# Enhanced White Matter Tracts Integrity in Children With Abacus Training

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**Abstract:** Experts of abacus, who have the skills of abacus-based mental calculation (AMC), are able to manipulate numbers via an imagined abacus in mind and demonstrate extraordinary ability in mental calculation. Behavioral studies indicated that abacus experts utilize visual strategy in solving numerical problems, and fMRI studies confirmed the enhanced involvement of visuospatial-related neural resources in AMC. This study aims to explore the possible changes in brain white matter induced by long-term training of AMC. Two matched groups participated: the abacus group consisting of 25 children with over 3-year training in abacus calculation and AMC, the controls including 25 children without any abacus experience. We found that the abacus group showed higher average fractional anisotropy (FA) in whole-brain fiber tracts, and the regions with increased FA were found in corpus callosum, left occipitotemporal junction and right premotor projection. No regions, however, showed decreased FA in the abacus group. Further analysis revealed that the differences in FA values were mainly driven by the alternation of radial rather than axial diffusivities. Furthermore, in forward digit and letter memory span tests, AMC group showed larger digit/letter memory spans. Interestingly, individual differences in white matter tracts were found positively correlated with the memory spans, indicating that the widespread increase of FA in the abacus group result possibly from the AMC training. In conclusion, our findings suggested that long-term AMC training from an early age may improve the memory capacity and enhance the integrity in white matter tracts related to motor and visuospatial processes. *Hum Brain Mapp 32:10–21, 2011.* 

**Key words:** abacus-based mental calculation; diffusion tensor imaging; fractional anisotropy; experience-dependent plasticity; children; myelination; white matter

Additional Supporting Information may be found in the online version of this article.

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## INTRODUCTION

Abacus is a sort of traditional calculator which has been used for thousand of years in China. Abacus masters can use an abacus to perform most arithmetic operations such as addition, subtraction, multiplication, division, square root, cubic root, etc. Instead of manipulating a physical abacus, some abacus experts can calculate mentally with an imaged abacus, and such calculation method is the so-called "abacus-based mental calculation (AMC)." However, AMC is not an expertise monopolized by the abacus veterans, but rather an efficient calculation strategy that can be mastered by children through training. In China, many primary school pupils and preschool children learn AMC as an avocation. They initially learn to perform a physical abacus with both hands simultaneously, and then practice to simulate abacus operation in mind with actual finger movements as if they could manipulate the imagined abacus beads. Eventually, they can manipulate numbers via an imagined abacus in mind without actual finger movements. Skilled abacus players demonstrate extraordinary ability of mental calculation. They can mentally calculate large numbers with more than 10 digits with unusual speed and accuracy [Stigler, 1984]. Mental arithmetic requires the integration of multiple cognitive functions including number recognition, retrieval of arithmetic facts, temporary storage of intermediate results, and manipulation of mental representations. Behavioral studies suggested that visual strategy underlines AMC ability [Hatano and Osawa, 1983; Hatta and Ikeda, 1988; Stigler, 1984], while linguistic processing plays an essential role in exact mental calculation in ordinary adults [Dehaene et al., 1999]. To date, some functional neuroimaging studies have suggested that digit working memory and mental calculation of adult abacus experts were associated with enhanced involvement of neural resources for visuospatial information processing [Hanakawa et al., 2003; Tanaka et al., 2002]. Moreover, our previous fMRI study revealed similar results in child abacus experts about 12-years old [Chen et al., 2006].

It should be noticed that the subjects in this study operate abacus with both hands simultaneously (see Fig. 1), and the fingers of two hands can cooperate perfectly. To our knowledge, in the course of development, fingers have been closely related to numerical processing, and finger use might be the fundamental basis of numerical knowledge to represent numerosities before symbolic representations are employed [Fuson, 1988; Rusconi et al., 2005]. Recently, Gracia-Bafalluy and Noel [2008] found an interesting phenomenon that finger training, which requires good finger differentiation, could increase young children's numerical performance, suggesting a functional link between finger gnosis and number skills. Based on the observations of the role of the fingers in the course of numerical learning, we can expect that the long-term training of AMC might affect numerical performance and brain functional activation (as mentioned earlier) and brain structure, for abacus children begin to learn abacus operation and AMC at a very early age (about 6-years old) and the abacus operation requires good finger differentiation.

However, only a few studies have addressed the issue of the impact of abacus training on calculation performance and on brain function in children [Chen et al., 2006; Stigler, 1984], and no study has focused on the impact of AMC training on children's brain structure. Structural changes in cortices are commonly found in brain regions known to be functionally involved in the particular skills after training and practice [Ilg et al., 2008]. AMC, as a unique calculation manner, has been found to induce differences in brain activated pattern between those with AMC training experience and those without [Hanakawa et al., 2003; Tanaka et al., 2002]. In this study, we aimed to clarify the question that whether and how the long-term training of AMC could exert influences on structural plasticity in children's developing brain. As many studies have demonstrated that human brain could be modulated to adapt to specific skills through training and practice [Bengtsson et al., 2005; Gaser and Schlaug, 2003; Imfeld et al., 2009; Jancke et al., 2009; Schmithorst and Wilke 2002], we expected anatomic changes in the AMC children. Based on the features in the AMC: (1) abacus players can operate either a true or an imagined abacus with both hands simultaneously, (2) visuospatial processing underlies AMC performance [Chen et al., 2006; Hanakawa et al., 2003; Hatano and Osawa, 1983; Hatta and Ikeda, 1988; Stigler, 1984; Tanaka et al., 2002], we hypothesize that long-term AMC training may increase fiber integrity in some brain regions of children, especially in areas of motor and visuospatial pathways. To test our hypothesis, we compared fractional anisotropy (FA) values between the AMC and control groups. Additionally, to obtain more details about the neurostructrual changes, radial and axial diffusivities were compared between groups as well, for they are thought to be related to myelination degree and axonal maturation [Song et al., 2002, 2003]. As superior digit working memory has been observed in abacus experts [Hatano and Osawa, 1983; Tanaka et al., 2002], forward digit/letter memory span tests were administered in current study to explore the relations between working memory capacity and white matter integrity.

