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Research Report

The neural pathway underlying a numerical working memory task in abacus-trained children and associated functional connectivity in the resting brain

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ABSTRACT

Training can induce significant changes in brain functioning and behavioral performance. One consequence of training is changing the pattern of brain activation. Abacus training is of interest because abacus experts gain the ability to handle digits with unusual speed and accuracy. However, the neural correlates of numerical memory in abacus-trained children remain unknown. In the current study, we aimed to detect a training effect of abacus-based mental calculations on numerical working memory in children. We measured brain functional magnetic resonance imaging (fMRI) activation patterns in 17 abacus-trained children and 17 control children as they performed two numerical working memory tasks (digits and beads). Functional MRI results revealed higher activation in abacus-trained children than in the controls in the right posterior superior parietal lobule/superior occipital gyrus (PSPL/SOG) and the right supplementary motor area (SMA) in both tasks. When these regions were used as seeds in a functional connectivity analysis of the resting brain, the abacus-trained children showed significantly enhanced integration between the right SMA and the right inferior frontal gyrus (IFG). The IFG is considered to be the key region for the control of attention. These findings demonstrate that extensive engagement of the fronto-parietal network occurs during numerical memory tasks in the abacus-trained group. Furthermore, abacus training may increase the functional integration of visuospatial-attention circuitry, which and thus enhances high-level cognitive process.

1. Introduction

As the old saying goes, "Practice makes perfect." Training and practice can improve a person's skills, as reflect in increase in accuracy and reduce in reaction times. Neuropsychological and brain imaging studies have shown that sufficient training can improve performance and alter brain activity (Buschkuehl et al., 2012; Jolles and Crone, 2012). The effect of

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training has been studied widely in the areas of mental calculation (Delazer et al., 2005; Hanakawa et al., 2003) and working memory (Klingberg, 2010; Olesen et al., 2004). Training has been found to enhance children's problem-solving skills and school reading performance (Holmes et al., 2009).

Recently, our study on the effect of abacus training on structural connectivity indicated that long-term abacus-based mental calculation (AMC) training might enhance the integrity of white matter tracks related to motor and visuospatial processes (Hu et al., 2011; Li et al., 2013). Previous studies have also shown that fronto-parietal network is mainly involved in mental calculation (Chen et al., 2006; Hanakawa et al., 2003) and digit memory tasks (Tanaka et al., 2002) in abacus experts. A longitudinal fMRI study of a skilled abacus user with right hemispheric brain lesion (Tanaka et al., 2012) and an EEG-fMRI case study (Ku et al., 2012) identified the importance of the fronto-parietal circuitry for performing AMC. Studies mentioned above suggest, that abacus training may improve the calculation ability, affect the pattern of cerebral specification and change white matter integrity. The fronto-parietal network plays an important role in all of these changes.

Although the training effect of AMC has been confirmed and the cognitive mechanisms and the neural correlates of mental calculation have been studied, the effect of training on untrained numerical working memory tasks and their neural correlates remain unknown. In the present fMRI study, we hypothesized that long-term abacus training gains could transfer to the untrained numerical working memory task. Furthermore, we hypothesized that the brain functional integration would be affected by training. Two groups of 10-year-old Chinese children (with and without abacus training) were recruited to perform two numerical working memory tasks (digit and bead match-to-sample tasks) in an MRI scanner. Using these tasks, we aimed to identify the specialized brain regions that are related to the memory of numerical information. In addition, we aimed to assess the effect of abacus training on brain functional connectivity. Based on previous studies (Chen et al., 2006; Hanakawa et al., 2003; Hu et al., 2011; Ku et al., 2012; Tanaka et al., 2002; Wang et al., 2013), we predicted that abacus-trained children would show greater activation than untrained children in the fronto-parietal regions on both tasks and that resting-state functional integration of this network would be significantly enhanced by training.

2. Results

2.1. Behavioral results

The accuracy and reaction time (RT) for each task were summarized in Table 1. A 2 (task) × 2 (group) mixed analysis of variance on RT yielded a group main effect ($F(1,32)=7.48$, $p=0.01$), indicating that abacus-trained subjects were faster than control subjects on both tasks. The main effect of task was not significant ($F(1,32)=0.322$, $p=0.575$). A parallel analysis was conducted for accuracy and revealed a main effect of task ($F(1,32)=10.23$, $p<0.01$), indicating that subjects were more accurate on the digit task than on the bead task.

Table 1 – The accuracy and reaction time for each task for each group.

Task	Correct (%)	Reaction time (ms)
Abacus		
Digits	89.1 (7.8)	774.5 (23.6)
Beads	81.0 (10.9)	793.9 (28.8)
Controls		
Digits	88.5 (9.6)	908.2 (25.0)
Beads	85.3 (7.3)	907.0 (28.4)

The main effect of group was not significant ($F(1,32)=0.112$, $p=0.74$). No significant interaction between group and task was observed in terms of either RT ($F(2,64)=0.356$, $p=0.555$) or on accuracy ($F(2,64)=2.394$, $p=0.132$).

