporate longitudinal designs to track neural and cognitive changes over time, providing insights into causal relationships. Another limitation of this study is the lack of control for cardiovascular fitness variables, such as heart rate or blood flow, which could affect BOLD signal interpretation and resting-state fMRI results. Future studies should include these measures to improve accuracy in functional connectivity assessments.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12993-025-00272-3.

Supplementary material 1

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Author contributions

JW was responsible for data curation, conceptualization, formal analysis, methodology, visualization, writing the original draft, reviewing and editing the manuscript, and project administration. SG contributed to data curation. JTwas involved in investigation and data curation. HH contributed to reviewing and editing the manuscript. CZ provided resources, reviewed and edited the manuscript, and supervised the project.

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Availability of data and materials

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

Declarations

Ethics approval and consent to participate

All experimental procedures were approved by the Ethics Committee of Shanghai University of Sport, China (No. 102772022RT082, Data: 13/09/2022).

Consent for publication

Informed consent was obtained in written form from all participants prior to their involvement in the study.

Competing interests

The authors declare no competing interests.

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