Abbreviations

| | |
|---|---|
| AMC | abacus-based mental calculation |
| DTI | diffusion tensor imaging |
| FA | fractional anisotropy |
| FSL | FMRIB software library |
| TBSS | tract-based spatial statistics |

## MATERIALS AND METHODS

### Subjects

Twenty five right-handed healthy abacus children (age = 10.48 ± 0.58 years, range: 9.61–11.58, 10 female) and twenty five right-handed healthy controls (age = 10.23 ±

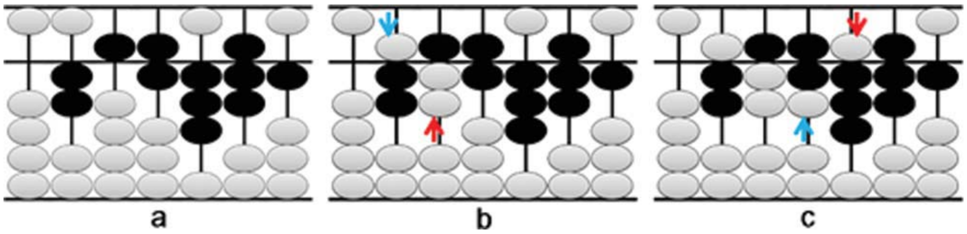


**Figure 1.**

(**a**) Abacus representation of 256371 (represented by the black beads); (**b**) when adding 256371 to 521500 for the first step, abacus players operate with the left forefinger and right thumb simultaneously; (**c**) the second step of addition. (Blue arrows marking left hand, red arrows marking right hand.). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

0.52 years, range: 8.89–11.51, 12 female) participated in this study. All abacus children have received AMC training for over 3 years and for about 3–4 h per week. The controls have no experience in AMC training. The Chinese version of Wechsler Intelligence Scale for Children-Revised (WISC-RC) was employed to assess the children's intelligence during the same week when their DTI data were acquired. WISC-RC consists of 12 subtests divided into two scales—verbal and performance. The six verbal tests use language-based items, whereas the six performance tests use visual-motor items. Five of the subtests in each scale (verbal and performance) produce scale-specific IQs, and the ten subtest scores produce a Full Scale IQ with the other two subtests excluded as redundant. Subjects' information was summarized in Table I.

All subjects participated in this study with consent by themselves and their parents. Our study was approved by the Ethics Committee of Zhejiang University.

## Behavioral Task: Forward Digit/Letter Memory Span Tests

To assess the participants' digit memory spans (DMS), several sequences of digits (1–9) were presented aurally at a rate of ~1 digit per second, and the participants were

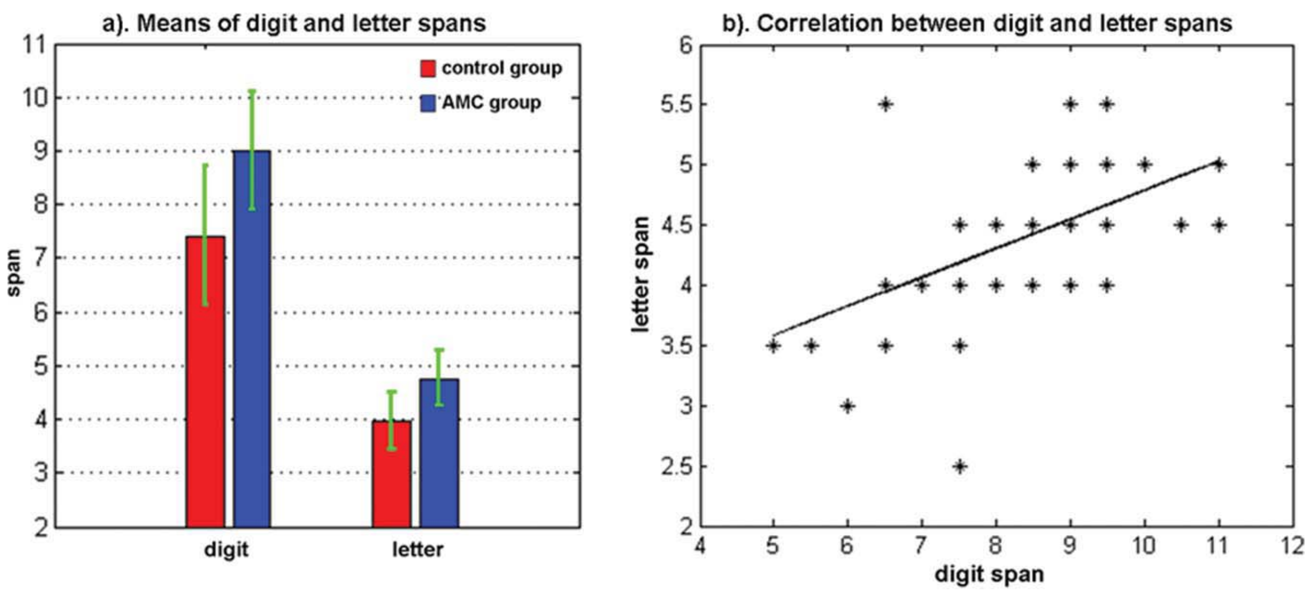


**Figure 2.**

Forward digit memory span (DMS) and letter memory span (LMS). (**a**) DMS mean (with standard deviation): 4.0 (0.5) in controls and 4.7 (0.5) in the AMC group; LMS mean (with standard deviation): 7.4 (1.3) in the control group and 9.0 (1.1) in the AMC group. Both DMS and LMS were found significantly higher in the AMC group than in the controls [for DMS: $t$ (48) = 5.4, $P$ = 0.00, and for LMS: $t$ (48) = 4.7, $P$ = 0.00]. (**b**) Significant positive correlation between DMS and LMS was found across all subjects ($r$ = 0.53, $P$ = 0.00). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

**TABLE I. Demographics of the AMC and control groups**

| | Gender | | Age | | |
|---|---|---|---|---|---|
| Group | Male | Female | Range | Mean | SD |
| Abacus | 15 | 10 | 9.61–11.58 | 10.48 | 0.58 |
| Control | 13 | 12 | 8.89–11.51 | 10.23 | 0.52 |

required to recall the digits in order after the presentation of the last digit. The task started with sequence of two digits, and the subjects were instructed to recall two digit sequences with the same length. The length of the sequence was increased by one if either one or both recalls for the same length were correct. The digit memory span was determined by the maximum length of digit sequence that the subject reached. If both trials of this length were recited successfully, the length was defined as the memory span; otherwise the length minus 0.5 was defined as the memory span. Procedures for the letter memory spans (LMS) were the same, with letters replacing digits.