2.2. fMRI results

2.2.1. General activity patterns

In the abacus-trained group, the digit working memory task induced activation in the bilateral supplementary motor area (SMA), left precentral gyrus, inferior parietal lobule (IPL), right angular gyrus, superior parietal lobule (SPL), and inferior occipital gyrus. In the untrained control group, the digit working memory task activated the bilateral SMA, insula, inferior occipital gyrus, left precentral gyrus, angular gyrus, and the IPL. The activity was lateralized to the left parietal lobe in the control group. The brain activation was displayed in Fig. 1A and Table S1. The pattern of activity observed in the control group during the digit task was consistent with previous neuroimaging studies (Dehaene et al., 1999; Gobel et al., 2004). The left angular gyrus is believed to underlie a verbal representation of numbers that is thought to be useful in counting and the retrieval of simple arithmetical facts from memory (e.g., three times four is twelve) (Dehaene et al., 2003; Piazza et al., 2006). The activation of this region in the current study suggests that control children used a verbal representation to memorize the digit strings during the retention intervals.

The bead working memory task induced symmetrical, bilateral activity in the SMA, precentral gyrus, IPL, SPL, insula, and inferior occipital gyrus. This activation pattern was similar for both groups (Fig. 1B and Table S1).

2.2.2. Group comparison analysis results

2.2.2.1. Digit working memory task. We made a direct comparison of brain activation in the abacus-trained group and the control group. The results of the comparison were illustrated in Fig. 2 and Table 2. The abacus-trained group showed significantly greater activation than the control group in the right SMA, right PSPL/SOG, left inferior precentral gyrus, left SOG, and in the left anterior precuneus. In contrast, only the left SMA showed greater activation in the control group than in the abacus-trained group.

2.2.2.2. Bead working memory task. The comparing of activation on the bead working memory task comparison between the abacus and control groups was shown in Table 2 and

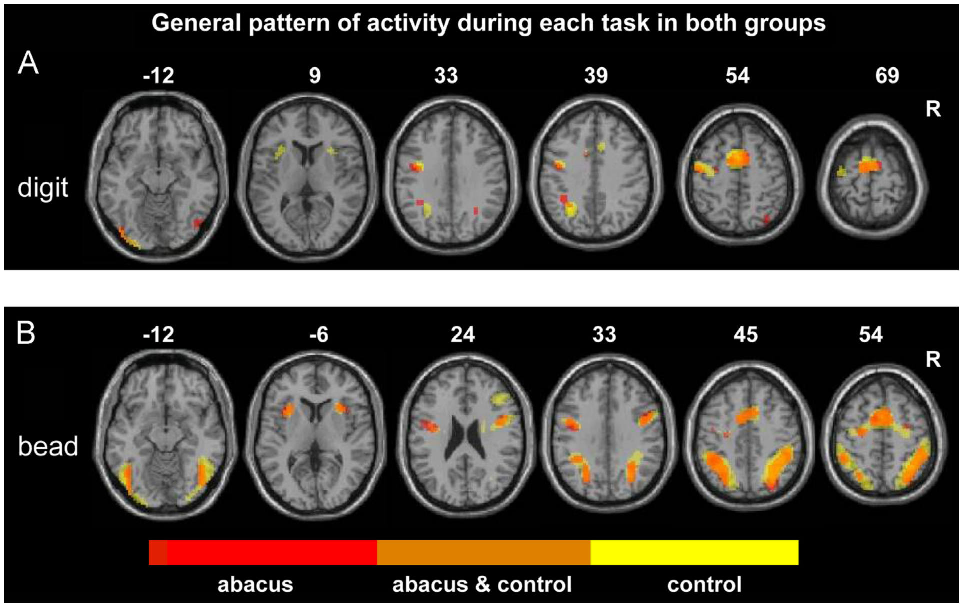

Fig. 1 – General pattern of activity during each task. (A) Activity during the digit working memory task relative to the resting state for the abacus-trained group and the control group ($p<0.001$, FDR corrected). (B) Activity during the bead working memory task relative to the resting state for the abacus-trained and control groups ($p<0.001$, FDR corrected). Significant activity in the abacus-trained children is shown in red, activity for the control children in yellow, and the spatial overlap of activity between the two groups in orange. The numbers on the axial slices indicate the *z* coordinate in mm; the right side of each section represents the right side of the brain.

Fig. 2. The abacus-trained group showed greater activation in the right SMA and right PSPL/SOG. Only the right intraparietal sulcus showed greater activation in the control group.

