Article

Football Juggling Learning Alters the Working Memory and White Matter Integrity in Early Adulthood: A Randomized Controlled Study

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Abstract: Cross-sectional studies suggest that motor skill learning is associated with working memory (WM) and white matter integrity (WMI). However, it has not been established whether motor skill learning improves WM performance, and information on its neural mechanisms have not been clearly elucidated. Therefore, this study compared WM and WMI across time points prior to and following football juggling learning, in early adulthood (18–20 years old), relative to a control group. Study participants in the experimental group were subjected to football juggling for 10 weeks while participants in the control category went on with their routine life activities for the same period of time and were not involved in the learning-related activities. Data on cognitive measurements and that from diffusion tensor imaging (DTI) were collected before and after learning. There was a significant improvement in WM performance of the experimental group after motor learning, although no improvement was observed in the control group. Additionally, after learning, DTI data revealed a significant increase in functional anisotropy (FA) in the genu of corpus callosum (GOCC) and the right anterior corona radiata (R.ACR) in the experimental group. Moreover, the better WM associated with football juggling learning was correlated to a higher FA. Mediation analysis suggested that FA in the GOCC acts as a mediation variable between football juggling learning and WM. These findings show that motor skill learning improves the WM and remodels WMI in early adulthood. With a particular emphasis on the importance of WMI in motor skill learning and WM, this study also revealed the possible neural mechanisms mediated by WMI.

Keywords: motor learning; football juggling; working memory; diffusion tensor imaging; fractional anisotropy

1. Introduction

Over the recent years, extensive research has been conducted on the relationship between motor skill learning and cognitive function [1,2]. In addition, acquisition and long-term retention of motor skills play a fundamental role in our daily lives [3]. Motor skill learning refers to the process of performing faster and more accurate movements through practice [4]. This process is closely associated with many cognitive functions, including attention [5], inhibition control [6], and working memory [7]. On the other hand, working memory (WM) refers to the processes used to temporarily store and manipulate information in the mind [2] and is regarded as a core component of cognitive function. Therefore, elucidation of motor skill learning and WM will provide theoretical insights that are applicable to the pathway and mechanisms of promoting cognitive development.

Additionally, studies involving participants' various age groups has demonstrated that motor learning has a strong positive impact on WM behavioral indicators [8–12]. Moreover, surveys involving tennis and soccer players, walkers, and musicians showed that people trained for long had better working memory performance than non-professional controls, and performance of the working memory was correlated with the level of motor skills [13–18]. However, current studies only focused on behavioral changes in WM, and the underlying mechanisms through which skill learning improves WM have not been clarified. Furthermore, advances in magnetic resonance imaging (MRI) and other technologies have facilitated studies on the relationship between working memory and brain structure at the neural level. For instance, Seidler et al. showed activated right dorsolateral prefrontal cortex and bilateral inferior parietal lobules through working memory tasks, while Lazar investigated the role of white matter structures in WM [2,19]. Recent studies have reported that WM is closely correlated with brain structure, including the prefrontal cortex, basal ganglia, and thalamus [20,21]. These studies do not establish whether motor skill learning plays a crucial role in cognitive behavior or in brain structure.

Numerous studies have demonstrated that motor skill learning and acquisition can cause changes in brain structure [22–27]. The brains of musicians, professional athletes, and others who have been trained for a long time have a different structure compared to those of non-professionals or novices [28]. Compared to non-musicians, musicians with long-term (more than 10 years) musical training were found to have a lower fractional anisotropy (FA) in their corona radiata and internal capsule, but higher FA in the genu of the corpus callosum [29]. World-class gymnasts were found to have lower FA in four regional deep white matter tracts when compared to non-athlete normal controls [28]. A number of longitudinal studies have also shown the effects of different types of skill training on white matter integrity (WMI). For example, Piervincenzi et al. performed 12 weeks of Quadrato Motor Training and found a significant increase in FA in some brain regions of the participants compared to the baseline, although there was a decrease in FA compared to the medium [30]. Studies involving learning the computer car racing game [31], balance [27], unicycling training [32], badminton [33], and the finger–thumb opposition sequence task [34] reported that motor skill learning can lead to changes in white matter integrity in related brain areas, leading to structural reorganization. White matter is composed of glial cells and myelin sheath neurons, and improvement of white matter integrity is conducive for effective neurotransmission in the brain, which in turn improves cognitive function [35,36]. As the most commonly evaluated WMI index, FA characterizes the directionality of constrained water diffusion in brain tissues [37,38]. Notably, an increase in FA is considered to indicate an improvement in WMI [39,40]. Over the past decade, studies have reported the benefits of motor skill learning on structural and functional cognitive health in human populations.

