Badminton Reshapes Brain Gray and White Matter Structure in Early Adulthood

Authors: Bai Xuejun, Shao Mengling, Liu Ting, Yin Jianzhong, golden flower, golden flower

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Abstract

Previous studies have found that the structure of visual-perceptual brain regions in ball sport athletes differs from that of non-athletes; however, whether these structural differences in brain regions are caused by training experience or innate structural differences remains unknown. This study adopts a longitudinal design, with early-adulthood adult non-athletes as participants (aged 23-27 years), randomly assigned to experimental and control groups. The experimental group participated in 12 weeks of badminton training, while the control group did not engage in any regular exercise training during this period. Structural and diffusion tensor imaging data were collected from all participants before and after the intervention. The results showed that after training, the experimental group exhibited increased gray matter volume in the left inferior occipital lobe, middle temporal gyrus, and inferior temporal gyrus, as well as increased fractional anisotropy (FA) in the bilateral posterior limb of the internal capsule and superior corona radiata. Further analysis revealed that the increase in FA was due to a decrease in radial diffusivity (RD). These findings suggest that badminton training can increase gray matter volume in brain regions related to visual-motion perception and increase myelination thickness of fiber tracts in adults.

Full Text

Altered Structural Plasticity in Early Adulthood after Badminton Training

BAI Xuejun[1], SHAO Mengling[1], LIU Ting[1], YIN Jianzhong[2], JIN Hua[1]
([1] Faculty of Psychology, Tianjin Normal University, Tianjin 300387, China)
([2] Department of Radiology, Tianjin First Center Hospital, Tianjin 300192, China)

Abstract

Previous research has revealed structural differences in visual-perceptual brain regions between athletes engaged in ball sports and non-athletes. However, it remains unclear whether these differences arise from training experience or innate structural variations. The present study employed a longitudinal design to investigate this question in early adulthood. Non-athlete adults aged 23–27 years were randomly assigned to either an experimental group, which underwent 12 weeks of badminton training, or a control group that engaged in no regular exercise during this period. Structural magnetic resonance imaging and diffusion tensor imaging data were collected from all participants before and after the intervention. The results demonstrated that the experimental group exhibited increased gray matter volume in the left inferior occipital lobe, middle temporal gyrus, and inferior temporal gyrus following training. Additionally, fractional anisotropy (FA) increased in the bilateral posterior limbs of the internal capsule and superior corona radiata. Further analysis revealed that these FA increases were attributable to decreased radial diffusivity (RD). These findings suggest that badminton training can enhance gray matter capacity in adult brain regions associated with visual-motion perception and increase myelin thickness in fiber tracts.

Keywords: badminton training; early adulthood; brain plasticity

Brain plasticity refers to changes in brain structure or function resulting from environmental influences or experience. This phenomenon has been widely applied in neural rehabilitation, delaying age-related brain degeneration, and promoting brain development in adolescents, becoming a prominent research focus in recent years. Studies have demonstrated that experts with specialized skills—such as musicians, professional athletes, and video game players—exhibit distinct brain structures and functions compared to non-experts or novices (Abreu et al., 2012; Bishop, Wright, Jackson, & Abernethy, 2013; Gaser & Schlaug, 2003; Gong et al., 2016; 2017; Luo et al., 2012; Park, Lee, Kwon, Lee, & Rhyu, 2015; Wang et al., 2013; Zhang et al., 2013).

Research investigating brain plasticity changes induced by motor training in adults has shown that three months of juggling training (Draganski et al., 2004), shooting training (Baeck et al., 2012), or balance training (Rogge, Roder, Zech, & Hotting, 2018) can alter adult brain structure or function. For instance, Rogge et al. (2018) compared 12 weeks of balance training versus relaxation training in adults and found that the balance training group showed improved balance ability and increased cortical thickness in brain regions related to visual, vestibular, and self-motion perception (such as visual association cortex, superior temporal cortex, posterior cingulate cortex, superior frontal sulcus, and precentral gyrus), along with decreased putamen volume. These findings indicate that motor experiences in daily life can modify adult brain plasticity. However, whether racquet sport training specifically alters structural plasticity in the adult brain remains unclear.