2.2.2.3. Conjunction analysis results. A conjunction analysis was performed on the digit and bead task imaging data (digit>rest & bead>rest) for both groups separately. As illustrated in Fig. 3 and detailed in Table 3, in the abacus-trained group, the right SMA and right PSPL/SOG areas was activated on both tasks. In the control group, no common region showed activation on both tasks. The group conjunction analysis revealed greater activation on the bead task than on the digit task in bilateral inferior parietal lobule and superior parietal lobule in both groups. No common region showed greater activation on the digit task than on the bead task in both groups.

2.3. *Functional connectivity results*

Resting-state functional connectivity analysis revealed that both the abacus-trained and control groups showed significant positive correlations between the right SMA and the bilateral precentral gyrus. The medial frontal cortex, insula cortex, and inferior frontal gyrus (IFG) also had significant positive correlations with the right SMA in both groups (Fig. 4 left panel). Bilateral superior parietal lobule, precuneus, and right superior frontal gyrus were found positively correlation with the right PSPL/SOG in both groups (Fig. 4 right panel).

A two sample *t*-test showed significantly increased functional connectivity between the right SMA and the right IFG ($x=32$, $y=23$, $z=-5$) in the abacus-trained group relative to the control group. No significant increase in functional connectivity between the right PSPL/SOG and other brain voxels was detected in the abacus-trained group relative to the control group (Fig. 4, the last row).

3. Discussion

The goal of the current study was to investigate the neural mechanisms underlying the memory of visual numerical information in abacus-trained children. Two stimulus types (digit and bead) were used in this study. Prior research has highlighted that abacus experts represent digits in the form of a visual image (Frank and Barner, 2012; Stigler, 1984) and utilize a visuospatial representation for digit memory and mental calculation (Chen et al., 2006; Hanakawa et al., 2003; Tanaka et al., 2002). Neuroimaging studies of digit memory and mental calculation in abacus expert have repeatedly found activation in the fronto-parietal network (Chen et al., 2006; Ku et al., 2012; Tanaka et al., 2002; Tanaka et al., 2012). Previous research has demonstrated that cognitive intervention and experience can have an impact on brain functional connectivity (Jang et al., 2011; Lewis et al., 2009). Therefore, we predicted that long-term abacus-trained children would exhibit higher activation in the fronto-parietal network and increase brain functional connectivity in this network compared with the controls.

In the present study, we found (1) A common fronto-parietal network (right SMA and PSPL/SOG) was invoked by the digit and bead working memory tasks in the abacus-trained group rather than in the controls. (2) Compared with the control group, enhanced resting-state functional integration between the right SMA and the right IFG was found in

