NEUROSCIENCE

RESEARCH ARTICLE

H. Zhou et al. / Neuroscience 507 (2022) 28–35

Right Fusiform Gray Matter Volume in Children with Long-Term Abacus Training Positively Correlates with Arithmetic Ability

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Abstract—Abacus-based mental calculation (AMC) training has a positive effect on number-related cognitive abilities. While visuospatial strategy may distinguish AMC from conventional calculation method, the underlying neural mechanism is still elusive. The current study aimed to address this question by examining the plasticity of fusiform induced by AMC training and whether this training affects the association between the volume of fusiform and behavioral performance in numerical cognitive tasks using voxel-based morphometry analysis. The results showed that gray matter volumes of bilateral fusiform were significantly smaller in the AMC group relative to the control group. In addition, the volume of right fusiform was positively correlated with digit memory span and negatively correlated with reaction time of an arithmetic operation task only within the AMC group. These results indicate that bilateral fusiform may be the essential neural substrate for AMC experts to recognize and reconstruct abacus-based representations for numbers. These results may advance our understanding of the neural mechanisms of AMC and shield some lights to potential interactions between brain development and cognitive training in children.

Key words: Abacus-based mental calculation, fusiform, neural plasticity, training.

INTRODUCTION

Abacus-based mental calculation (AMC) is a mental calculation method that outperforms conventional verbal-based calculation in terms of calculation ability (Hatano et al., 1977; Hatano and Osawa, 1983; Hatano et al., 1987; Chen et al., 2006; Wang, 2020). AMC experts could mentally solve mathematic problems involving numbers in excess of ten digits in a rapid and precise way (Hatano et al., 1977; Chen et al., 2006). They also demonstrate better number-related cognitive abilities than non-experts, such as digit memory span and numerical processing efficiency (Tanaka et al., 2002; Hu et al., 2011; Wang et al., 2013; Yao et al., 2015). In addition, the training effect of AMC could also transfer to visuospatial working memory (WM) and executive control ability (Wang et al., 2017; Wang et al., 2019a), indicating AMC as a potential training paradigm to improve individual's cognitive ability. However, the neural mechanism underlying the extraordinary calculation ability of AMC and how AMC training improves individual's number-related cognitive ability are still elusive, and understanding of these questions has significant implications for developing efficient in-class training programs to help children with learning disabilities such as dyscalculia.

Behavior wise, participants could acquire AMC skill through long-term training. They would first learn to calculate on a physical abacus using fingers to move beads up or down according to rules. Then they learn to imagine an abacus and do calculations on the imaginary abacus with finger movements as if they were moving the beads on it. With practice, participants could perform calculation with the imaginary abacus without finger movements. It has been suggested that AMC experts use visuospatial strategies to perform digit memory and mental calculation tasks with an imaginary abacus, so-called "mental abacus", as a media,

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Abbreviations: ACC, accuracy; AMC, abacus-based mental calculation; ANOVA, analysis of variance; AO, arithmetic operation; DMS, digit memory span; LMS, letter memory span; RT, reaction time.

https://doi.org/10.1016/j.neuroscience.2022.11.006
0306-4522/

whereas non-experts rely upon linguistic strategies (Hatano et al., 1977; Hatano and Osawa, 1983; Stigler, 1984; Hatano et al., 1987; Frank and Barner, 2012). Relatedly, the neuroimaging studies have consistently reported significant activation in frontal and superior parietal lobule (a region constituting the dorsal visual stream) in AMC tasks (Hanakawa et al., 2003; Chen et al., 2006; Wu et al., 2009; Ku et al., 2010; Ku et al., 2012; Tanaka et al., 2012; Du et al., 2013), and the neural plasticity of this frontoparietal network induced by AMC training has been found to mediate its transfer effects to other cognitive abilities, such as visuospatial working memory and executive control (Dong et al., 2016; Wang et al., 2017; Wang et al., 2019a; Zhou et al., 2019; Zhou et al., 2020). In contrast, conventional calculation relies on a brain network including Broca's area (Tanaka et al., 2002), indicating the involvement of a verbal strategy in conventional calculation. However, the execution of complex visual behaviors requires interaction between ventral and dorsal visual pathways and an appropriate use of object/tool is largely based on crosstalk from the ventral stream (Creem and Proffitt, 2001; Almeida et al., 2013; Cloutman, 2013; Milner, 2017). A previous study further suggested that the knowledge of object-associated manipulation is retrieved from the ventral object processing pathway to guide motor actions (Almeida et al., 2013). In the case of AMC, the ventral visual stream may serve as primary neural underpinnings of the bead operation knowledge acquired by long-term AMC training. In addition, the "mental abacus" is thought to be constructed by a series of bead columns with each column representing one digit (Frank and Barner, 2012). Therefore, the ability of AMC experts to represent and manipulate large numerical value would attribute to their expertise in reconstructing number representations in the form of imaginary bead columns. Such psychological construct of mental abacus representations provides a theoretical basis for searching the neural substrates underlying AMC in the ventral pathway.