Nevertheless, cross-sectional studies on racquet sports suggest that these activities may indeed reshape adult brain structure or function. Resting-state functional studies have found that badminton athletes show greater amplitude of low-frequency fluctuation (ALFF) in the cerebellum but lower ALFF in the left superior parietal lobe compared to novices, along with greater functional connectivity between the left superior parietal lobe and frontal regions (Di et al., 2012). Electrophysiological research has demonstrated that when watching badminton match videos, badminton athletes exhibit significantly larger C1 component amplitudes in the occipital lobe (thought to reflect primary visual cortex activity) than non-athletes (Jin et al., 2010). When viewing radial motion stimuli, badminton athletes show shorter N2 latencies in the middle temporal gyrus compared to non-athletes (the authors considered their selected electrodes to represent the middle temporal gyrus) (Hulsdunker, Struder, & Mierau, 2017). Task-based functional studies have revealed that during visual anticipation tasks, badminton athletes not only demonstrate higher accuracy than non-athletes but also show greater activation in the middle temporal gyrus (Wright, Bishop, Jackson, & Abernethy, 2011).

Structurally, Di et al. (2012) found that badminton athletes have greater cerebellar gray matter density than novices. Wu, Zhang, Zeng, and Shen (2015) observed that badminton athletes exhibit larger gray matter volumes primarily in the right precentral gyrus, right orbital frontal gyrus, left superior frontal gyrus, left inferior parietal lobule, and left precuneus compared to non-athletes. Shen et al. (2014) compared white matter differences between basketball athletes and non-athletes, finding that basketball athletes showed significantly greater fractional anisotropy (FA) in the middle occipital gyrus than non-athletes.

However, all these studies employed cross-sectional designs, making it impossible to determine whether the observed functional or structural differences result from training experience or innate predispositions. Therefore, while previous cross-sectional findings provide some basis for the feasibility of longitudinal intervention research, it remains unclear whether racquet sport training can actually alter structural plasticity in the adult brain.

Recent large-scale data from 1.2 million participants revealed that racquet sports offer the highest comprehensive value among physical activities, being highly effective for promoting mental health and reducing the risk of various fatal diseases (Chekroud et al., 2018). Badminton is one of the most popular fitness activities in China, with over 200 million participants—second only to running (iResearch, 2015; Liu, 2018). Moreover, compared to other racquet sports, badminton has lower requirements for venue, technical skill, and physical fitness, making it highly feasible. Consequently, using badminton as a model to investigate the impact of motor experience on adult brain plasticity offers good generalizability, social significance, and ecological validity.

The present study aimed to examine whether short-term racquet sport training can alter brain structure in early adulthood using badminton as an example. Intervention duration is a critical parameter in such studies: overly brief interventions may fail to produce observable effects, while excessively long ones may increase attrition rates and reduce feasibility. We selected a 12-week duration because previous research has demonstrated that 12 weeks of training can induce structural changes in relevant brain regions (Draganski et al., 2004; Rogge et al., 2018), and this timeframe minimizes potential reductions in participant engagement and data loss due to academic schedules, thereby enhancing intervention feasibility. The study recruited university students without regular exercise habits, randomly assigning them to experimental and control groups. The experimental group underwent 12 weeks of badminton training, while the control group maintained their original lifestyle without any regular physical exercise. Structural and diffusion tensor imaging (DTI) data were collected before and after the intervention. Voxel-based morphometry (VBM) and tract-based spatial statistics (TBSS) were used to examine changes in gray matter volume and white matter fiber FA induced by badminton experience. Based on previous research showing that athletes have greater gray matter volume and white matter FA than non-athletes, we hypothesized that the experimental group would show increased gray matter volume and white matter FA after badminton training. Since badminton involves training in perceiving complex dynamic visual information (Hulsdunker et al., 2017), we further hypothesized that structural changes would likely occur in brain regions associated with visual-motion perception. The occipital lobe and middle temporal gyrus are key regions for visual-motion perception processing, and previous studies have shown that badminton athletes exhibit significantly different function in these regions compared to non-athletes (Jin et al., 2010; Hulsdunker et al., 2017; Wright et al., 2011). Additionally, research indicates that functional plasticity changes induced by motor training are accompanied by structural changes (Wei & Luo, 2010; Wei, Luo, & Li, 2009; Wei, Zhang, Jiang, & Luo, 2011). Accordingly, we hypothesized that structural changes following badminton training would be located in the occipital lobe and middle temporal gyrus.