Moreover, remodeling of brain structures by motor skills may involve complex pathways that lead to WM improvements. Additionally, WMI has been reported to be associated with WM throughout the life cycle [5,41–43]. However, most of the current studies are horizontal in nature and are, therefore, unable to draw valid conclusions on causal mechanisms. In addition, the reported results are heterogeneous due to the different types and degrees of skill learning. Most of the existing studies on skill learning adopt simple tasks (such as finger sequence learning and computer game learning), which focus on the learning of upper limbs or brain processing, but do not involve a lot of body coordination, sensory perception, and spatial ability. As such, they cannot be extended to complex and real motor skill learning. Moreover, football is an open-skill exercise that needs mobilization of more cognitive resources in the process of implementation and therefore has better effects in promoting cognition [14,44–48]. Furthermore, the learning process has higher requirements for information processing, limb control, and sequence memory.

Therefore, the effects of learning the complex juggling processes in football on WM and WMI in a real learning environment should be evaluated. This will elucidate the

relationship between motor skills learning, working memory, and the brain. In addition, this study may reveal the complex pathways through which motor skills improve cognition.

Consequently, we selected football juggling as the motor skill learning task. Additionally, we used diffusion tensor imaging (DTI) technology and working memory test tools to evaluate the effects of football juggling learning on WMI and WM in early adulthood. This was done to elucidate the relationship between motor skill learning and brain plasticity. On the basis of the above background, we hypothesized that (i) football juggling learning can improve the working memory and remodel white matter integrity in early adulthood; (ii) improvement of working memory caused by football juggling learning is related to changes in white matter integrity; and (iii) remodeling of white matter integrity, induced by football juggling learning, mediates the improvement of working memory.

2. Materials and Methods

2.1. Study Participants

A total of 111 college students aged 18 to 20 years (40 females and 71 males) from Yangzhou, China, were recruited in this study. They were randomly allocated into 2 groups: the experimental and control groups. The experimental group had 68 participants (23 females and 45 males), while the control category had 43 participants (17 females and 26 males).

The inclusion criteria were (i) being 18–20 years of age, (ii) right-handedness, and (iii) normal vision without color blindness. The exclusion criteria were drug abuse, any genetic disease, general intelligence problems, or any medical conditions that limited physical activity or could affect study results. Ethical approval for this study was obtained from the ethics and human protection committees of the Affiliated Hospital of Yangzhou University (2017-YKL045-01). All participants were required to provide written consent after receiving a detailed explanation of the experimental procedure.

A total of 94 participants (41 in the control group and 53 in the experimental group) passed the screening test, while the rest failed because (i) they had an injury that was not related to football (n = 1), (ii) the academic record of football juggling did not reach the standard (n = 11) (the criteria are described in a later section), (iii) they had a missing DTI image (n = 4), or (iv) they had missing test data on working memory (n = 1).

Demographic information (age, gender, weight, and height) of the participants was obtained at baseline. We performed a series of physical fitness tests to control for factors that might have affected the ability to learn football juggling. This was also done to measure the physical fitness of the subjects at baseline. The physical fitness test was divided into 3 parts: lower limb strength, speed sensitivity, and flexibility. The test item for lower limb strength was the standing broad jump (M) [49], which for speed sensitivity was a 4×10-m shuttle run (S) [50], while the test item for flexibility was sit-and-reach (CM) [51].