As an important region constituting the ventral visual pathway, fusiform may play an essential role in recognizing numbers and reconstructing corresponding abacus representations. Indeed, the fusiform has been documented in many previous AMC neuroimaging studies. For example, visual stimulation of larger numbers elicited higher activation in left fusiform gyrus in adults with long-term abacus use experience (Hanakawa et al., 2003). Children with long-term AMC training experience also showed higher activation in fusiform than control children did during calculation tasks (Chen et al., 2006). In a recent resting-state fMRI study, higher nodal local efficiency in right fusiform was found in the AMC children experts (Weng et al., 2017). In addition to these functional changes, decreased volume of gray matter in left fusiform, compared with a control group, was also reported (Li et al., 2013). In summary, both functional and structural findings have indicated the engagement of fusiform in AMC. However, evidence on the effect of AMC training on fusiform gray matter volume and its implications in number-related cognitive ability is still incomplete. In respect to fusiform functions, the left fusiform is related to semantic information processing, whereas the right fusiform is predominantly involved in processing visuo-perceptual information of object in visual object recognition (Simons et al., 2003; Bruffaerts et al., 2013). Based on researches mentioned above, we hypothesized that while both left and right fusiform may be essential for AMC, the right fusiform may be more closely related with the performance of number-related cognitive tasks in AMC individuals. To test this hypothesis, we conducted a voxel-based morphometry (VBM) analysis on MRI structural data. This investigation would extend previous findings and provide more direct evidence on the relationship between AMC training-induced brain structural changes and number-related cognitive abilities, which has significant implications for understanding the neural mechanisms of AMC and developing efficient intervention strategies for individuals who have difficulty in performing number-related tasks (e.g., children with mathematical learning disabilities).

EXPERIMENTAL PROCEDURES

Participants

Participants were recruited from an elementary school in the urban area of Heilongjiang province, China. The participants were recruited at the beginning of grade one and were assigned to two classes randomly. The neuroimage data were collected after grade three but before grade four when one of the classes had received AMC training for more than 3 years and for 3–4 h/week during school days (the AMC group), while another class (the control group) was doing group reading at the same class time and had no experience with abacus or AMC training. Both the AMC group and the control group included 19 participants, and two from each group were excluded because of large motion artifacts, leaving 17 healthy children (10 males, mean age = 10.39 years, SD = 0.53, range = 8.89–11.06 years) in the AMC group and 17 healthy children (seven males, mean age = 10.06 years, SD = 0.47, range = 9.61–11.58 years) in the control group. The Chinese version of Wechsler Intelligence Scale for Children-Revised (WISCRC) was administrated to estimate intelligence quotient (IQ) (Wechsler, 1974; Chan, 1979). The two groups were well matched in gender, IQ, and age (minimum $p = 0.062$). An arithmetic operation (AO) task and two memory span tests were conducted and all participants underwent an fMRI scan session (see details below). One AMC child and one control child were excluded from the statistical analyses of the AO task due to the inability to complete the task. All participants were reported to have normal or corrected-to-normal vision. Informed consent was obtained from all participants and their parents. Our study was approved by the Ethics Committee of Zhejiang University.