Methods

Participants

Forty-four university students volunteered for the experiment and were randomly divided into two groups. The experimental group initially comprised 22 participants, though one failed to complete the post-test, leaving 21 valid participants (9 males, 12 females; mean age = 24.48 ± 1.17 years, range 23–27 years). The control group initially comprised 22 participants, with four failing to complete the post-test, leaving 18 valid participants (7 males, 11 females; mean age = 24.06 ± 0.73 years, range 23–26 years). The two groups were matched in gender ratio, age ($p > 0.05$), and education level, with no significant differences between them. All participants were right-handed as assessed by the Edinburgh Handedness Inventory (Oldfield, 1971), had normal or corrected-to-normal vision without color blindness or weakness, and were in good health with no history of brain trauma, drug dependence, psychiatric disorders, neurological diseases, or family history of such conditions. None had any professional or amateur training history in any sport, nor did they regularly engage in ball sports activities or watch ball sports competitions in their spare time. All participants signed informed consent forms before the experiment and received compensation upon completion. The study was approved by the Ethics Committees of the Tianjin Normal University Academy of Psychology and Behavior and Tianjin First Center Hospital.

Experimental Design

We employed a 2 × 2 mixed design with group (experimental vs. control) as a between-subjects factor and test time (pre-test vs. post-test) as a within-subjects factor. The experiment consisted of three phases: pre-test, badminton training, and post-test. The pre-test and post-test involved identical brain structural scans. Only the experimental group participated in 12 consecutive weeks of badminton training, while the control group engaged in no regular physical exercise during this period.

Badminton Training

The badminton training took place in a university gymnasium's badminton training hall. The intervention consisted of three sessions per week (Monday, Wednesday, Friday), each lasting one hour, for 12 consecutive weeks. Each training session comprised three components: First, the instructor demonstrated and explained correct badminton movements (e.g., serving, smashing) or skills (e.g., anticipating ball trajectory based on opponent's body movements, returning the ball to left/right or front/back court based on opponent's position). This portion lasted approximately 10 minutes. Second, participants practiced in pairs, during which the instructor observed each participant's movements and posture, providing guidance when necessary. This portion lasted approximately 30 minutes. Third, participants played freely in pairs for approximately 20 minutes. During the final week, the instructor organized group competitions with singles matches between pairs.

Brain Imaging Acquisition

All participants were scanned using a Siemens 3.0T magnetic resonance imaging system at Tianjin First Center Hospital. T1-weighted structural images were acquired using a gradient recalled echo sequence (GRE) with the following parameters: TR = 1900 ms, TE = 2.52 ms, flip angle = 9°, FOV = 240 mm × 256 mm, matrix = 240 × 256, 176 slices, slice orientation right-to-left, contiguous slices, slice thickness = 1 mm, gap = 0.5 mm, voxel size = 1 mm × 1 mm × 1 mm, scan time = 4 minutes 10 seconds per participant.

DTI data were acquired using an echo-planar imaging sequence (EPI) with parameters: TR = 4200 ms, TE = 0.4 ms, flip angle = 90°, FOV = 230 × 230, matrix = 128 × 128, 32 slices, slice orientation bottom-to-top, interleaved scanning, slice thickness = 4 mm, gap = 0.4 mm, voxel size = 1.8 mm × 1.8 mm × 4 mm, 64 diffusion gradient encoding directions, b1 = 0 mm^2/s, b2 = 1000 mm^2/s, scan time = 4 minutes 47 seconds.

VBM Analysis

Structural data preprocessing was performed using CAT12.5 (http://www.neuro.uni-jena.de) based on MATLAB R2013a (www.mathworks.com/trademarks). Prior to preprocessing, raw T1 data were converted to TINF format. Each participant's two time-point structural images were registered to their mean image using inverse-consistent realignment. Tissue probability maps (TPM) were used to segment each participant's mean image into gray matter, white matter, and cerebrospinal fluid. Spatial normalization was achieved using the DARTEL method, with normalization parameters applied to each participant's time-point structural images to obtain normalized gray matter segmentation maps for each time point, which were then modulated. Normalized image quality was inspected, and modulated gray matter segmentation maps were smoothed with an 8 × 8 × 8 mm^3 kernel for subsequent statistical analysis.

Group-level statistical analysis was conducted in SPM12 (http://www.fil.ion.ucl.ac.uk/spm/). Intracranial volume (ICV) was included as a covariate in a 2 × 2 repeated-measures ANOVA with group as a between-subjects factor and test time as a within-subjects factor. Significance was defined as $p < 0.05$ after family-wise error (FWE) correction at the voxel level, with $k > 50$ (Everts et al., 2009). Gray matter volume values from brain regions showing significant interactions were extracted for post-hoc analysis (paired samples t-tests) in SPSS 22.0.