2.2. Study Design and Procedure

This was a randomized trial with a 2×2 factorial design using time (phase of testing—pre-test and post-test) as the within-subject factors, and group (two conditions—experimental, control) as the between-subject factors. The entire experiment consisted of 3 parts: pre-test, motor learning, and post-test. It was ensured that the pre-test and post-test locations, measurement tools, test time, testers, and instructions were consistent.

Study participants were also asked to provide their sociodemographic information. The Edinburgh Handedness Inventory [52], Raven's Standard Progressive Matrices (SPM) [53], and the 90-item Symptom Checklist (SCL-90) [54] were completed for all participants. Then, they were asked if they had experienced systematic football training and football juggling practice. Their eligibility for MRI scanning was also determined, after which they were required to sign the informed consent form. Finally, participants were screened on the basis of the selection criteria and randomized into the experimental and control groups. Physical fitness tests were performed before the beginning of the experiment. The experimental group was subjected to football juggling for 10 weeks, while the

control category continued with their routine life and were not involved in learning-related activities for the same period of time. Working memory tests and DTI were performed before (pre-test) and after (post-test) learning.

2.3. Football Juggling Learning

The motor learning plan was performed for 10 weeks for a total of 70 times, once a day, and each session lasted for 30 min. The learning venue was fixed while time was based on the law of football juggling learning as well as the preliminary experiments.

The learning methods were self-study and self-study training, using videos for guidance. Each time before learning commenced, learners were required to engage in warm-up activities (including jogging and freehand exercises) for 8–10 min. Then, they were required to practice on their own on the basis of the practice methods and movements explained in the teaching videos. Additionally, they were allowed to watch the teaching videos at any time during the 30-min learning process. Fixed professionals corrected and guided the learners' mistakes in motor learning through using a uniform instruction language. After learning, participants were allowed to relax for 8–10 min.

The standard for skill learning was to complete 35 sets of football juggling at a go. This was based on the standards for the Grading of Students' Football Skills, as recommended by the General Office of the Ministry of Education [55].

2.4. Assessment of Working Memory

The WM was measured using a sub-function of the test-tool designed by Chen [56,57], and WM performances of the participants were assessed through an n-back task. As a commonly used method of measuring working memory in cognitive neuroscience research, the n-back task has been widely used in the past decade [58]. Tasks were programmed using E-Prime, containing 1-back and 2-back conditions, which has been found to be suitable for this age [59,60]. Before starting the test, the screen presented unified instructions to prompt the subjects to get ready. The task consists of a series of changing letter stimuli (i.e., B, D, L, Y, P) displayed in the center of a computer screen. Each stimulus was displayed on a black background for 2000 ms, and each phase's duration was 2000 ms. Participants were asked to carefully read the letters and press "F" on the keyboard if the letter presented was the same as the nth (first or second) letter presented before, or "L" if it was different. "F" and "L" trials each accounted for 50% of the trials. Pressing the wrong button or failing to respond within 300–1500 ms were each considered incorrect responses. Each task consisted of 25 stimuli, and 12 stimuli were practiced (did not count in the results) before the formal test, with a 1-min rest interval between tests. The reaction time (RT) and accuracy (ACC; proportion of correct responses in n-back task) were recorded and averaged as the main behavioral index, where a shorter RT and greater ACC reflected better performance. By comparing the pre-test 1-back task with the 2-back task, we were able to exclude individual differences in the 2-back task. Therefore, the RT and ACC of the 2-back task can represent the working memory performance of the participants. Participants were asked to perform the 1-back and 2-back tasks at baseline, and only the 2-back task in the posttest.

2.5. DTI Imaging Acquisition and Analysis

Images were acquired using a 3.0T GE Healthcare whole-body high-speed imaging device equipped for echo planar imaging (GE Discovery MR750w 3.0T). Then, MRI scans were performed at the Affiliated Hospital of Yangzhou University. Participants were laid in a supine position and sedated during the examination. Head stabilization was achieved using foam pads, and any form of noise was reduced using the 29dB-rating earplugs. The DTI protocol was TR = 16,500 ms, TE = 96.2 ms, flip angle = 90°, field of view (FOV) = 224 × 224 mm, acquisition matrix size = 112 × 112, 70 interleaved slices, voxel size = $2 \times 2 \times 2$ mm^3, 3 B0 images, 30 diffusion-weighted images, and b value = 1000 s/mm^2.