## Image Acquisition

All the participants underwent the same protocol for DTI scanning using a 3.0 T Philips MRI scanner with SENSE coil technology. DTI data were obtained using single-shot echo planar imaging sequence (TR/TE = 5,500/78 ms, FOV = 240 mm, matrix size = 288 × 288, 50 slices, slice thickness = 3 mm, no gap) with 15 isotropically distributed orientation for the diffusion-sensitizing gradients at a *b*-value of 800 s/mm$^2$, and one nondiffusion image was obtained.

## Data Analysis

### Preprocessing

Eddy current distortions and head motion artifacts in the DTI dataset were corrected by applying affine alignment of each diffusion-weighted image to the nondiffusion image, using FMRIB's diffusion toolbox (FSL, version 4.1.0; www.fmrib.ox.ac.uk/fsl, [Smith et al., 2004]). After this process, the diffusion tensor elements were estimated by solving the Stejskal and Tanner equation [Basser et al., 1994]. The eigenvalues ($\lambda_1$, $\lambda_2$, and $\lambda_3$) were obtained by diagonalizing the tensor matrix. The diffusion indices FA, axial diffusivity and radial diffusivity of each voxel were defined as follows:

$$\mathrm{FA} = \frac{\sqrt{(\lambda_1-\lambda_2)^2+(\lambda_1-\lambda_3)^2+(\lambda_2-\lambda_3)^2}}{\sqrt{2(\lambda_1^2+\lambda_2^2+\lambda_3^2)}}$$

$$\text{Axial diffusivity} = \lambda_1$$

$$\text{Radial diffusivity} = \lambda_{23} = \frac{\lambda_2+\lambda_3}{2}$$

All eigenvalues and FA maps were calculated using DTIFit within the FMRIB Diffusion Toolbox (also a part of FSL). After alignment of every subject's FA map to standard MNI152 space, tract-based spatial statistics for FA images was carried out using package TBSS (part of FSL, for detailed description about TBSS please refer to Smith et al. [2006]) with the following steps. First, the mean FA image and its skeleton were created from the control and AMC groups in MNI152 space. Then, each subject's FA map was projected onto the skeleton and voxelwise statistics were made across subjects for skeletonized FA images. An FA threshold of 0.2 was set to differentiate between white and grey matter.

Axial and radial diffusivity skeletons were constructed with skeleton-projection parameters estimated from FA skeleton procedure, using tbss_non_FA procedure provided in FSL.

### Statistical analysis

***Behavioral performance.*** To investigate the AMC training influences on intelligences, full scale IQs and scaled scores of each subtest were compared between the AMC group and the controls using independent two-sample *t*-test. Differences between the two groups in working memory spans were evaluated with independent two-sample *t*-test, and the relation between DMS and LMS was examined as well.

***Whole-brain average skeleton FA.*** White matter (WM) fractional anisotropy is thought to be related to fiber integrity and the decline in FA is often used as an index of deterioration of WM health. To investigate whether AMC training has a global impact on brain white matter development, we compared the average skeleton FA between the two groups with independent two-sample *t*-test and investigate the relations between the average skeleton FA values and digit/letter memory spans.

***Voxelwise statistics of FA, axial, and radial diffusivity.*** To explore the possible local alteration of WM tracts, the independent two-sample *t*-test was administered voxel by voxel using randomize procedure (randomize v2.1, a package of FSL) with 5,000 permutations. The significance threshold for between-group differences was set at $P < 0.05$. Correction for multiple comparisons was carried out using threshold-free cluster enhancement method which is somewhat similar to cluster-based thresholding but generally more robust, and can avoid the need for the arbitrary initial cluster-forming threshold [Smith and Nichols, 2009].

***Relations between working memory spans and regional DTI measurements.*** To further explore the relations between the behavioral performances and the regional brain white integrity, linear regressions were employed to examine the correlations between the digit/letter memory spans and the averages of FA, axial diffusivity, and radial