TBSS Analysis

Raw DTI data were first converted to compressed FSL format, and raw T1 data were converted to NIFTI format. DTI data preprocessing was performed using FSL v5.0 (https://fsl.fmrib.ox.ac.uk/fsl/), including: eddy current correction to address image distortion caused by head motion and eddy currents during acquisition; skull stripping with a threshold of 0.2 to remove non-brain tissue; and calculation of FA, L1, L2, and L3 metrics. TBSS data analysis was then conducted in a virtual machine terminal: "tbss_1_{preproc}*.nii.gz" removed outliers from preprocessed FA maps; "tbss_2_{reg} –T" nonlinearly registered each participant's FA map to the standard FMRIB58_{{{FA}}_{{1mm}}} template; "tbss_3_{postreg} –S" generated mean FA images and mean FA skeletons across all participants; and "tbss_4_{prestat} 0.2" created a mask of the mean FA skeleton and projected it into each participant's native space, generating an FA skeleton for each participant.

A 2 × 2 repeated-measures ANOVA with 5000 permutations was performed on all participants' FA skeletons using nonparametric statistical analysis in FSL v5.0. Significance was set at $p < 0.05$ using threshold-free cluster enhancement (TFCE) correction. Statistical maps were localized to the JHU ICBM-DTI-81 white matter template. FA values from regions showing significant interactions were extracted for post-hoc analysis (paired samples t-tests) in SPSS 22.0.

ROI Analysis

FA reflects the ratio of axial to radial water diffusion in white matter fibers. To further investigate the causes of FA changes, brain regions showing significant interactions in the TBSS results were defined as regions of interest (ROIs). Axial diffusivity (AD) and radial diffusivity (RD) values were extracted for each ROI, and repeated-measures ANOVAs were performed on AD and RD in SPSS 22.0. As the primary focus was on the interaction between group and test time—that is, whether the training intervention induced structural changes—only interaction results are reported.

Results

Gray Matter Volume Results

Significant group × test time interactions were observed in the left inferior temporal gyrus, left inferior occipital lobe, and left middle temporal gyrus [Figure 1: see original paper]. Post-hoc tests revealed that the experimental group showed significantly increased gray matter volume in these regions after training ($ps < 0.001$). In contrast, the control group showed no significant differences between pre-test and post-test in the left inferior occipital lobe and inferior temporal gyrus ($ps > 0.05$), but a significant decrease in gray matter volume in the left middle temporal gyrus ($p < 0.001$) [Figure 2: see original paper], . Independent samples t-tests on pre-test gray matter volumes in these regions revealed no significant differences between groups ($ps > 0.05$): left inferior occipital lobe, $t(37) = 1.33$, $p = 0.191$; left inferior temporal gyrus, $t(37) = 1.91$, $p = 0.065$; left middle temporal gyrus, $t(37) = 0.91$, $p = 0.369$.

Note: The figure shows axial slices in MNI space; left in the image represents the right hemisphere. A: Left inferior occipital lobe ($x = -33$, $y = -78$, $z = -6$, $k = 111$, $F = 60.50$, $pFWE < 0.001$). B: Left inferior temporal gyrus ($x = -44$, $y = -50$, $z = -9$, $k = 127$, $F = 56.18$, $pFWE = 0.001$). C: Left middle temporal gyrus ($x = -51$, $y = -39$, $z = 8$, $k = 79$, $F = 51.08$, $pFWE = 0.002$).

White Matter Results

Significant group × test time interactions were observed in the bilateral posterior limbs of the internal capsule and bilateral superior corona radiata [Figure 3: see original paper]. FA values from these four regions were extracted for post-hoc analysis in SPSS, revealing that the experimental group showed significantly increased FA after training ($ps < 0.05$), while the control group showed significantly decreased FA ($ps < 0.05$) .

Note: The figure shows axial slices in MNI space; left in the image represents the right hemisphere. A: Left posterior limb of internal capsule ($x = -24$, $y =$

-11, z = 15, k = 32, pTFCE = 0.045). B: Right posterior limb of internal capsule (x = 25, y = -13, z = 15, k = 253, pTFCE = 0.019). C: Left superior corona radiata (x = -27, y = -18, z = 21, k = 79, pTFCE = 0.040). D: Right superior corona radiata (x = 29, y = -17, z = 21, k = 22, pTFCE = 0.049; x = 27, y = -20, z = 25, k = 6, pTFCE = 0.050; x = 21, y = -17, z = 39, k = 126, pTFCE = 0.044). Green: mean FA skeleton. Background: standard MNI152 template.