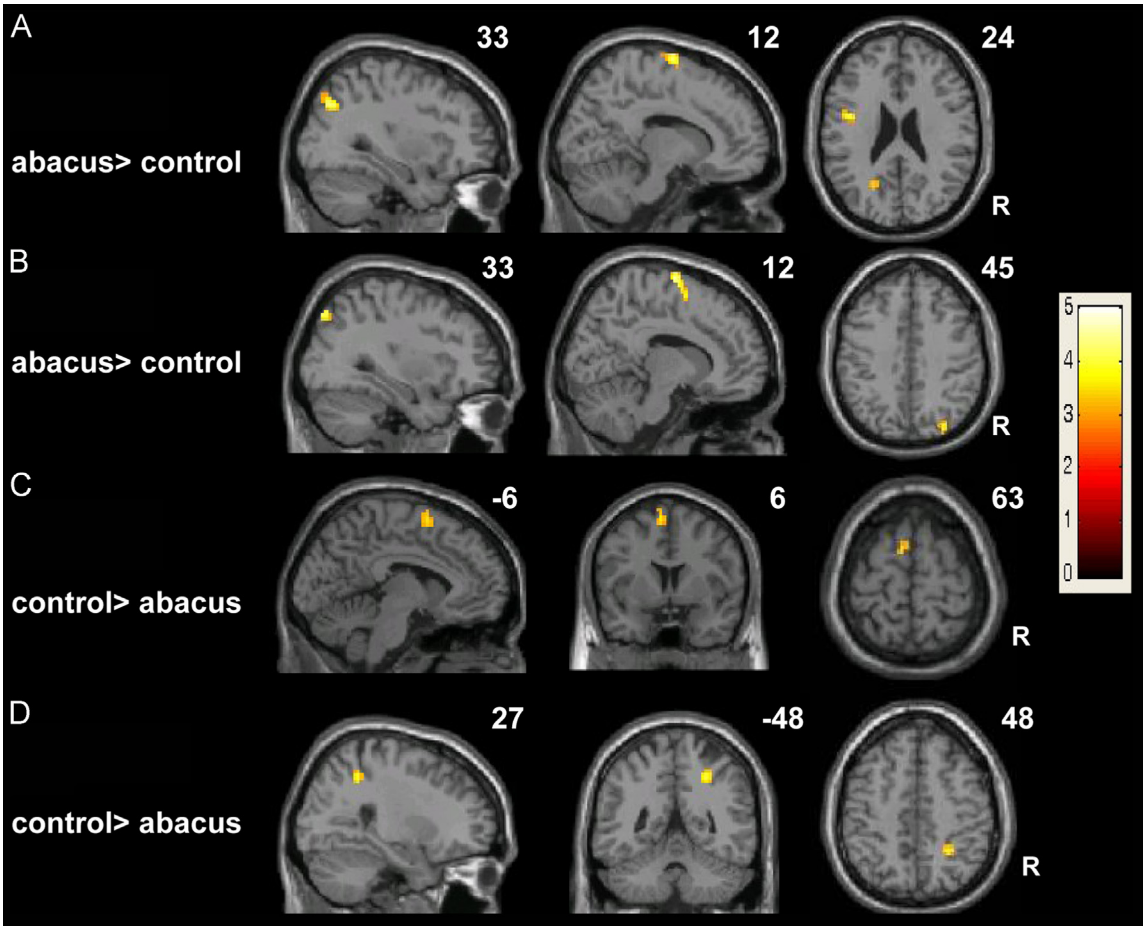

Fig. 2 – Statistical comparisons of the abacus-trained and control groups. (A–B) These regions showed significant activation in the abacus vs. control comparison on the digit and bead working memory tasks, respectively. (C–D) These regions showed significant activation in the control vs. abacus comparison on the digit and bead working memory tasks, respectively. These brain regions showed significant activation between groups (abacus and control) and stimulus type across the whole brain. The statistical threshold was set at $p<0.05$ using the AlphaSim correction (a combination of a $p<0.005$ threshold and a minimum cluster size of 23 voxels) (A, C-Digit), (B, D-Bead).

Table 2 – Summary of significant activations between abacus and control group across the whole brain.

Comparisons	Statistical values			Coordinates anatomical location			
	Cluster size	*t*-Value	*p*-Value	x	y	z	Region
Digits							
Abacus > Control	59	4.44	0.000	33	−72	36	R Sup parietal/occipital gyrus
	23	4.19	0.000	12	−6	75	R Supp_motor_area
	31	3.94	0.000	−42	0	24	L Inf precentral gyrus
	34	3.96	0.000	0	−39	57	L Precuneus
	27	3.44	0.000	−21	−63	24	L Sup occipital gyrus
Control > Abacus	25	3.55	0.000	−6	6	63	L Supp_motor_area(BA6)
Beads							
Abacus > Control	24	4.22	0.000	32	−74	47	R Sup parietal/occipital gyrus
	47	4.46	0.000	12	−6	75	R Supp_motor_area
Control > Abacus	26	3.87	0.000	27	−48	48	R intraparietal sulcus

The MNI coordinates and *t*-values for the local maxima of the centers of the voxel clusters; BA = brodmann area; R = right hemisphere; L = left hemisphere; Inf = inferior; Sup = superior; Supp = supplementary. The statistical threshold was set at $p<0.05$ using AlphaSim correction (with combination of threshold of $p<0.005$ and a minimum cluster size of 23 voxels).

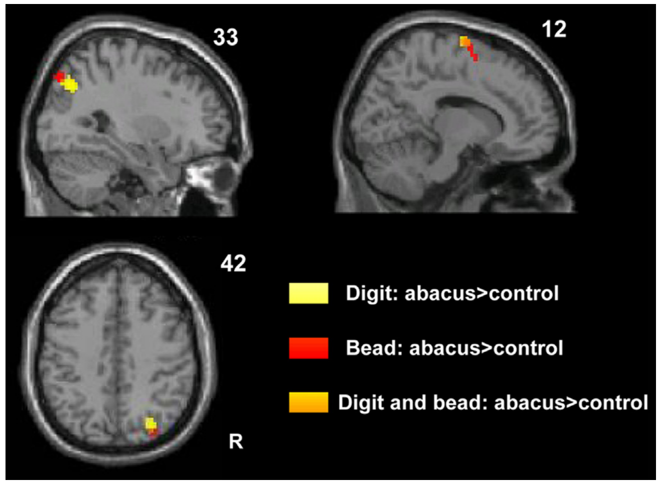

Fig. 3 – Conjunction analysis across tasks for abacus-trained > controls. Regions that exhibited a significant response above baseline to both the digit and bead match-to-sample tasks are shown for abacus-trained vs. control children in the same image space ($p<0.001$, uncorrected, 5 contiguous voxels). R: right.

Table 3 – The conjunction analysis results.