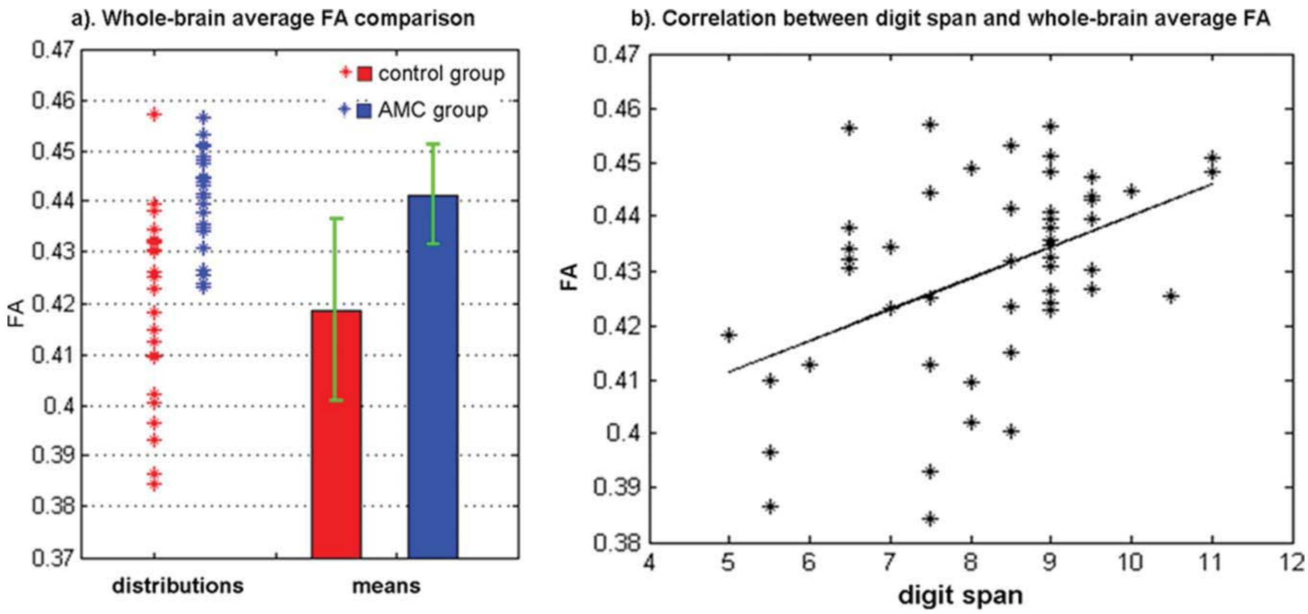


**Figure 3.**

Whole-brain average skeleton FA comparison. (**a**) Blue stars mark the control group (mean ± SD = 0.42 ± 0.018), red stars the abacus group (mean ± SD = 0.44 ± 0.009). The whole-brain average skeleton FA in the AMC group is significantly higher than that in the controls [$t$ (48) = 5.55, $P$ = 0.000]. (**b**) The whole-brain average skeleton FA was found significantly and positively correlated with digit memory span across all subjects ($r$ = 0.45, $P$ = 0.001). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

diffusivity within regions showing between-group differences in voxelwise FA statistics.

## RESULTS

### Behavioral Performances

In the intelligence tests with WISC-RC, scale scores in three subtests were found significantly higher in the AMC group than in the control group: digit span [$t$ (48) = 6.26, $P$ = 0.00], information [$t$ (48) = 2.82, $P$ = 0.01] and coding [$t$ (48) = 4.69, $P$ = 0.00]. The coding subtest scores were positively related to that in the digit span subtest ($r$ = 0.34, $P$ = 0.02) and the information subtest ($r$ = 0.32, $P$ = 0.02) across all subjects. When the digit span scores and the coding scores were included, full IQ scores were higher in the AMC group ($P < 0.03$) but no difference ($P$ = 0.27) was detected between groups when the digit span scores and the coding scores were not included.

Mean (±SD) of the DMS in the AMC group was 9.0(±1.1), and 7.4(±1.3) in the controls, respectively. For the LMS, mean (±SD) in the AMC group was 4.8(±0.5), while 4.0(±0.5) was observed in the control group. Compared with the control group, memory spans were found larger in the AMC group both in the DMS ($t$ = 5.43, $P$ = 0.00) and LMS ($t$ = 4.65, $P$ = 0.00), as shown in Figure 2a. Furthermore, the DMS and the LMS were found significantly correlated across all subjects ($r$ = 0.53, $P$ = 0.00), as shown in Figure 2b.

### Imaging Preprocessing Results

Mean of the postaligned FA images and mean of the skeleton FA with threshold of 0.2 were demonstrated in Figure 1 in Supporting Information.

### Whole-Brain Average Skeleton FA

The whole-brain average (±SD) of skeleton FA was 0.42 (±0.018) in the control group, while that of the abacus group was 0.44 (±0.009). Statistical result indicates that global mean of skeleton FA was significantly higher in the abacus group ($t$ = 5.55, $P$ = 0.00). Besides, the whole-brain averages of skeleton FA were significantly correlated with the digit working memory spans across all subjects ($r$ = 0.45, $P$ = 0.001; see Fig. 3).

### Voxelwise Statistics of FA, Axial and Radial Diffusivity

Compared with the control group, increased FA values in the abacus group were mainly located in three WM regions: (1) occipitotemporal junction in the left hemisphere (Fig. 4a), (2) premotor projection from right