FA increases can result from increased AD, decreased RD, or a combination of both. To determine the cause of FA changes, the four ROIs showing significant interactions (left posterior limb of internal capsule, right posterior limb of internal capsule, left superior corona radiata, right superior corona radiata) were analyzed for AD and RD changes. For AD, no significant interactions were observed in any of the four ROIs (ps > 0.05). For RD, significant interactions were found in the bilateral posterior limbs of the internal capsule (left: F(1, 37) = 19.13, $p < 0.001$, $^2 = 0.34$; right: F(1, 37) = 29.01, $p < 0.001$, $^2 = 0.44$) and bilateral superior corona radiata (left: F(1, 37) = 15.68, $p < 0.001$, $^2 = 0.30$; right: F(1, 37) = 34.70, $p < 0.001$, $^2 = 0.48$). Simple effects analysis revealed that the experimental group showed significantly decreased RD in the bilateral posterior limbs of the internal capsule and right superior corona radiata after training (ps < 0.01), with no significant change in the left superior corona radiata ($p > 0.05$). In contrast, the control group showed significantly increased RD in the bilateral posterior limbs of the internal capsule and bilateral superior corona radiata at post-test (ps < 0.01) [Figure 4: see original paper], .

Discussion

The present study investigated the effects of badminton training on brain structural plasticity in early adulthood. Regarding gray matter volume, the experimental group showed increased volume in the left inferior occipital lobe, middle temporal gyrus, and inferior temporal gyrus after training, while the control group exhibited decreased volume in the left middle temporal gyrus. These results indicate that badminton training can increase gray matter capacity in adult brain regions involved in visual-motion perception processing. For white matter, the experimental group demonstrated FA increases in the bilateral posterior limbs of the internal capsule and superior corona radiata driven by decreased RD, whereas the control group showed FA decreases driven by increased RD in these regions. This pattern suggests that badminton training may increase myelin thickness in adult white matter fibers.

The finding of increased left inferior occipital lobe gray matter volume in the experimental group aligns with our hypothesis. The inferior occipital lobe is part of the extrastriate visual cortex, and recent research (Hu et al., 2018) has identified neurons in extrastriate visual cortex that encode motion information (direction-selective neurons), which are highly sensitive to motion contrast and play an important role in figure-ground segregation. Behavioral studies have shown that badminton athletes outperform non-athletes in coherent motion judgment tasks using random dot patterns (Kong et al., 2012). The increased gray matter volume in the inferior occipital lobe may be related to repeated encoding of motion information between static courts and dynamic balls and opponents during badminton play. In badminton scenarios, opponents' movements, the flying shuttlecock, and the static background create motion contrast stimuli.

The middle temporal gyrus is involved in processing biological motion (Grezes et al., 2001; Peuskens, Vanrie, Verfaillie, & Orban, 2005) and understanding others' action intentions (Lestou, Pollick, & Kourtzi, 2008; Pelphrey, Morris, & McCarthy, 2004). For example, viewing point-light displays of biological motion (e.g., walking) elicits greater bilateral middle temporal gyrus activation than viewing rigid motion (Grezes et al., 2001). Similarly, observing point-light actions with different intentions activates the superior temporal sulcus more strongly than actions with identical intentions (Lestou et al., 2008). More directly, studies have implicated this region in visual-perceptual tasks during motor activities (Abreu et al., 2012; Bishop et al., 2013; Wright et al., 2011). For instance, badminton athletes show greater middle temporal gyrus activation than non-athletes when viewing badminton video clips for visual anticipation (Wright et al., 2011). The increased gray matter volume in the middle temporal gyrus after badminton training likely reflects the rich dynamic information and precise visual anticipation demands inherent to the sport. Badminton is a time-constrained competitive sport where visually anticipating the shuttlecock's landing point is crucial for success, and analyzing opponents' biological motion to understand their intentions is essential for accurate prediction. Behavioral experiments have confirmed that professional badminton athletes possess superior visual anticipation abilities compared to non-athletes or novices (Abernethy & Zawi, 2007; Alder, Ford, Causer, & Williams, 2014; Jin et al., 2011). Another experiment within this project found that participants' visual anticipation ability for badminton improved significantly after three months of training (Liu et al., 2017).

The observed increase in inferior temporal gyrus gray matter volume in the experimental group may reflect changes in pattern recognition for badminton actions. Research indicates that the inferior temporal gyrus is associated with pattern recognition within an expert's domain (Bilalic, Langner, Erb, & Grodd, 2010). Bilalic et al. (2010) compared chess experts and novices during chess-related visual search tasks, finding that experts outperformed novices in searching normal chess positions, demonstrating superior pattern recognition ability. Imaging results showed greater inferior temporal gyrus activation in experts during pattern recognition tasks, suggesting this region's involvement in chess pattern recognition. Numerous studies have shown that domain-specific experts exhibit better pattern recognition within their specialty than non-experts or novices (Bilalic et al., 2010; Hohmann, Troje, Olmos, & Munzert, 2011; Smeeton, Ward, & Williams, 2004). For example, basketball, soccer, and ice hockey athletes show superior recall and recognition of specific actions and teammate/opponent positions. Experts' advantage in pattern recognition is thought to reflect their extensive storage of domain-specific patterns and their ability to quickly compare observed patterns with stored representations (Abernethy, 1996). In this study, repeated badminton practice may have enabled participants to acquire specialized knowledge about specific action structures, facilitating pattern recognition through comparison of observed opponent movements with stored patterns for anticipatory judgments.