Comparisons	Statistical values			Coordinates anatomical location			
	Cluster size	t-Value	p-Value	x	y	z	Region
Conjunction of digit and bead							
Abacus > Control	5	3.37	0.000	30	−78	42	R sup parietal/occipital gyrus
	15	4.37	0.000	12	−6	75	R Supp_motor_area
Control > Abacus	NO						

The MNI coordinates and t-values for the local maxima of the centers of the voxel clusters; BA = brodmann area; R = right hemisphere; Sup = superior; Supp = supplementary. Threshold for significant clusters reported here was set at $p<0.001$ (uncorrected) and a cluster size of 5 voxels.

the abacus-trained children. (3) At the behavioral level, the abacus-trained children performed both tasks much faster than control children.

3.1. *Brain activation*

Comparing with the controls, a common fronto-parietal network was invoked by both tasks in the trained group. This network was also involved in the short-term digit memory task in the abacus expert (Tanaka et al., 2002). The parietal cortex, especially the PSPL, plays a critical role in visuospatial tasks, such as visuospatial working memory and visuomotor processing (Faillenot et al., 1999; Hamzei et al., 2002; Hanakawa et al., 2003; Simon et al., 2002). The posterior parietal cortex is a key neural locus for mental representation of the visual world (Todd and Marois, 2004). Functional neuroimaging studies of mental imagery have identified specific activation in the superior parietal lobule (Formisano et al., 2002; Sack et al., 2005). These studies reported right but not the left parietal cortex engagement in the execution of visuospatial judgments. The SMA proper, a typical premotor area, has strong connections to the primary motor cortex. The SMA is thought to subserve motor execution (Picard and Strick, 1996) and to be involved in processing dynamic visuospatial imagery (Lamm et al., 2001; Sack et al., 2008). The activation of the right SMA in abacus-trained children might result from the children's frequent use of both hands during abacus training and from the use of visuospatial imagery strategy in both tasks. The enhanced fiber integrity of the right SMA/premotor projection was observed in abacus children, suggesting the effects of abacus training on white matter (Hu et al., 2011). Abacus-trained children had undergone approximately three years of training, so they entered the experiment with a rich experience in numerical knowledge. The trained children also learned how to use a physical abacus with both hands simultaneously, which may account for the activation of areas related to motor movements in the abacus-trained group. Thus, our finding suggests that higher activation of fronto-parietal network in abacus-trained children may result from the long-term abacus training. The current study offered additional evidence for effects of abacus training on brain activity.

3.2. *Resting-state functional connectivity analysis*

The right IFG plays a critical role in inhibition and attentional control (Hampshire et al., 2010). One recent study demonstrated that the right IFG is functionally connected with the pre-SMA, suggesting its general role in attentional control (Duann et al., 2009). The right IFG mediates the attention-based detection of

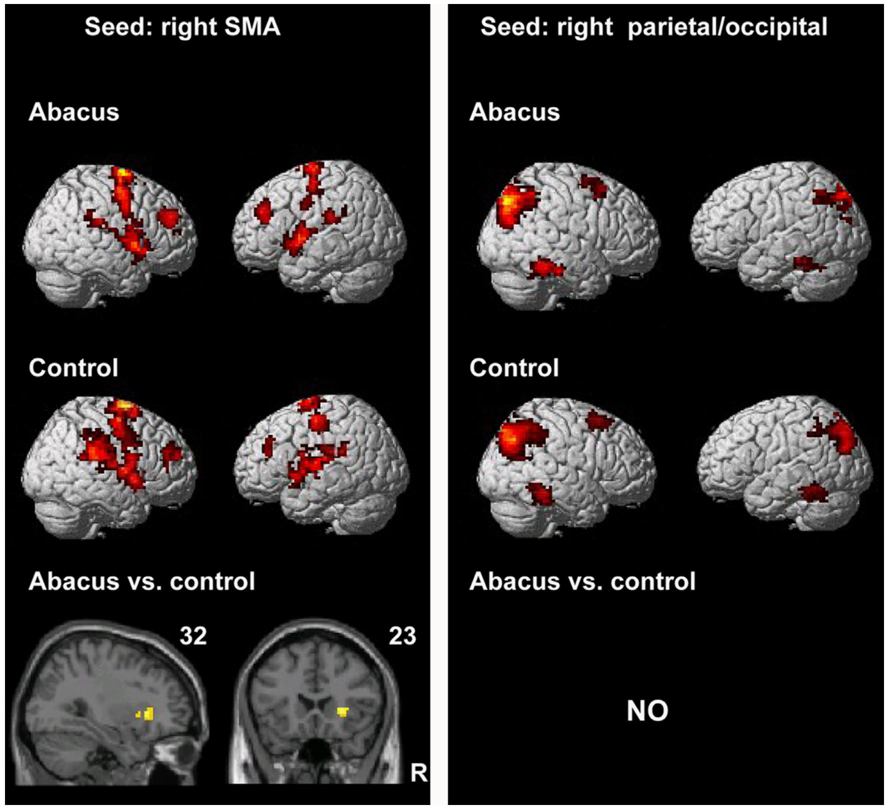

Fig. 4 – Resting-state functional connectivity findings. The pattern of significant positive correlations for the right SMA ($x=12$, $y=-6$, $z=75$; left panel) and the right superior parietal/occipital lobe ($x=30$, $y=-78$, $z=42$; right panel) in the abacus-trained group (first row) and in the control group (middle row) is shown. Significant between-group comparisons indicate increased functional connectivity between the right SMA and right IFG ($x=32$, $y=23$, $z=-5$; bottom row) in the abacus-trained group. R: right.