BEHAVIORAL MEASURES

Memory span tests

The Memory span was measured by Digit Memory Span (DMS) test and Letter Memory Span (LMS) test. In the

DMS test, several digital series (one to nine) were presented orally at a rate of approximately-one digit per second. After the presentation of the last digit, participants were instructed to recall the digits in order. The test started with two digits and there were two digital series for each length. The length of the next series was increased by one if either one or both recalls for the previous series were correct. The memory span was determined by the maximum length of digit series that the subject reached. If both trials of a series were recited successfully, the length of the series was defined as the memory span; if only one trial was recited successfully, the length minus 0.5 was defined as the memory span. The LMS test was the same as the DMS test except using letters instead of digits. The DMS and LMS data were used in a previous study (Hu et al., 2011), but its relationship with brain gray volume has never been reported.

ARITHMETIC OPERATION TASK

In the AO task, the participants were asked to calculate the sum of three addends. These addends were vertically aligned in the middle of a CRT computer screen, with the following setting: font = DigifaceWide, font size = 22, face color (R, G, B) = (0, 0, 0), background color = (127, 127, 127), the coordinates for three addends were (x = 0, y = 36), (x = 0, y = 0) and (x = 0, y = −36). In order to ensure that participants have enough time to calculate, no time window for calculation was set. The presentation of the addends would be terminated after participants entered their answers by pressing the SPACE bar. The answers would be shown on the screen. The next trial would be started automatically after participants pressed the ENTER key to confirm their answers. Four levels of task difficulty were designed by changing the addends from 1-digit numbers to 4-digit numbers with each level consisting of 20 trials (Fig. 1). For the control group, only 1- and 2-digit levels were administrated because 3- and 4-digit levels were too difficult for them to finish. The task always started from 1-digit condition followed by 2-, 3-, and 4-digit conditions. The task paused automatically after the completion of every 20 trials. Subjects were instructed to take a break and press the SPACE bar to continue when they were ready.

IMAGING DATA COLLECTION AND ANALYSIS

The MRI data were collected on a Philips 3.0 Tesla scanner (Achieva) using a sagittal T1-weighted sequence with following parameters: TR/TE = 30 ms/5 ms; FOV = 230 × 230 mm^2; phase/frequency encoding steps = 322/256; matrix = 560 × 560; voxel size = 0.41 × 0.41 × 1 mm^3; 168 slices without gap. The raw data were mainly processed using DARTEL toolbox released with SPM8 package (https://www.fil.ion.ucl.ac.uk/spm/), implemented on Matlab™ platform (r2008a) for Windows™. First, segment procedure was performed to obtained the spatial normalization parameters (*seg_sn.mat), which were then imported into DARTEL pipeline to write out rigidly transformed versions of the tissue class images including gray matter and white matter in an isotropic spatial resolution of 1.5 × 1.5 × 1.5 mm^3. Second, the segmented gray matter/white matter images were averaged across all participants to create an initial template. Deformations from this template to each of the individual images were computed, and the template was then re-generated by applying the inverses of deformations to the images and averaging. This procedure was repeated six times. Thirdly, the tissue class images were spatially normalized to MNI space with the total of signal from each region preserved so that areas that were expanded during warping were correspondingly reduced in intensity, which are so-called modulated images. Finally, the modulated images were smoothed with a Gaussian blurring kernel of 10 mm full width at half maximum (FWHM). The smoothed images were used in the statistical analysis to compare structural volumes between groups.

STATISTICAL ANALYSES

Independent t-test was conducted to test the difference of gray matter volume between the two groups. Based on the hypothesis we proposed, a small volume correction method was used. The mask of occipital fusiform was generated by applying a threshold of 25 % to the occipital fusiform atlas provided by FSL (https://fsl.fmrib.ox.ac.uk/). Results were corrected for multiple comparisons using false discovery rate (FDR $P_{\_corr} < 0.05$) implemented in the xjview toolbox (https://www.alivelearn.net/xjview).