Regarding white matter, FA reflects the ratio of axial to radial water diffusion in white matter fibers, with higher FA indicating greater axial than radial diffusion. FA increases can result from increased AD, decreased RD, or a combination of both. Our findings revealed that FA increases in the bilateral posterior limbs of the internal capsule and superior corona radiata after badminton training were caused by decreased RD. FA is influenced by multiple factors, including neuron number, density, diameter, and myelin thickness (Beaulieu, 2002; Blumenfeld-Katzir, Pasternak, Dagan, & Assaf, 2011). Previous research has shown that AD is sensitive to axonal damage (Sun, Liang, Cross, & Song, 2008; Zhang et al., 2009), whereas RD is sensitive to myelin damage, with decreased RD associated with increased myelination (Kim et al., 2007; Song et al., 2002; Zhang et al., 2009). For example, Zhang et al. (2009) induced spinal cord damage in rats and found that RD increases correlated positively with myelin disintegration. Song et al. (2002) compared myelination, AD, and RD in shiverer mice versus healthy mice, finding that shiverer mice exhibited myelin loss, greater RD than healthy mice, but no AD differences. Therefore, the physiological basis for the RD-decrease-driven FA increase observed after badminton training in our study likely reflects increased myelin thickness in fiber tracts induced by training.

The superior corona radiata projects upward to motor and premotor cortices and downward to the posterior limb of the internal capsule and cerebral peduncle. The internal capsule is a white matter plate composed of ascending and descending fibers connecting the cerebral cortex with the brainstem and spinal cord. The posterior limb of the internal capsule contains the corticospinal tract, where motor and sensory fibers are highly concentrated. The observation of FA changes in these regions after short-term badminton training suggests that these white matter areas possess substantial structural plasticity, consistent with previous literature. Studies have shown that various short-term training interventions (three weeks of visuomotor training, Wang, Casadio, Weber, Mussa-Ivaldi, & Parrish, 2014; four weeks of left-hand sequential motor training, Reid, Sale, Cunnington, Mattingley, & Rose, 2017) can induce FA increases in these regions. For instance, Wang et al. (2014) found that three weeks of visuomotor training increased FA and decreased RD in the posterior limb of the internal capsule and superior corona radiata. Short-term training-induced FA changes are thought to result from repeated motor practice or motor learning and are associated with behavioral improvements in the trained activity (Reid et al., 2017; Wang et al., 2014). Collectively, we speculate that the RD-decrease-driven FA increase observed after training in our experimental group may reflect increased myelin thickness resulting from badminton motor learning, enabling more efficient and rapid information transmission between central and peripheral nervous systems during motor execution.

However, our results differ from studies of experts with long-term (over ten years) training experience, such as musicians (Schmithorst & Wilke, 2002) and golfers (Jancke, Koeneke, Hoppe, Rominger, & Hanggi, 2009), which found lower FA in the internal capsule and corona radiata compared to non-musicians and less skilled athletes. These authors suggested that decreased FA is associated with more skilled, automated movements. Several factors may account for these discrepancies. The white matter FA changes induced by motor training may be sport-specific: badminton is a competitive, interactive sport with high demands on visual-motion perception, whereas music training and golf are non-competitive with lower visual-motion perception demands. Alternatively, motor training may induce nonlinear changes in FA over time. Differences in experimental design may also contribute, as studies consistent with our findings used longitudinal designs, while expert studies used cross-sectional designs. These possibilities require more rigorous experimental designs in future research to isolate and determine their contributions.