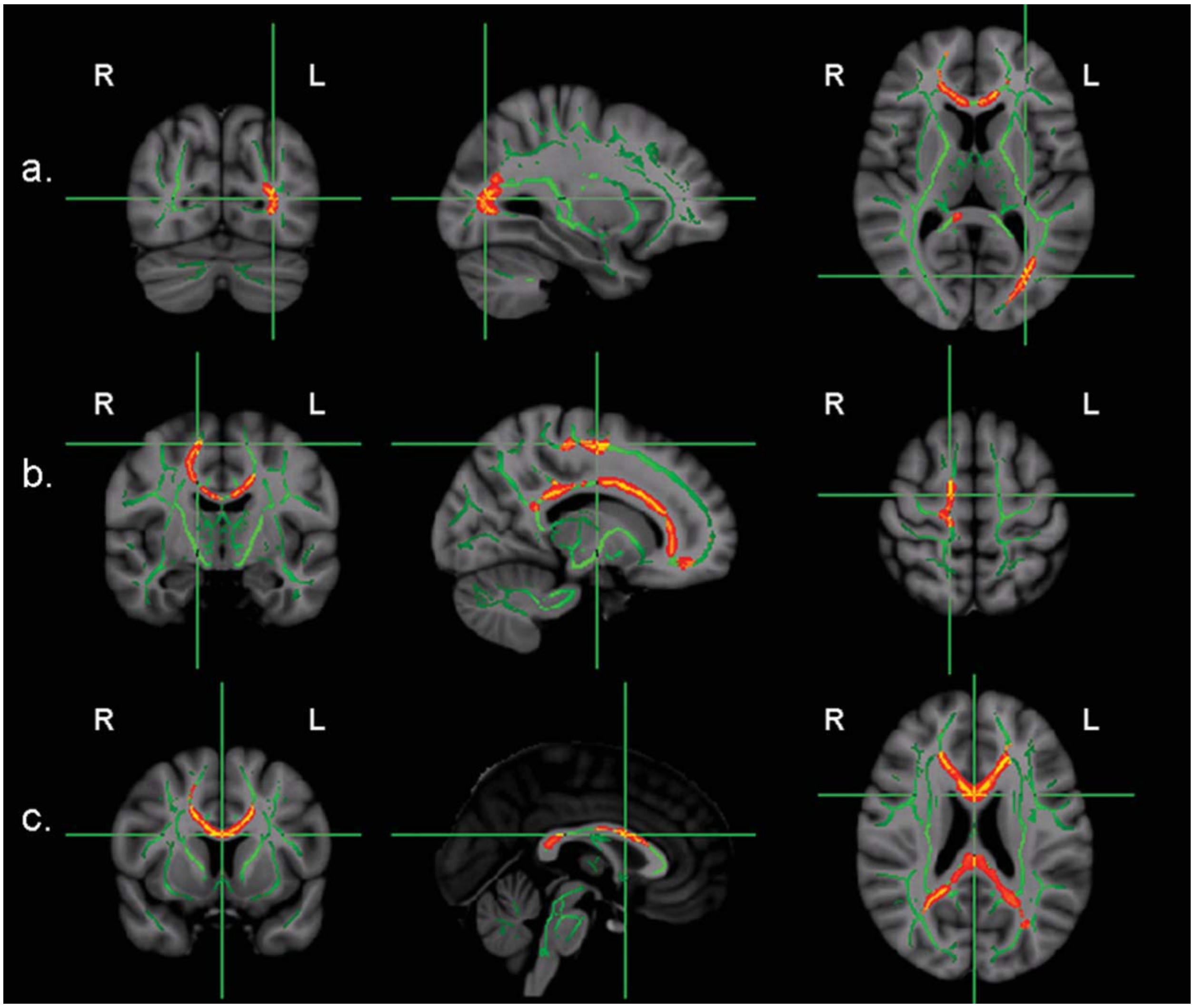


**Figure 4.**

Whiter matter structures showing significant enhancement of FA in the AMC group ($P < 0.05$, corrected for multiple comparisons) in: (**a**) left occipitotemporal conjunction area (cross-hairs in MNI coordinates at cross: $x = -29$ mm, $y = -73$ mm, and $z = 9$ mm), (**b**) projection extending from corpus callosum to right premotor area (cross-hairs in MNI coordinates: $x = 15$ mm, $y = -9$ mm, and $z = 57$ mm) and (**c**) corpus callosum (cross-hairs in MNI coordinates: $x = 1$ mm, $y = 8$ mm, and $z = 22$ mm). No regions have been found with higher FA in the control group as compared with the abacus group. The statistical map was overlapped onto the mean of FA skeleton (green) and MNI152 $1 \times 1 \times 1$ mm$^3$ template (gray-scale) for visualization purpose. (L: left; R: right). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

premotor area to midanterior corpus callosum (Fig. 4b), and (3) the splenium and anterior midbody at the midsagittal corpus callosum (Fig. 4c). No region was detected with higher FA values in the control group, and no region was found with axial diffusivity difference between groups. Additionally, other than regions with increased FA, radial diffusivity was also found lower in the abacus group in the right hemisphere, including posterior limb of the internal capsule, posterior thalamic radiation, the corona radiata, optic radiation and occipitotempral junction (Fig. 5a). Between-group differences in FA and radial diffusivity were shown in 3D in Figure 2 in Supporting Information.

## Relations Between Working Memory Spans and Regional DTI Measurements

The DMS was found positively correlated with the regional average of FA ($r = 0.36$, $P = 0.01$), negatively correlated with the regional average of radial diffusivity ($r = -0.35$, $P = 0.01$), and not correlated significantly with the