task-relevant stimuli (Duann et al., 2009; Sharp et al., 2010). Another previous study showed that only a limited amount of visual information can be stored in short-term memory (Todd and Marois, 2004). The right IFG is engaged in retrieving an alternative memory to overwhelm the limited capacity of processing resources. The right IFG is recruited during the encoding or retrieval of a target memory while other memories are inhibited (Aron et al., 2004). In the abacus-trained group, working memory for digits and mental calculations were associated with the enhanced involvement of visuospatial information processing resources (Hanakawa et al., 2003; Tanaka et al., 2002). Such information processing strategy requires the integration of multiple cognitive functions. Increased brain functional connectivity of the visuospatial-attention loop in the abacus-trained group might result from the long-term abacus training. The frequent use of the fronto-parietal network in the AMC training might enhance the functional connectivity of this circuit, and thus facilitate the communication within this network. As this network has been previously identified as attention network (Markett et al., 2013), AMC-trained children might develop enhanced their attentional control capability. There is evidence that attentional processing of task-relevant information is achieved through increased functional connectivity between higher-level fronto-parietal regions and lower-level sensory-specific cortical areas (Gazzaley et al., 2007). Our recent study on the effect of abacus training on structural connectivity indicated that long-term abacus training enhanced white matter fractional anisotropy in the right premotor projection (Hu et al., 2011). The enhancement of white matter integrity in the right premotor projection might account for the enhanced functional connectivity found in the current study.. In summary, our results support the assumption that abacus training might change the brain activation and enhance functional integration in children.

3.3. *Behavioral level analysis*

The response of abacus-trained children was faster than that of the control children. This finding is in line with other studies reporting that abacus experts performed a match-to-sample task faster than controls (Hatta and Miyazaki, 1989; Stigler, 1984). A plausible explanation for this faster response is that the abacus training might result in the use of a more efficient processing strategy in the digit and bead comparison tasks in abacus-trained group. The abacus-trained children that participated in current study had received abacus training for approximately three years. With such intensive training, they can acquire the ability to image an abacus in mind and use it for calculation (Stigler, 1984). They can use this skill in the digit memory task and this ability can be transferred to other cognitive tasks (Hatta and Miyazaki, 1989). In the present study, the trained children may use the mental abacus to represent the visual numerical materials (such as digits and beads), which means that both of digits and beads stimuli were converted into a simple mental abacus based representations (Frank and Barner, 2012). According to Frank and Barner's column-based model, abacus experts use improved visual resources to store numbers in parallel. Each cardinality corresponds to a column with well-structured beads on mental abacus. With long-term training, the process of converting the visual numerical materials into a mental abacus based representation is extremely fast and automatic. These may account for the decreased reaction time in the trained group. Contrary to our hypothesis, no group differences were observed in accuracy on both tasks, possible due to ceiling effect.

3.4. Limitations

There are several limitations to the current study that need to be addressed. Firstly, as a cross-sectional study, the absence of the pre-training measurement was a primary limitation. Imaging data were collected only after the abacus children had undergone training for three years. Although we carefully matched the two groups for age, gender, and educational levels, we cannot exclude the impact of other potential variables, such as parental socio-economic status. Secondly, because the sample size was relative small, results reported in the current study need to be confirmed with a larger sample. Thirdly, no group differences in accuracy were found in both tasks, possibly ceiling effect. Future studies with more challenging are needed to address this issue. Finally, previous neuroimaging findings showed that both increases and decreases in brain activation could be induced by cognitive training (Buschkuehl et al., 2012). In the present study, however, only increased brain activation was found in the trained group. Future studies should pay more attention to this discrepancy to advance our understanding of the training effects.

3.5. Conclusion

In conclusion, our data showed greater activation in the right PSPL/SOG and SMA on two working memory tasks in the abacus-trained group than in the control group. In addition, compared with the control group, the abacus-trained group demonstrated increased resting-state functional connectivity, which was most prominent in the fronto-parietal network (right SMA) and the core region of the ventral frontal attention network (right IFG). These results provide new evidence for brain plasticity associated with abacus skill acquisition and suggest that the right fronto-parietal network is engaged in the short-term memory and retrieval of numerical information in abacus children. Furthermore, the results also suggest that abacus training might improve children's ability to allocate their attentional resources through enhancing brain functional connectivity between the frontal and parietal regions. In summary, our results suggest that abacus training may modulate the brain functioning in short-term memory and retrieval of numerical information in children, which may have some implications for instruction of alternative arithmetic learning strategy for children with dyscalculia.