Thereafter, processing of the diffusion MRI dataset was implemented using the "Pipeline for Analyzing Brain Diffusion Images (PANDA) (http://www.nitrc.org/projects/panda/, accessed on 29 September 2020)" MATLAB toolbox [61]. The main procedures included an initial pre-processing and computation of DTI metrics for statistical analysis, where local diffusion homogeneity (LDH) = 7 voxels, smooth: normalizing resolution = 2 mm, and smoothing kernel = 6 mm.

The preprocess steps included conversion of DICOM files, estimation of brain mask, cropping raw images, correcting for eddy-current effects, and calculating diffusion tensor metrics. Then, we normalized the diffusion metrics into the MNI space through atlas-based analysis, after which we calculated regional diffusion metrics by averaging the values within each region of the JHU ICBM-DTI-81 atlas, which showed 50 brain regions [62–65]. Furthermore, the mean FA value of each region was extracted for statistical analysis. All procedures were fully automated and completed by PANDA.

2.6. Statistical Analyses

Data processing and statistical analyses were performed using the SPSS 25.0 (IBM Corp., Armonk, NY, USA) statistical analysis package.

Demographic variables were compared between the control and exercise groups using independent sample *t*-tests for continuous variables (age, BMI, physical fitness tests). Moreover, chi-squared tests for sex proportion were performed to determine whether demography and physical fitness of the 2 groups were different at baseline.

Repeated-measures analyses of variance (ANOVAs) along with post hoc simple effect analyses were performed to determine the effects of the intervention on WMI and WM. Because of the longitudinal design of this study, differences between changes in RT of n-back and the FA before and after motor learning were calculated as changes in working memory and white matter integrity. Moreover, Pearson correlation coefficients (*r* values) were calculated for changes in motor learning, FA, and WM to determine whether there was any correlation between the change in working memory and remodeling of white matter integrity induced by motor learning. *p*-values < 0.05 were considered to be statistically significant. Furthermore, mediation analysis was performed with football juggling learning as the predictor variable (X) and FA (M), as well as WM as outcome variables (Y). This was done in order to test the indirect effect of football juggling learning on WM through FA. In addition, a bootstrapping approach was implemented, and macro PROCESS was applied (http://www.processmacro.org, accessed on 29 September 2020) in this analysis as it has been shown to produce reliable results in neuroimaging studies [66–68]. In the bootstrapping approach, PROCESS estimated the direct and indirect effects between a defined set of variables by applying an ordinary least squares path analytic framework. Inference of indirect (mediated) effects was subsequently assessed through bootstrap confidence intervals. The significance of indirect effects was assumed if the 95% confidence interval (*95%-CI*) did not include a zero. The number of bootstrap samples was set to n = 5000 and unstandardized regression coefficients (*coeff*) along with standard errors (*SE*) presented for each effect. Mediation analyses were repeated using standardized (z-trans formed) variables to obtain standardized regression coefficients (Std *coeff*). Moreover, variables involved in the correlation and regression processes were converted into z-scores, and data were presented as descriptive statistics: mean ± standard deviation (M ± SD).

3. Results

Demographic data of the participants are presented in Table 1. Studies have reported that physical fitness of participants may affect individual working memory and brain structures [69–71]. Therefore, we tried as much as possible to control interference variables.

In this study, only 94 participants completed the study, with 41 in the control group (24 males and 17 females) and 53 in the experimental category (38 males and 15 females). The two groups were similar with respect to age, gender, BMI, and physical fitness test (*p* > 0.05).

Table 1. Demographic characteristics of participants (M ± SD).

Variables	Control Group	Experimental Group
N	41	53
Gender (male/female)	24/17	38/15
Age (years)	18.49 ± 0.746	18.26 ± 0.524
BMI (height/weight^2)	21.81 ± 3.145	20.61 ± 2.737
4 × 10-m shuttle run (s)	11.47 ± 1.042	11.71 ± 0.860
Standing broad jump (m)	1.99 ± 0.331	1.98 ± 0.283
Sit-and-reach (cm)	13.64 ± 8.185	12.37 ± 6.018

Note: Values are presented as mean ± SD or percentages unless otherwise indicated.