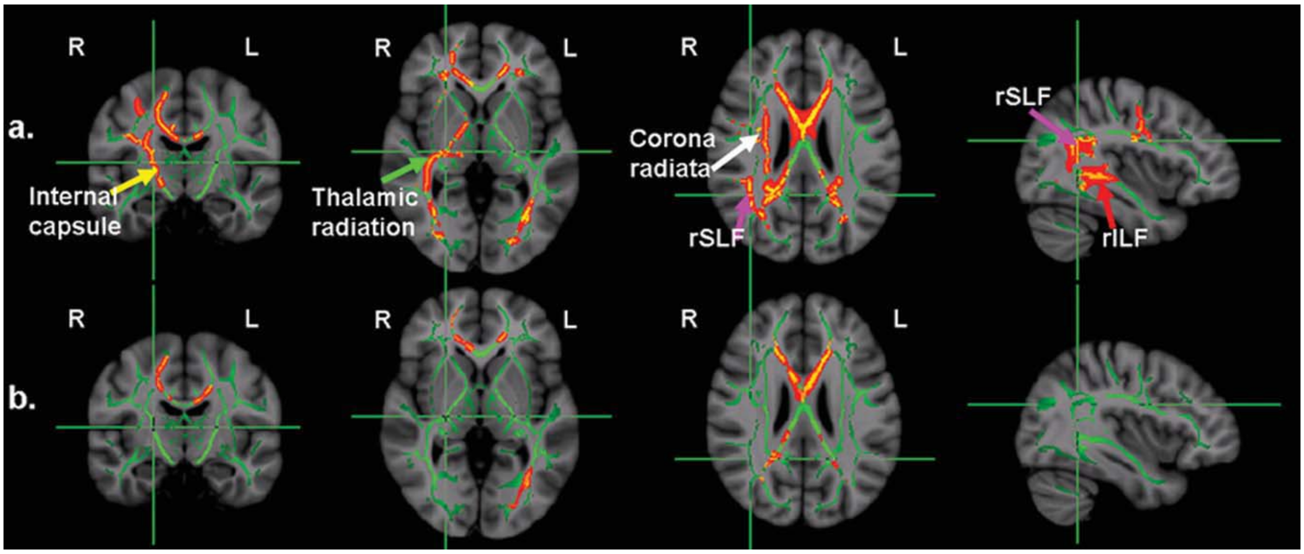


**Figure 5.**

Radial diffusivity showed greater sensitivity than FA to micro-neurostructure changes. (**a**) Radial diffusivity differences and (**b**) FA differences between the AMC and control groups (corrected $P < 0.05$). Posterior limb of internal capsule (marked by yellow arrow), posterior thalamic radiation (marked by green arrow), corona radiata (marked by white arrow), temporal part of superior longitudinal fasciculus (rSLF, marked by pink arrows), and inferior longitudinal fasciculus (rILF, marked by red arrow) showed significant decreased radial diffusivity only in the right hemisphere in the AMC group but no significant differences in FA. (L: left; R: right). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

regional average of axial diffusivity (see Fig. 6). The similar relations were found between the LMS and the regional white matter integrity.

## DISCUSSION

In the behavioral tasks, digit and letter memory spans were found significantly higher in the AMC group when compared with the controls (Fig. 2a) and significantly correlated across all subjects (Fig. 2b). Using TBSS method, we demonstrate for the first time the changes in brain WM integrity induced by long-term training of AMC in Chinese abacus children. Increased WM FA in the abacus group was observed in the corpus callosum, the left occipitotemporal junction and the right premotor projection (see Fig. 4), while no regions with decreased FA in the abacus

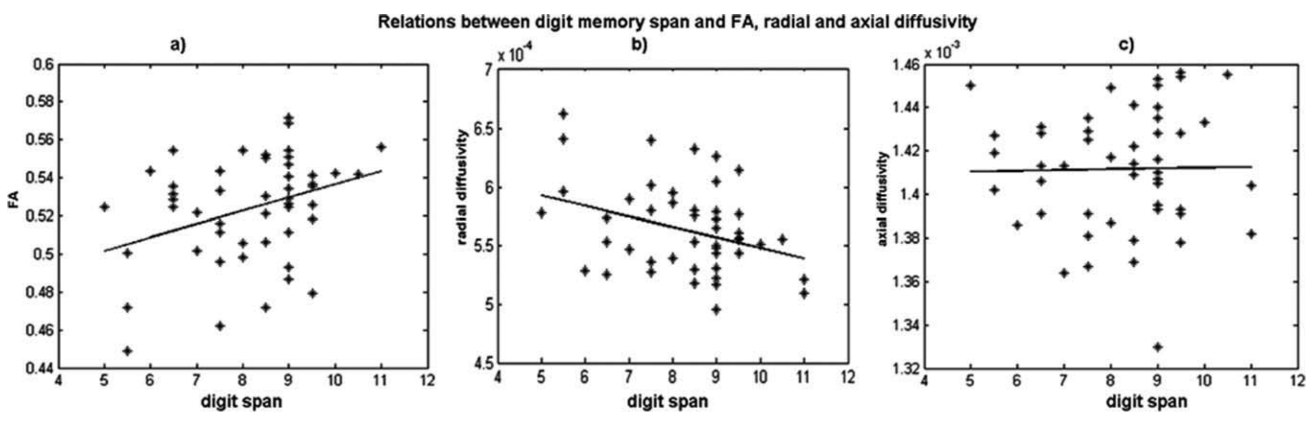


**Figure 6.**

Relations between digit memory span and the averages of FA, radial diffusivity and axial diffusivity within regions showing increased FA in the AMC group. Across all subject, the digit memory span was a) positively correlated with the regional average of FA ($r = 0.36$, $P = 0.01$), (**b**) negatively correlated with the regional average of radial diffusivity ($r = -0.35$, $P = 0.01$, and (**c**) not correlated significantly with the regional average of axial diffusivity ($r = 0.02$, $P = 0.89$).

group were detected. Furthermore, lower radial diffusivity was found in the abacus group (see Fig. 5), but no significant difference was found in axial diffusivity between groups. Besides, working memory spans were found associated with brain white matter integrity (Figs. 3 and 6).

### Whole-Brain Average Skeleton FA

FA is thought to be related to WM integrity, and the decline in FA is often viewed as an index of decreasing WM health. As shown in Figure 3, the whole-brain average skeleton FA is significantly higher in the abacus group than in the controls. In this study, the participants were about 10-years old and this age bracket is crucial for brain development. During the training period of over 3 years, the children with AMC training gradually develop to adapt to the operation with either a true or an imagined abacus. The training-induced gradual brain structural modulation could eventually accumulate to make significant differences in WM integrity between abacus children and their control peers. As the superior digit working memory in the AMC group likely results from the AMC training, the positive correlation between digit working memory and global brain white matter integrity could be an evidence of training-induced brain modulation.

### Voxelwise Statistics of FA, Axial, and Radial Diffusivity

Voxelwise statistics revealed that FA values increased in the abacus group in left occipitotemporal junction, right premotor projection and corpus callosum (see Fig. 4), and radial diffusivity decreased in internal capsule, posterior thematic radiation, right occipitotemporal junction and the regions with increased FA mentioned earlier (see Fig. 5). Axial diffusivity, however, showed no difference between groups. That is, the increase of FA in the abacus group was mainly driven by the decrease of radial diffusivity. As radial diffusivity was thought to reflect the myelination degree while radial diffusivity axon maturation [Song et al., 2002, 2003], it makes sense that AMC training likely results in the significant acceleration of myelination process but exerts little influence on axonal maturation.

The regional differences in DIT measurements between the AMC group and the controls are discussed below.