Unexpectedly, we also observed structural changes in the control group, including decreased gray matter volume in the middle temporal gyrus and decreased white matter FA after the intervention. This phenomenon may reflect normal lifespan brain development. Numerous studies have found that gray matter volume begins to decline during childhood or even earlier developmental periods (Ge et al., 2002; Kalpouzos et al., 2009; Pfefferbaum et al., 1994; Sowell et al., 2003; Tamnes et al., 2013). For example, Pfefferbaum et al. (1994) measured brain volume in 161 healthy individuals aged 3 months to 70 years and found that gray matter volume peaked at age 4 and subsequently declined. Tamnes et al. (2013) tracked gray matter volume in 8–19-year-olds over 2.6 years, finding annual decline rates exceeding 1% in many cortical regions, with the greatest declines in frontal and lateral temporal regions by age 20. Research on white matter fiber changes across the lifespan indicates that most white matter matures early, with FA in occipital and frontal lobes peaking in late adolescence and 50% of corticospinal tract voxels reaching maximum values around age 20 before declining (Westlye et al., 2010). Notably, intervention studies have shown statistically significant brain volume declines in control groups over short time spans. For example, Lovden et al. (2012) assigned young adults (20–30 years) to either four months of navigation training (42 days, 50 minutes daily) in a virtual zoo or a walking control task with equivalent motor demands. The navigation training group showed increased hippocampal gray matter volume, while the control group showed decreased hippocampal volume, which the authors attributed to normal age-related decline. Thomas et al. (2009) conducted three structural scans in healthy participants (mean age 32.5 years), with a 2-week no-intervention interval between the first and second scans, and a 2-week visuomotor training interval (joystick task, 25 minutes per session, 6 sessions) between the second and third scans. They found significant gray matter density decreases in the bilateral parahippocampal gyrus, right insula, and right precuneus during the no-intervention phase. We therefore speculate that the observed middle temporal gyrus gray matter volume decrease in our control group represents normal age-related brain development.

One might question whether using a “non-racquet sport” control group, such as indoor running, would have prevented the observed middle temporal gyrus decline—or whether the control group’s changes resulted from lack of exercise rather than lack of badminton training specifically. Although our study cannot directly exclude this possibility due to the absence of an active control group, indirect evidence suggests this is unlikely. First, research has linked the middle temporal gyrus to visual-motion perception (Peuskens et al., 2005). Sumiyoshi et al. (2014) found that seven days of wheel running in mice increased gray matter volume in motor and visual cortices, attributing motor cortex changes to exercise volume and visual cortex changes to environmental enrichment. This suggests that even with a running control group matched for exercise volume, participants would not experience the rich visual dynamic environment of badminton training. While motor cortex changes might not differ between groups, visual perception-related brain regions likely would. Second, another cross-sectional study from our lab compared motion perception among badminton athletes, sprinters, and ordinary adults, finding that badminton athletes showed significantly higher perceptual sensitivity than both sprinters and ordinary adults, who did not differ from each other. For radial motion specifically, badminton athletes showed higher sensitivity than sprinters and ordinary adults, with ordinary adults higher than sprinters (Liang, Yin, Liu, Zhu, Lin, & Jin, under review). This suggests that running alone may not induce behavioral changes in motion perception, and by extension, may not alter structure or function in visual-motion perception brain regions. Nevertheless, more direct evidence requires future studies with more rigorous designs and univariate/multivariate pattern analysis methods.

This intervention study extends previous cross-sectional findings but has several limitations requiring further investigation. First, research indicates that gray matter volume and white matter FA change nonlinearly during training (Draganski et al., 2004; Scholz, Klein, Behrens, & Johansen-Berg, 2009), yet our study only collected data at two time points, precluding examination of the relationship between brain plasticity and training duration. Future studies should collect data at multiple time points during training. Second, our 12-week intervention was relatively brief, limiting comparability with studies of athletes with over a decade of training. Future research should extend training duration and intensity. Third, we did not directly assess changes in visual-motion perception sensitivity using paradigms such as random dot arrays, making it difficult to infer relationships between observed structural changes and behavioral performance. Future studies should incorporate behavioral measures to more directly link functional brain changes with behavioral outcomes. Fourth, although participants were randomly assigned, we could not fully control for baseline visual acuity differences. While no research has linked visual acuity to brain plasticity in non-blind individuals, and previous studies have not considered visual acuity in exercise-induced structural plasticity (Bezzola, Merillat, Gaser, & Jancke, 2011; Draganski et al., 2004; Hamzei, Glauche, Schwarzwald, & May, 2012;

Jonasson et al., 2017; Lakhani et al., 2016; Reid et al., 2017; Rogge et al., 2018; Taubert et al., 2010; Tavor, Botvinik-Nezer, Bernstein-Eliav, Tsarfaty, & Assaf, 2019), we cannot completely exclude a role for baseline visual acuity. Future intervention studies should control for this factor. Fifth, our control group involved "no physical exercise training," which demonstrates that badminton as an exercise intervention can alter adult brain structure but cannot directly establish the specificity of these changes to badminton training. Future research should include active control groups, such as indoor running, to address this question.