3.1. Working Memory Data

Descriptive data for RT and ACC for the n-back task are presented in Table 2. Paired-sample *t*-test was used to compare statistical differences between 1-back and 2-back test at baseline to exclude individual differences in 2-back. Repeated measurements were used to analyze changes in the 2-back test of early adulthood, before and after learning football juggling.

Table 2. Analysis of experimental and control groups for WM and FA (M ± SD).

Variables	Control Group		Experimental Group	
	Baseline	Posttest	Baseline	Posttest
		1-back task		
RT	680.954 ± 182.830		669.432 ± 120.663	
ACC	0.948 ± 0.034		0.959 ± 0.044	
		2-back task		
RT	1109.885 ± 179.623	1069.991 ± 215.187	1101.474 ± 160.020	911.799 ± 184.143
ACC	0.740 ± 0.167	0.815 ± 0.119	0.791 ± 0.171	0.894 ± 0.114
		FA		
R.ACR	0.419 ± 0.029	0.411 ± 0.023	0.419 ± 0.023	0.427 ± 0.027
GOCC	0.618 ± 0.022	0.611 ± 0.018	0.617 ± 0.023	0.623 ± 0.021

Note: RT, reaction time; ACC, accuracy; FA, fraction anisotropy; R.ACR, right anterior corona radiate; GOCC, genu of corpus callosum.

By comparing the RT and ACC of 1-back and 2-back tasks at baseline, we observed significant differences between 1-back and 2-back tasks in RT (control group: $p = 0.000 < 0.001$, experimental group: $p = 0.000 < 0.001$) and ACC (control group: $p = 0.000 < 0.001$, experimental group: $p = 0.000 < 0.001$). Thus, individual differences in 2-back task could be excluded.

A significant group × time interaction ($F (1, 92) = 16.42$, $p = 0.000 < 0.001$, *partial η^2 = 0.151*) was observed in the RT of the 2-back task. However, follow-up analysis did not reveal any significant differences ($p > 0.05$) between the groups at baseline. Additionally, simple effect analysis revealed that RT was significantly reduced in the exercise group ($p = 0.000 < 0.001$), although there was no significant change in the control group ($p > 0.05$) between the pre-intervention and post-intervention tests. Moreover, there was no significant group × time interaction ($F (1, 92) = 0.66$, $p > 0.05$, *partial η^2 = 0.007*) in the ACC of the 2-back task, and no significant differences ($p > 0.05$) were observed between the groups at baseline.

3.2. White Matter Structure Data

The effect of football juggling learning on white matter integrity (FA) was analyzed by repeated measurement ANOVA. Notably, only results on interactions were reported because this study focused on interactions between the groups and test time i.e., whether football juggling learning caused changes in WMI.

After family-wise error (FWE) correction, ANOVAs in FA revealed significant group by time interactions in the R.ACR ($F (1, 92) = 11.05$, $p = 0.001 < 0.05$, *partial η^2 = 0.107*) and