#### *Occipitotemporal junction*

The occipitotemporal junction contains fibers from many tracts, including inferior longitudinal fasciculus (ILF), inferior fronto-occipital fasciculus (IFOF), and optic radiation (OR). As a major associative connection between occipital and temporal lobes, ILF is suggested to mediate fast transfer of visual signal to anterior temporal regions [Catani et al., 2003], as well as to be related to visual recent memory [Tusa and Ungerleider, 1985]. IFOF, running from the frontal lobe to the occipital and temporal lobes ipsilaterally, is suggested to be crucial for language semantic processing [Mandonnet et al., 2007]. As known, OR is the pathway carrying information from the thalamic lateral geniculate nucleus to the visual cortex. Functions of these fiber tracts mentioned earlier imply that the occipitotemporal junction is likely to play an important role in integrating visual and semantic information. That is to say, the acceleration of the myelination in this region may reflect the integration of abacus, lexical and phonetic representations of numbers in the AMC tasks.

#### *Right premotor projection*

As we know, abacus players operate abacus with both hands simultaneously in the initial stage of the AMC training. Bimanualness in operation with abacus could be one of the factors that affect myelination of the premotor projection. Besides, premotor cortex is important in dynamic visuospatial imagery [Lamm et al., 2001] and plays an important role in the translation from a visual or auditory cue to an associated movement [Passingham, 1989]. Furthermore, premotor cortex was reported to be critical in updating verbal information and spatial information [Tanaka et al., 2005]. Thereby, the enhancement of WM integrity in the right premotor projection could mainly result from two factors: (1) the frequent use of left fingers for abacus operation and (2) the greater involvement of neuroresources for spatial information processing in the right hemisphere in the AMC tasks.

#### *Corpus callosum*

FA enhancement in the abacus group was observed in splenium and anterior midbody at the midsagittal corpus callosum (Fig. 4c). With diffusion tensor imaging technique, Hofer and Frahm [2006] demonstrated that fibers in splenium project to parietal, occipital and temporal regions while fibers in anterior midbody project to premotor and supplementary motor areas. Additionally, a neuroimaging research [Formisano et al., 2002] indicated that there is functional segmentation between left and right parietal cortices. They suggested that the left parietal cortex was likely involved in the generation of spatial mental images while the right parietal cortex engaged in the manipulation and comparison of such images. Bilateral premotor areas and posterior parietal regions were found engaged in the AMC tasks [Chen et al., 2006; Hanakawa et al., 2003]. According to the functional segmentation viewpoint, imagined abacus may be generated in the left hemisphere and manipulated in the right half. Long-term AMC training, relying on visuospatial processing, is likely to enhance the functional interaction between the left and right hemispheres, hence enhanced fiber integrity in the corpus callosum.

### *Areas observed with radial diffusivity difference*

As shown in Figure 4, corpus callosum, right premotor projection and left occipitotemporal junction demonstrated increased FA and decreased radial diffusivity in AMC group. Moreover, decreased radial diffusivity was also observed in the right hemisphere regions including posterior limb internal capsule, posterior thalamic radiation, corona radiata, superior longitudinal fasciculus, and inferior longitudinal fasciculus (see Fig. 5).

Posterior thalamic radiation and occipitotemporal junction are thought to be components of visual spatial attention network [Tuch et al., 2005]. And, temporal part of superior longitudinal fasciculus and inferior longitudinal fasciculus are suggested to mediate fast transfer of visual signal to anterior temporal regions [Catani et al., 2003] and to play an important role in visual recent memory [Tusa and Ungerleider, 1985]. The employment of visuospatial strategy in AMC is likely to contribute to the acceleration of myelination in these visuospatial related regions mentioned earlier. The internal capsule is a major route connecting cerebral cortex to brainstem and spinal cord while corona radiata, connecting with the internal capsule, contains both descending and ascending axons that carry nearly all of the neural traffic from and to the cerebral cortex. The frequent use of left fingers in AMC might contribute much to the enhanced myelination in these two fiber tracts.

In short, more regions in right than left hemisphere were found with decreased radial diffusivity in the AMC group (see Fig. 5). This finding supports the hypothesis that spatial information is processed predominately in right hemisphere [Formisano et al., 2002; Kohler et al., 1998].

A further question remains that why radial diffusivity seems more sensitive than FA to the changes of neurostructures in our study. We examine this question from a mathematic view. The first, second, and third eigenvalues ($\lambda_1$, $\lambda_2$, and $\lambda_3$) estimated from DTI data are related to the major, intermediate, and minor axes of a diffusion ellipsoid. For isotropic diffusion ($\lambda_1 = \lambda_2 = \lambda_3$), FA is zero, and in the case where there is a strongly preferred direction of diffusion [$\lambda_1 \gg (\lambda_2 + \lambda_3)/2$], FA approaches to one. Without any difference in axial diffusivity ($\lambda_1$) between groups, as found in our study, FA values depend heavily on radial diffusivity [$(\lambda_2 + \lambda_3)/2$]. In such circumstance, radial diffusivity is more sensitive than FA to the changes of neurostructures, for the variances in axial diffusivity weaken the sensitivity of FA.

## Relations Between Behavioral Performances and DTI Measurements

Working memory refers to the mechanism or system underlying the maintenance and processing of task-relevant information during the performance of a cognitive task [Baddeley et al., 1974; Daneman and Carpenter, 1980]. Using an event-related functional MRI study, Tanaka et al. [2002] found that superior short-term memory for digit was associated with greater activity in cortical areas related to visuospatial working memory. Additionally, previous behavioral studies indicated that abacus training is helpful to improve short-memory capacity in children [Bhaskaran et al., 2006; Lee et al., 2007]. In this study, digit working memory spans were found larger in the AMC group (see Fig. 2), which confirms the effects of AMC training. Besides, digit working memory spans were positively correlated with the global average of skeleton FA (Fig. 3b). Further analysis showed that, within regions showing different fiber integrity between the two groups, digit working memory spans were positively correlated with the regional average FA, negatively correlated with the regional average radial diffusivity and not correlated with regional average axial diffusivity (see Fig. 6). These results indicate that improvement in working memory capacity by AMC training could be related with enhancement in white matter tracts integrity.