In conclusion, short-term badminton training increased gray matter volume in adult brain regions related to visual-motion perception and increased myelin thickness in the posterior limb of the internal capsule and superior corona radiata. These findings demonstrate that both gray matter and white matter retain plasticity in early adulthood.

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Appendix 1: Covariance Analysis Results

Using pre-test values as covariates, post-test values were analyzed, yielding results consistent with the repeated-measures analysis:

(1) Covariance Analysis of Gray Matter Volume

With pre-test volumes of the left inferior occipital lobe, left inferior temporal gyrus, and left middle temporal gyrus as covariates, ANCOVAs on post-test volumes revealed significant group differences: left inferior occipital lobe, F(1,

37) = 45.59, $p < 0.001$, $^2 = 0.56$, with the experimental group (0.260 ± 0.003) significantly higher than the control group (0.234 ± 0.003); left inferior temporal gyrus, F(1, 37) = 46.18, $p < 0.001$, $^2 = 0.56$, with the experimental group (0.327 ± 0.003) significantly higher than the control group (0.301 ± 0.003); left middle temporal gyrus, F(1, 37) = 49.91, $p < 0.001$, $^2 = 0.58$, with the experimental group (0.393 ± 0.003) significantly higher than the control group (0.266 ± 0.003). These results indicate that after controlling for pre-test differences, the experimental group showed significantly greater gray matter volume than the control group in these regions following badminton training, consistent with the repeated-measures ANOVA results.

(2) Covariance Analysis of White Matter FA

With pre-test FA values of the bilateral posterior limbs of the internal capsule and bilateral superior corona radiata as covariates, ANCOVAs on post-test FA revealed significant group differences: left posterior limb of internal capsule, F(1, 37) = 21.07, $p < 0.001$, $^2 = 0.37$, with the experimental group (0.665 ± 0.004) significantly higher than the control group (0.634 ± 0.005); right posterior limb of internal capsule, F(1, 37) = 22.53, $p < 0.001$, $^2 = 0.39$, with the experimental group (0.685 ± 0.003) significantly higher than the control group (0.662 ± 0.003); left superior corona radiata, F(1, 37) = 17.62, $p < 0.001$, $^2 = 0.33$, with the experimental group (0.639 ± 0.004) significantly higher than the control group (0.615 ± 0.004); right superior corona radiata, F(1, 37) = 30.10, $p < 0.001$, $^2 = 0.46$, with the experimental group (0.593 ± 0.003) significantly higher than the control group (0.570 ± 0.003).

(3) Covariance Analysis of White Matter RD

With pre-test RD values as covariates, ANCOVAs on post-test RD revealed significant group differences: left posterior limb of internal capsule, F(1, 37) = 17.72, $p < 0.001$, $^2 = 0.33$, with the experimental group ($3.87 \times 10^{-4} \pm 6 \times 10^{-6}$) significantly lower than the control group ($4.23 \times 10^{-4} \pm 6 \times 10^{-6}$); right posterior limb of internal capsule, F(1, 37) = 13.62, $p = 0.001$, $^2 = 0.27$, with the experimental group ($3.73 \times 10^{-4} \pm 4 \times 10^{-6}$) significantly lower than the control group ($3.96 \times 10^{-4} \pm 4 \times 10^{-6}$); left superior corona radiata, F(1, 37) = 5.93, $p = 0.02$, $^2 = 0.14$, with the experimental group ($4.47 \times 10^{-4} \pm 6 \times 10^{-6}$) significantly lower than the control group ($4.71 \times 10^{-4} \pm 7 \times 10^{-6}$); right superior corona radiata, F(1, 37) = 12.64, $p = 0.001$, $^2 = 0.26$, with the experimental group ($4.50 \times 10^{-4} \pm 4 \times 10^{-6}$) significantly lower than the control group ($4.77 \times 10^{-4} \pm 5 \times 10^{-6}$).

(4) Covariance Analysis of White Matter AD

With pre-test AD values as covariates, ANCOVAs on post-test AD revealed no significant group differences in any region (left posterior limb of internal capsule: $p = 0.16$; right posterior limb of internal capsule: $p = 0.140$; left superior corona radiata: $p = 0.228$; right superior corona radiata: $p = 0.165$).

These results demonstrate that after controlling for pre-test differences, the experimental group showed significantly higher FA and significantly lower RD than the control group in the bilateral posterior limbs of the internal capsule and superior corona radiata, with no significant AD differences. This confirms that the FA increase in the experimental group was driven by decreased RD, consistent with the repeated-measures ANOVA results.

Note: Figure translations are in progress. See original paper for figures.

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