4. Experimental procedure

4.1. Subjects

At the beginning of their schooling, the children were randomly assigned into two groups. After grouping, no children applied to change their group or stop participation. Seventeen healthy, right-handed abacus-trained children (10 females; mean age: 10.46 y; range: 9.6–11.2 y) and 17 healthy, right-handed control children (8 females; mean age: 10.51 y; range: 9.8–11.3 y) participated in this study. Informed consent was obtained from both the children and their parents. All subjects were from urban families of the same city and all were screened for neurological and psychiatric illnesses, as well as for any medications with central nervous system effects. The abacus-trained children had been practicing abacus operation and abacus mental calculation for 2–3 h per week for approximately 3 years. The control children had no experience with either abacus operation or abacus mental calculation. All participants were recruited from different classes of the same grade of the elementary school.in Weifang city, China, and studied the same curriculum except the abacus training. The fMRI experiment was performed with the approval of the ethics committee of Zhejiang University.

4.2. Materials

Four-digit Arabic numbers were used as stimuli in the digit working memory task, while two columns of beads were used in the bead working memory task. Both digit and bead were presented in black on gray background (see Fig. 5).

4.3. fMRI task

The fMRI experiment, using a blocked design, consisted of two sessions (see Fig. 1). All subjects completed both sessions and were allowed to rest for approximately one minute between sessions to diminish the effects of fatigue. Each session consisted of 6 blocks (half with a digit working memory task and half with a bead working memory task), and each block included 6 trials ($4\text{ s} \times 6\text{s} = 24\text{ s}$). In total, every session included 36 trials and lasted 246 s. Each trial started with a black "#" on the gray background displayed for 500 ms, followed by a blank gray screen for 500 ms. Then, a target stimulus was presented on the center of the screen for 500 ms. After a 1000 ms delay period, during which only a fixation cross appeared on the screen, a test stimulus was presented for 500 ms. Following these event was a 1000 ms with a fixation cross. Participants were asked to judge whether the target and test stimuli were identical or different by pressing the response buttons with their right or left index finger, respectively. Once the test stimulus appeared, participants were required to make a judgment as soon as possible. The accuracy of the judgment and the reaction time were recorded for each trial.

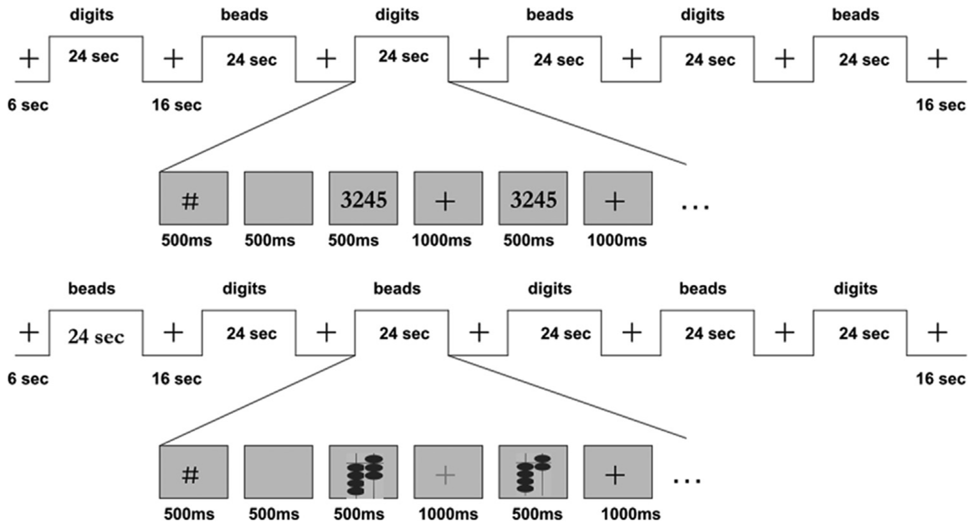

Fig. 5 – Experimental design of the digit and bead match-to-sample tasks. The experiment consisted of two sessions with each session containing 3 blocks of digit and bead match-to-sample tasks. Each block contained 6 trials and each trial lasted 4 s. In each trial, participants were asked to respond by pressing one of two buttons to indicate whether the second stimulus was same as the first stimulus. They pushed the left button to indicate "same" and the right button for "different." A "#" symbol indicated the start of each trial. This was followed by a gray screen, after which the stimuli appeared in the center of the screen.