For memory span tests, independent sample t-tests were used to test between-group differences in performance. Repeated measures analyses of variance (ANOVAs) were conducted on the median reaction time (RT) and accuracy (ACC) of the AO task with Condition (1-digit and 2-digit) as the within-subject factor and Group (AMC and control) as the between-subject factor to test group and condition differences. Post-hoc tests were further performed with Bonferroni correction $p < 0.05$. Pearson correlations were calculated between fusiform volume and behavioral performance within each group. Group difference of the correlation would be tested if any significant correlation was detected.

RESULTS

Behavioral results

The results showed that the AMC group displayed greater memory spans than the control children in both DMS and LMS tests (DMS: t (32) = 3.40, p = 0.002; LMS: t (32) = 4.69, p < 0.001, Fig. 2A). There was such a difference in the correlation between digit and letter memory span between AMC and control groups (z = 1.99, p = 0.047) that the correlation between digit and letter memory span was significant in control (r = 0.53, p = 0.03), but not in the AMC group (r = −0.16, p = 0.54).

Fig. 1. Presentation of the arithmetic operation task. Three addends were vertically aligned in the screen and four difficulty levels were included in the task, with the addends changing from one to four digits.

For the AO task, there was no trade-off effect of performance as there was no correlation between RT and ACC in 1-digit or 2-digit condition within the two groups (minimum $p = 0.23$). The repeated ANOVA analyses indicated that, for RT, there were significant main effects of Condition (F (1, 30) = 223.09, $p < 0.001$) and Group (F (1, 30) = 113.94, $p < 0.001$), as well as the Condition by Group interaction (F (1, 30) = 116.43, $p < 0.001$). Post-hoc analyses with Bonferroni correction indicated that the RTs were significantly longer in the control group than that in the AMC group under both 1- and 2-digit condition (both $p < 0.001$, Fig. 2B) and RTs of 2-digit condition were significantly longer than that of the 1-digit condition in both AMC ($p = 0.006$) and control group ($p < 0.001$). The interaction between group and condition was driven by the greater condition difference in control versus AMC group. For ACC, significant main effect of Condition and Condition by Group interaction effect were found (Condition main effect: F (1, 30) = 19.76, $p < 0.001$; interaction: F (1, 30) = 7.43, $p = 0.011$). Post-hoc analyses indicated the AMC group showed a higher ACC than the control group at 2-digit condition ($p = 0.044$, Fig. 2B) and ACC was significantly lower at 2-digit condition in the control group ($p < 0.001$) but not in the AMC group ($p = 0.234$).

STRUCTURAL MRI RESULTS

The independent t-test showed significant smaller volume of bilateral fusiform in the AMC group relative to the control group (right fusiform: t (33) = −3.63, MNI coordinates (31.5, −75, −10.5); left fusiform: t (33) = −4.80, MNI coordinates (−31.5, −69, −7.5), Fig. 3A).

CORRELATIONS BETWEEN BEHAVIORAL AND STRUCTURAL MRI DATA

For the memory span, there was a significant positive correlation between the volume of right fusiform and the DMS in the AMC group ($r = 0.57$, $p = 0.016$, Fig. 3B) but not in control group ($r = -0.31$, $p = 0.227$) and this correlation was significant different between two groups ($z = 2.57$, $p = 0.010$). A significant negative correlation between the volume of right fusiform and letter memory span was found in control group ($r = -0.53$, $p = 0.027$), but this correlation was not different between two groups ($z = 0.70$, $p = 0.485$). No significant correlation was found between volume of left fusiform and memory spans (Supplementary Material S1).

For the AO task, the ACCs were averaged for 1- and 2-digit conditions as well as for 3- and 4-digit conditions in the correlational analyses, whereas RTs were first normalized by Z-score transformation and then averaged. There was a significant negative correlation between the volume of right fusiform and the mean Z_{RT} of 1- and 2-digit trials in AMC group ($r = -0.73$, $p = 0.001$, Fig. 3B) but not in control group ($r = 0.02$, $p = 0.936$). This correlation was significantly different between the two groups ($z = 2.42$, $p = 0.016$). A significant correlation was also found between the volume of right fusiform and the mean Z_{RT} of 3- and 4-digit trials in the AMC group ($r = -0.72$, $p = 0.002$). In the control group, there was a significant correlation between the volume of right fusiform and the mean ACC of 1- and 2-digit trials ($r = -0.51$, $p = 0.045$),