GOCC (F (1, 92) = 11.41, p = 0.001 < 0.05, *partial* η^2 = 0.110). However, follow-up analysis showed no significant differences (p > 0.05) between the groups at baseline (Figure 1).
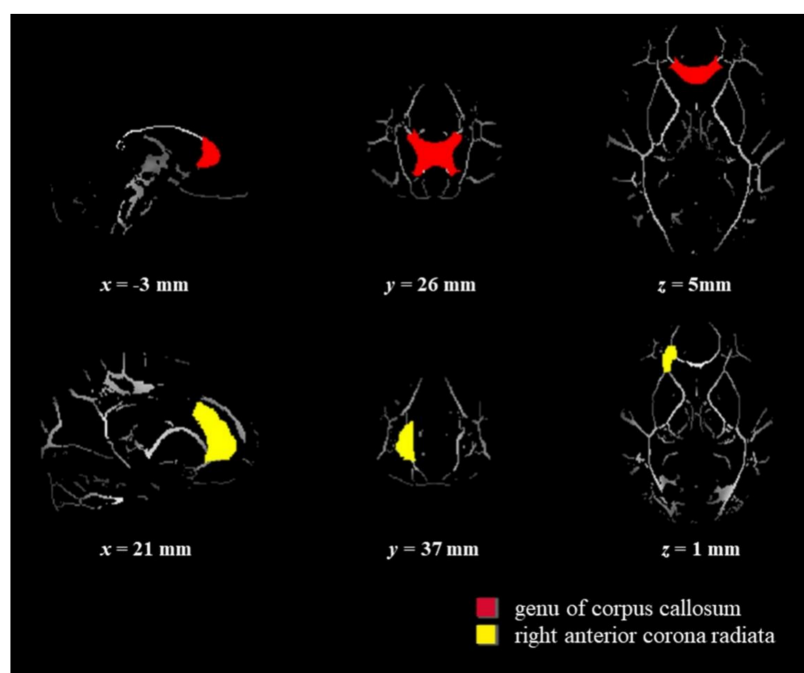
Figure 1. Brain regions with significant interaction effects on FA. Note: These are the sagittal, coronal, and horizontal views. The right hemisphere is on the left while the left hemisphere is on the right. Study-specific FA skeleton, representing the place of principal WM tracts, is shown in red and yellow, overlaid on the FMRIB58-FA-skeleton-1mm atlas map.

Moreover, simple effect analysis revealed that the FA of the R.ACR exhibited an upward trend in the exercise group (p = 0.017 < 0.05) and a downward trend in the control category (p = 0.024 < 0.05). Additionally, the FA of GOCC showed an upward trend in the exercise group (p = 0.028 < 0.05) and a downward trend in the control category (p = 0.013 < 0.05). Specific FA values of the brain regions with significant interactions are shown in Table 2.
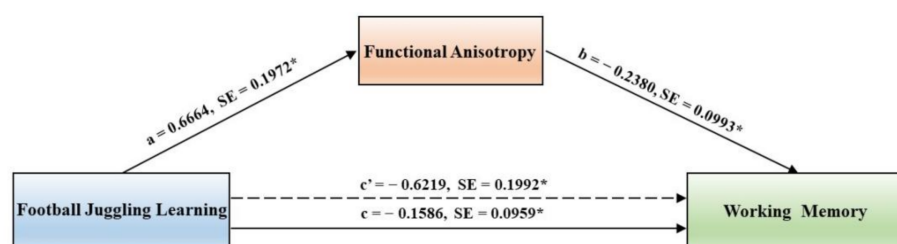
3.3. Mediation Model

Correlation analysis was used to examine the difference between RT of the 2-back task and the difference between the FA of GOOC and R.ACR, before and after football juggling learning. It was found that the difference between the FA of GOCC (r = −0.341, p = 0.001) and R.ACR (r = −0.298, p = 0.004) was negatively correlated with the difference in the RT of the 2-back task.

On the basis of previous research hypotheses and analysis results, we selected the "football juggling learning" group as an independent variable, change in the RT of the 2-back task was taken as a dependent variable, while FA changes in GOCC and R.ACR were taken as mediating variables to conduct a mediation model regression analysis.

There was a significant association between football juggling learning and FA changes in GOCC (*coeff* = 0.6664, *SE* = 0.1972, *95%CI* = 0.2746 to 1.0581, t = 3.3784, p = 0.0011). Moreover, a significant association between FA change in GOOC and changes in the RT of the 2-back task was confirmed (*coeff* = −0.2380, *SE* = 0.0993, *95%CI* = −0.4353 to −0.0408, t = −2.3973, p = 0.0186).

The mediation model, through FA changes in GOCC, showed that football juggling learning had a significant positive indirect (mediated) effect with changes in the RT of the 2-back task (indirect effect: *coeff* = −0.1586, *SE* = 0.0959, *95%CI* = −0.3873 to −0.0191). Furthermore, football juggling learning also had a significant direct effect on the RT of

the 2-back task (direct effect: *coeff* = −0.6219, *SE* = 0.1992, *95%CI* = −1.0175 to −0.2263, *t* = −3.1225, *p* = 0.0024) (Figure 2).