## Intelligence, Training, Brain Developing, and Diseases

In the intelligence tests with WISC-RC, the six verbal tests include information, digit span, vocabulary, arithmetic, comprehension and similarities, whereas the six performance tests include picture completion, picture arrangement, block design, object assembly, coding and mazes. In our study, scale scores were found significantly higher in the AMC group than in the control group in such three subtests as digit span, information, and coding, which confirms the influence of AMC training on digit memory [Bhaskaran et al., 2006; Tanaka et al., 2002] and further suggests that AMC training improves the ability in digit-symbol substitution (as indicated in coding subtest). Interestingly, digit memory spans, higher in the AMC group than in the controls, were found positively correlated with WM integrity. Results from other studies also showed positive correlations between FA and behavioral measures such as reading ability [Beaulieu et al., 2005; Klingberg et al., 2000; Niogi and McCandliss, 2005], performance in a speeded lexical decision task [Gold et al., 2007], and musical sensorimotor practice [Bengtsson et al., 2005]. The positive correlation between digit memory spans and individual FA values in current study provides new evidence for the argument that higher FA might be behaviorally beneficial.

From a view of neurodevelopment, brain maturation is a complex process that continues well beyond infancy [Gao et al., 2009], and adolescence is thought to be a key period of brain rewiring. During the process of brain maturation, brain functions and underlying neurostructures could be modulated by training. Properties and intensity of the training are important in domain-specific brain modulations, while the onset of the training is also a crucial factor. It was reported that, compared with the controls, enlarged anterior callosa [Schlaug et al., 1995] and increased mean diffusivity in corticospinal tracts [Imfeld et al., 2009] were only found in the early onset subgroup of musicians which had started musical training before the age of 7. Participants in this study all started the AMC training before the age of 7, which may partly account for the enhancement of white matter integrity.

Besides, in normal populations, FA values development followed an inverted *U*-shaped curve, while the radial diffusivities followed a *U*-shaped curve [Hasan et al., 2009]. Our results indicate that variance of whiter mater health indices (such as FA and radial diffusivity) might be experience-related. Especially, long-time intensive training may modulate the development of brain WM, but the underlying mechanism remains unknown. Increased and decreased FA resulting from training could be found in separate brain regions [Schmithorst and Wilke, 2002]. Interestingly, both increased FA [Bengtsson et al., 2005] and decreased FA [Imfeld et al., 2009; Schmithorst and Wilke, 2002] in the internal capsule have been reported to result from music training. In this study, we detected only increased FA regions in the AMC group. We speculate that the fast development-induced increase in FA may suppress the training-induced decreasing trends in FA.

Contrast to training-induced FA increase, reduced FA was reported in a broad spectrum of diseases [Fling et al., 2008; Keller et al., 2003; Nave et al., 2008; Price et al., 2007; Sowell et al., 2008]. The corpus callosum receives a great many interests, for FA reduction in corpus callosum is related to many diseases such as schizophrenia [Keller et al., 2003], Multiple Sclerosis [Fling et al., 2008], fetal alcohol spectrum disorders [Sowell et al., 2008], spinocerebellar ataxia type 1 and 2 [Nave et al., 2008], first-episode psychosis [Price et al., 2007], and so on. Despite the relations between training-induced plastic modulations and DTI measurements still remain poorly understood and a matter of controversy [Alexander et al., 2007; Ashtari et al., 2007; Beaulieu, 2002], whether the training-induced enhancement of WM integrity can reduce the risk of demyelination diseases as mentioned earlier is an interesting question.

### Limitations

In WISC-RC intelligence tests, scaled scores of the digit span and the coding subtests were significantly higher in the AMC group, we speculated that the AMC training could improve children's ability in number-related operations, including digit-symbol mapping (as indicated in the coding subtest). Furthermore, in forward digit/letter memory span tests, the positive correlation between digit memory spans and letter memory spans implies that the AMC training not only improves the working memory capacity for digits but also for letters. The strength of these arguments, however, was weakened by the absence of pretests administered before the AMC training in this study. As for brain white matter integrity, the variation in FA relates to multiple factors including age, gender, handedness, and cognitive abilities [Schmithorst et al., 2008]. In this study, we investigated the AMC training influence on brain structures by comparing white matter integrity between two groups with or without AMC training experience, and attribute the resultant differences to the AMC training by assuming no differences between the two groups before the AMC training due to the absence of pre-examination for brain structures. We recently started a project to investigate the influence of AMC training on brain development, a longitudinal study monitoring the developmental trajectories of children's IQ and brain structures.

Diffusion images in our study were acquired with nonisotropic spatial resolution which is suggested to underestimate FA values in regions containing crossing fibers [Oouchi et al., 2007]. Besides, TBSS has limitations in the interpretation of changes in regions of crossing tracts or tract junctions [Smith et al., 2006]. Taking anisotropic voxel effects and the shortage of TBSS into consideration, it is a complicate thing to interpret FA differences in regions with crossing fiber such as occipitotemporal junction.

## CONCLUSIONS

With two matched groups of children aged about 10 years, we investigated the AMC training influences on children's behavioral performance and brain structures. Higher digit/letter working memory capacity was found in the AMC group. Using diffusion tensor imaging technique, we found that, compared with the control group, the AMC group showed (1) increased FA in corpus callosum, right premotor projection and left occipitotemporal junction; (2) decreased radial diffusivity in corpus callosum, right premotor projection, bilateral occipitotemporal junction, posterior limb of the internal capsule, corona radiate and posterior thalamic radiation; (3) no difference in axial diffusivity. Individual differences in working memory capacity were significantly and positively correlated with the global FA means of fiber tracts. The different radial diffusivities and the comparable axial diffusivities indicate that the increase in FA in the AMC group was mainly driven by the changes in radial diffusivity rather than axial diffusivity. Further analysis indicates that long-term AMC training may affect brain development by enhancing neuron myelination process of some fiber tracts responsible for motor and visuospatial processing.

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