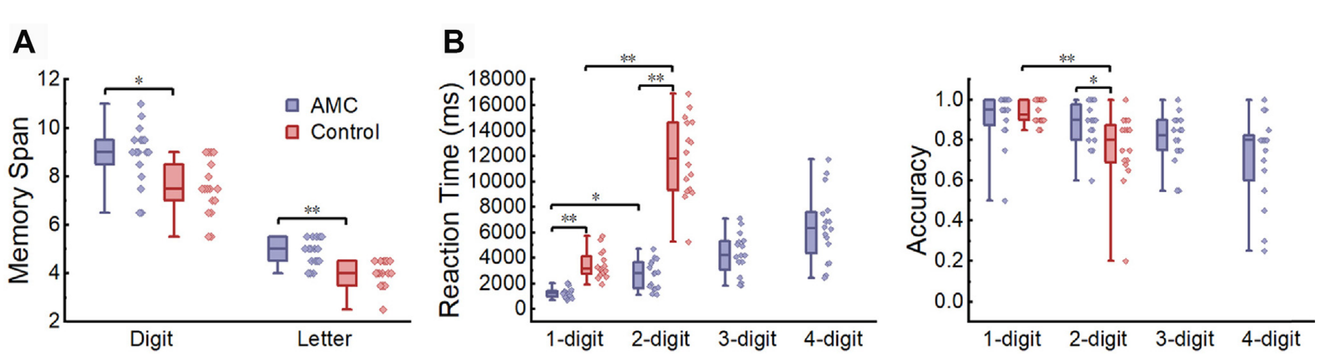

Fig. 2. Behavioral results. (**A**). Group differences in letter and digit memory span tests. (**B**). Differences between groups and conditions in reaction time and accuracy of the arithmetic operation task. *$p < 0.05$, **$p < 0.001$. The "box" depicts the median and the 25th and 75th quartiles and the "whisker" shows the 5th and 95th percentiles of the data.

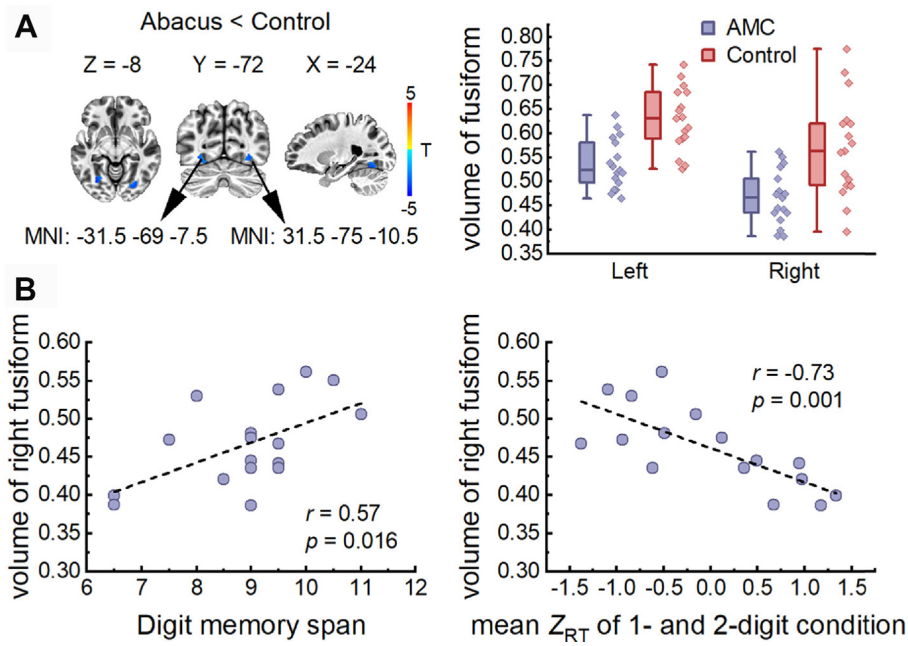

Fig. 3. Fusiform ROIs and the correlation of gray matter volume with behavioral indexes. (**A**). Fusiform regions showing significant group difference (left) and its corresponding box-and-whiskers plot (right). The ''box'' depicts the median and the 25th and 75th quartiles and the ''whisker'' shows the 5th and 95th percentiles of the data. (**B**). Scatter plot of the correlation between right fusiform volume and behavioral indexes within the AMC group.