Figure 2. FA mediated the association between motor learning and working memory. Depiction of the applied mediation model: Unstandardized coefficients and standard errors for each path of the mediation model are presented. Note that c represents the direct effect while c' denotes the indirect effect. * indicates significance at *p* < 0.05.

4. Discussion

In this study, 10 weeks of football juggling learning in early adulthood were shown to improve WM and changes in the WMI of the GOCC and R.ACR regions. Additionally, improvements in WM (2-back task) associated with football juggling learning were correlated with the remodeling of WMI (FA). Moreover, mediation analysis revealed that WMI (FA) as a partial mediator of the relationship between football juggling learning and WM in specific white matter bundles.

4.1. Behavior

Studies have shown that motor skill learning can improve WM. In this study, the WM of the experimental group was found to be better than that of the control category, consistent with the findings from previous studies [12,72]. Moreover, previous studies involving preschoolers [9] and young adults [11] showed that different motor skill learning tasks can effectively improve WM. In this study, the 2-back task was used to reveal significant improvements in RT after football juggling learning in early adulthood, although there was no significant improvement in ACC. This may have been due to different cognitive task paradigms [73]. In early adulthood, cognitive abilities are firmly established, and therefore the 2-back task was relatively easy for this age group. As a result, it was difficult to obtain a significant difference in accuracy while response time was more sensitive to changes in WM. Moreover, we considered different cognitive aspects of response time and accuracy for n-back tasks. With an increase of N in N-back task, the capacity load of working memory is higher, while response time may reflect the processing speed of working memory [74,75]. Significant differences in response times in our study may have been due to processing speed. Several studies have shown the benefits of skill training for processing speed [11,76,77]. Unfortunately, we did not use some cognitive paradigms for processing speed to make this comparison. Some researchers believe that mental manipulation in sports can promote cognitive development. Some researchers believe that psychological control during exercise can boost cognitive development. Fun and more complex sports (especially those that involve learning and teamwork) may have different effects than simple sports [78]. In summary, the behavioral results were verified, i.e., skill learning has a beneficial effect on WM (at least in speed) in early adulthood.

4.2. White Matter Integrity

Studies have reported that FA characterizes directionality of constrained water diffusion in the brain tissue [37]. In addition, changes in FA are affected by many factors, including neuron numbers, density, diameter, and myelin sheath thickness [79]. In this study, an increase in FA was observed in the GOCC and R.ACR of the exercise group, although it decreased in the control category. These results should be further evaluated.

There was a significant increase in the FA of GOCC and right ACR in the experimental group. An increase in FA is generally considered to indicate an improvement in WMI. In addition, the corpus callosum (CC) has been shown to have an important role in interhemispheric communication and synchrony [80] as it is the bundle of white matter that connects the left and right cerebral hemispheres. The anterior part of CC contains fibers projecting into the prefrontal, premotor, and supplementary motor cortical areas [81]. Therefore, it could be involved in any aspect of cognitive function, especially those involving higher cognitive abilities. Moreover, radiating corona projects upward to the motor area as well as the anterior motor area of the cerebral cortex and reaches down to the posterior limb of the internal capsule and the cerebrum. This is the place where motor and sensory conduction fibers are highly concentrated [33]. These findings were confirmed by previous studies on badminton [33], visual space training [82], and finger sequence learning [34]. Therefore, we hypothesized that football juggling improves WMI in these areas, thereby enhancing cortical associations linked to movement.

Interestingly, we also revealed structural changes in the brains of participants in the control group. Low FA values were recorded in the GOCC and right ACR in the control group, and this phenomenon may be consistent with lifelong brain development. Studies have shown that most of the peak values in FA and MD occur before the age of 35. Macrostructurally, the total volume of the brain is usually at 90% complete development by the age 6 [83,84]. Early development of the CC has been confirmed, with most of the changes occurring before adolescence or the age of 20 [85]. Therefore, it was postulated that changes observed in the GOCC and Right ACR of the control group, were normal phenomena in lifelong brain development.