4.4. *MRI data acquisition*

Imaging was performed on a 3.0 T Philips MRI scanner with a standard eight-channel head coil. For task fMRI scanning, a $T2^*$-weighted single-shot echo-planner imaging sequence (TR=2000 ms, TE=30 ms, flip angle=90°, gap between slices=0.8 mm, slice thickness=4 mm, field of view=230 mm, matrix size=64×64, and 33 transverse slices) was adopted. Visual stimuli were projected onto a screen and viewed by participants through a mirror. The images were acquired using an interleaved slice scan order. In addition, a $T2^*$-weighted 155 volume resting state fMRI scan was collected. During the resting-state fMRI scanning, subjects were instructed to lie in a relaxed way with their eyes open. The resting-state scans were always acquired before the task scans. The subjects' head were stabilized with a foam cushion to minimize motion during imaging.

4.5. *Task fMRI data statistical analysis*

The analysis of task fMRI data was carried out using SPM8 software (v4290, FIL, London, http://www.fil.ion.ucl.ac.uk/spm). The first three scans were discarded from the analysis. Images were corrected for slice timing, spatially aligned to the first volume of each session, and normalized to the Montreal Neurological Institute (MNI) standard template at a resolution of $3\times3\times3\ mm^3$. Functional images were spatially smoothed with a 6 mm full width at half maximum Gaussian smoothing kernel. The smoothed data for each participant were analyzed voxel by voxel with a fixed effects model. A 128 s temporal high pass filter was applied to remove low-frequency drifts.

Statistical analysis was performed by modeling the different conditions convolved with a hemodynamic response function as explanatory variables within the context of the general linear model on a voxel-by-voxel basis. Realignment parameters were included as additional regressors in the statistical model. Fixation periods were included in the model as the rest condition. Condition-specific effects at a single-subject level were performed to created images of parameter estimates, which were then entered into a second-level analysis as contrasts (Friston et al., 1994). This process involved creating two contrast images that compared brain activations during the digit and bead match-to-sample tasks to the rest state for each subject.

At the second level, multiple analyses were performed to characterize the neural changes underlying the effects of abacus training on the memory pathways involved in making digit and bead judgment. First, a one-sample *t*-test was performed on the digit versus rest and bead versus rest conditions for each group to identify the cognitive control regions recruited across subjects. The corrected statistical threshold was set at $p<0.001$ (FDR corrected) with a cluster size of 10 voxels. Second, two-sample *t*-tests were run to compare the abacus-trained and control groups on the digit vs. rest and bead vs. rest comparisons. The between groups comparisons were calculated using a corrected statistical threshold of $p<0.05$ (a combined threshold of $p<0.005$ and a minimum cluster size of 23 voxels). This correction was conducted using the AlphaSim program in the resting-state fMRI Data Analysis Toolkit (REST, http://restfmri.net/forum/rest) with a FWHM of 6 mm (Song et al., 2011). Within-subject comparisons between tasks were also analyzed. Third, the resulting statistical maps were then used to perform a conjunction analysis (Friston et al., 1999) to reveal regions exhibition more activation induced in both tasks in the abacus-trained children than in the control group. Specifi cally, the conjunction analysis was applied to the two between-group difference maps for digit vs. rest and bead vs. rest. Similar conjunction analysis was applied to the two between-task difference maps for abacus-trained group and control group. The group conjunction analysis was performed to examine which areas were differentially engaged in the two tasks. The conjunction analyses were calculated using an uncorrected statistical threshold of $p<0.001$.

4.6. *Resting-state functional connectivity analysis*

Preprocessing and statistical analysis of the resting-state data was conducted using SPM8 and REST software. Data preprocessing included slice timing correction, motion correction, spatial normalization, and smoothing (FWHM=6 mm). Temporal bandpass filtering (0.01–0.08 Hz) was also conducted. The following nine variables were used as covariates: average white matter signal, average cerebrospinal fluid signal, the global signal, and the six motion parameters. To generate a seed-based correlation map, the average time course from a seed region were first extracted and then correlated with the time courses from each voxel in the whole brain. Seed regions were 12 mm diameter spheres centered on the local maxima of the conjunction analysis results. Correlation coefficients were converted by Fischer's z transform (Fox et al., 2005). For each group, individual z maps were analyzed with a one-sample *t*-test to identify voxels showing positively correlated with the seed region. For the between-group comparison, two-sample *t*-tests were used to compare z maps between the two groups. The significance level for both one-sample and two-sample *t*-tests was set to $p<0.05$ using the AlphaSim correction (combining a threshold of $p<0.01$ and a minimum cluster size of 39 voxels). The between-group comparison was restricted in the voxels significantly correlated with the seed region, by using an explicit mask from the union set of the one sample *t*-test results ($p<0.001$, uncorrected).

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.brainres.2013.09.030.

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