whereas in the AMC group, this correlation was not significant ($r = -0.27$, $p = 0.318$), and this correlation was not different between AMC and control groups ($z = 0.72$, $p = 0.470$). No significant correlation was found between right fusiform volume and ACC of the 3- and 4-digit trials in the AMC group ($r = 0.27$, $p = 0.311$) and no other significant correlation between left fusiform volume and AO behavioral indexes was found (Supplementary Material S1).

DISCUSSION

Our primary results showed that children with AMC expertise displayed lower bilateral fusiform volume than control children, and there were significant correlations between the volume of right fusiform and DMS as well as RTs of the AO task only in the AMC group. These findings imply that AMC expertise may reshape the ventral visual pathway, and fusiform, especially the right fusiform may underlie children's better performance in numerical cognitive tasks.

REDUCED GRAY MATTER VOLUME OF BILATERAL FUSIFORM IN THE AMC GROUP

The fusiform has been considered to play an important role in AMC (Hanakawa et al., 2003; Chen et al., 2006; Li et al., 2013), but how AMC training impacts fusiform is unclear. In this study, we found lower gray matter volume in the AMC group relative to the controls, and the arithmetic ability, which was better in the AMC children, was positively correlated with fusiform volume within the AMC group. These seemly contradictive results may reflect an interaction between normal development and training on the MRI-based biometrics for gray matter. On one hand, the effect of development may induce a reduction in gray matter volume in both AMC and control groups according to previous studies showing consistent decrease of gray matter volume after 6 years old (Gennatas et al., 2017; Dong et al., 2020; Bethlehem et al., 2022). As individual's cognitive ability improves steadily from childhood to adolescent (Davidson et al., 2006; Davidow et al., 2018), it is reasonable that the reduction of gray matter volume has a positive effect on cognition in typically developed children. Pruning may be the primary factor underlying this developmental process (Shaw et al., 2006; Bray et al., 2015; Gennatas et al., 2017; Sakai, 2020). On the other hand, most studies have shown increased gray matter volume after training in both children (Krafnick et al., 2011; Sterling et al., 2013) and adults (Lovden et al., 2013; Colom et al., 2016). But the training-induced decrease of gray matter volume was also reported (Hänggi et al., 2010; Takeuchi et al., 2011; James et al., 2014; Scholz et al., 2015; Brooks et al., 2016; Gotink et al., 2018), and the volume change is quite dynamic (Zatorre et al., 2012). Therefore, whether training would increase or decrease gray matter volume is dependent on many factors. We speculated that our results may reflect such an interaction that while AMC training may accelerate the pruning process to form a stable fusiform neural substrate for the abacus expertise, which is possible because the experience-dependent selective elimination of synapses may help to sculpt neural circuitry supporting specific cognitive abilities (Huttenlocher and Dabholkar, 1997; Shaw et al., 2006; Takeuchi et al., 2011; Wang et al., 2019b). After pruning, the sculpted neuronal network may form new synapse, spines, angiogenesis to enhance the efficiency to meet the high demand of AMC calculation (Zatorre et al., 2012), so that the MRI-detected gray matter volume would increase as function of local micro-enhancement. In short, there might be an accelerated pruning process that accounts for the lower group-level fusiform gray matter volume, whereas the local microstructure enhancement might account for the positive correlation between gray matter volume and the abacus expertise in the calculation task in the AMC children.