Additionally, recent studies have evaluated the effects of motor learning on the brain, and evidence shows that motor learning can cause microstructural changes in WMI [28,30,32]. The theory of brain plasticity has been supported by studies highlighting that brain structure and function can continuously be shaped by the external environment and experience. Our findings also confirm that motor learning causes changes in WMI.

4.3. The Relationship between Football Juggling Learning, WM, and WMI

Correlation analysis has shown that improvement in WM, due to football juggling learning, is associated with the remodeling of WMI. The WMI pathways are critical for efficient processing, and their properties may affect WM processes and contribute to their limited capacity [19]. Mediation analysis revealed that FA in the GOCC acts as a partial mediator between football juggling learning and WM, consistent with the previous hypothesis and potentially reflecting the underlying neurobiological factors in the brain. Previous cross-sectional studies [80,86] have reported the complex pathways through which physical activity improves cognitive performance through WMI. Ruotsalainen et al. confirmed the regulatory role of the corpus callosum in physical activity and WM. Bundles in the genu of the corpus callosum bend forward into the frontal lobes, and this plays a central role in most aspects of cognition and behavior throughout evolution [87]. This may have been the cause of the changes in WM observed in this study. Studies have confirmed the connection between the prefrontal cortex and WM [20,21,88]. This may be the neural mechanism through which motor learning improves WM in early adulthood by remodeling white matter tracts. The relationship between the corpus callosum and cognition has been reported in many studies [89,90]. A study by Martin-Loeches showed a correlation between the shape of the corpus callosum and different cognitive performance [89]. The processing speed of the working memory task in this study attracted attention. The authors interpreted this result as a correlation between the shape of the corpus callosum and the speed of mental processing, which connects to our discussion on cognition. Information processing speed is closely correlated with the reasoning ability of brain white matter structures, and two previous studies confirmed a significant correlation between mental processing speed and WMI [91,92]. This may explain the correlation between GOCC and cognition in our study. Moreover, the practice of corona radiata and WM has been demonstrated in studies

involving older adults [93–95]. These studies reflect the importance of complete ACR white matter tracts for WM performance. In these areas, age-related fibrous integrity may have profound effects on cognitive function, as compared to the decrease in FA in the control group. It has been proven in many imaging studies that WM is mainly provided by the frontal-parietal network [96–99]. However, there were no significant changes in these white matter bundles (such as superior longitudinal fasciculus or fronto-occipital fasciculus) in our study. We postulated that it might be because the learning task in our experiment required more body coordination and sensory perception ability, and changes in working memory in the results of our study were regulated by such brain structures.

Recent studies on brain imaging have reported the importance of WMI in WM. Our results confirmed the neurobiological mechanism through which motor skills improve cognitive function, providing a reference for future research. It is important to consider individual differences in WMI to understand the role of skill learning in improving cognitive performance.

4.4. Strengths and Limitation

We used a longitudinal experimental study design and the complex process of "football juggling learning" as an action learning task to explore the relationship between football juggling learning, changes in WMI, and improvement in WM. This therefore added on to the results from previous cross-sectional studies and simple learning tasks. However, despite the insightful findings, the study had a number of limitations. First, due to the different cognitive paradigms selected, we only observed significant changes in response time to the 2-back task. Given that cognitive ability is firmly established in early adulthood, a more difficult working memory paradigm for this age should have been selected for measurement. Meanwhile, changes in working memory capacity and mental processing speeds should be interpreted with caution. Second, we did not analyze other WMI indicators, including mean diffusivity (MD), radial diffusivity (RD), and axial diffusivity (AD). Studies on these indicators may therefore reveal the relationship between motor skill learning, WMI, and cognition. Finally, we only compared the data at two time points (before and after learning). Future studies should therefore collect data at multiple time points during the intervention process since action-learning-induced FA changes may be nonlinear.

5. Conclusions

Ten weeks of football juggling learning was able to improve WM and remodel WMI in early adulthood. Improvements in WM after football juggling learning were associated with WMI remodeling. Moreover, WMI acted as a partial mediator variable between football juggling learning and WM. This study provides a reference for future studies exploring the impact of motor learning on cognition from the WMI perspective.

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