THE ROLE OF RIGHT FUSIFORM IN AMC

Previous literatures have suggested a functional disassociation of left and right fusiform (Simons et al., 2003; Ma and Han, 2012). The left fusiform gyrus is related to semantic information processing and shows reliably enhanced activation after perception of visual words and pseudowords than perception of other highly similar control stimuli (McCandliss et al., 2003) and is related with reading ability (Beelen et al., 2022; Centanni et al., 2019; Tan et al., 2011). Whereas, the right fusiform is more related with visuo-perceptual information processing of object in visual object recognition (Simons et al., 2003; Bruffaerts et al., 2013). Subjects who have expertise in AMC are thought to transfer numbers to abacus representations (Frank and Barner, 2012; Barner et al., 2016). In the current study, the digit memory span was positively correlated with right fusiform volume only in the AMC group and a significant correlation between letter and digit memory span was found only within the control group. These results indicate that the AMC group may conduct a different strategy when they need to retain information of digits. The specialization of right fusiform for mental abacus image may facilitate the intermediate processing of digits (e.g., abstract extraction of digit information using mental abacus instead of linguistic code) and therefore improve the digit working memory. It is worth noting that left fusiform was also reported to be activated in mental-operation task in previous studies (Hanakawa et al., 2003; Chen et al., 2006), and the numbers composed by more digits evoked higher activation in the left but not right fusiform (Hanakawa et al., 2003). However, the encoding of numbers is too simple to characterize individual's AMC ability assessed with complex calculation tasks. The positive correlation between gray matter volume of right fusiform and arithmetic task performance reported in the present study provides clear evidence to support that the right fusiform may be the essential neural substrate underlying the visuospatial strategy of AMC. It is interesting for future studies to further survey the functional laterality of fusiform in AMC.

A POTENTIAL NEURAL MECHANISM UNDERLYING THE AMC VISUOSPATIAL STRATEGY

Potential visuospatial strategy in AMC experts has been extensively investigated by previous studies (Hanakawa et al., 2003; Chen et al., 2006; Wu et al., 2009; Zhou et al., 2019). The long-standing view is that the frontoparietal network is the main neural substrate supporting AMC, and this point is supported by the observation that the lesion of premotor and parietal regions results in the loss of AMC ability (Tanaka et al., 2012). While these high-level cognitive brain regions have been consistently shown to be essential of AMC, the role of some relative low-level regions such as fusiform has been less discussed. The positive correlation between fusiform gray matter volume and AMC ability reported in the present study, when combined with previous findings (Hanakawa et al., 2003; Li et al., 2013; Weng et al., 2017), suggests that the fusiform may account for the ability to transform numbers into imaginary abacus representations (Frank and Barner, 2012; Weng et al., 2017), and then transmit them to high-level frontoparietal regions for further operations including maintenance and arithmetic manipulation. However, how fusiform interacts with the frontoparietal network to support the visuospatial strategy of AMC warrants further investigations in future.

LIMITATIONS

There are several limitations of the current study. First, we do not have an active control group and it leads to a question that whether the neural plasticity is induced by the general training procedure or the specific AMC training method. Second, our sample size is relatively small. Though the correlation between right fusiform gray matter volume and AMC ability has moderate effect, future studies with larger sample size are needed to confirm these results. Lastly, the causal association between AMC training and gray matter change should not be concluded merely by these preliminary results due to lack of MRI data prior training.

In summary, the present study found that children with long-term AMC training have smaller volume of bilateral fusiform and the volume of right fusiform was related to the performance in numerical cognitive tasks. These findings not only provide evidence that AMC training may induce brain plasticity facilitating the development in arithmetic ability in children but also suggest that AMC might be a potential intervention strategy for individuals (e.g., children with mathematical learning disabilities) who have difficulty in performing number-related tasks using conventional verbal-based methods.

ACKNOWLEDGEMENTS

This work was supported by the China Brain Project (No. 2021ZD0200409), the Fundamental Research Funds for the Central Universities (No.2022QZJH09), the Zhejiang Province 'Qianjiang Talent Program', and the National Natural Science Foundation of China (No. 81971245).

I have read and have abided by the statement of ethical standards for manuscripts submitted to Neuroscience.

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APPENDIX A. SUPPLEMENTARY DATA

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neuroscience.2022.11.006.

(Received 8 June 2022, Accepted 7 November 2022)
(Available online 15 November 2022)