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Prospective demonstration of brain plasticity after intensive abacus-based mental calculation training: An fMRI study

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Abstract

Abacus-based mental calculation is a unique Chinese culture. The abacus experts can perform complex computations mentally with exceptionally fast speed and high accuracy. However, the neural bases of computation processing are not yet clearly known. This study used a BOLD contrast 3T fMRI system to explore the brain activation differences between abacus experts and non-expert subjects. All the acquired data were analyzed using SPM99 software. From the results, different ways of performing calculations between the two groups were seen. The experts tended to adopt efficient visuospatial/visuomotor strategy (bilateral parietal/frontal network) to process and retrieve all the intermediate and final results on the virtual abacus during calculation. By contrast, coordination of several networks (verbal, visuospatial processing and executive function) was required in the normal group to carry out arithmetic operations. Furthermore, more involvement of the visuomotor imagery processing (right dorsal premotor area) for imagining bead manipulation and low level use of the executive function (frontal-subcortical area) for launching the relatively time-consuming sequentially organized process was noted in the abacus expert group than in the non-expert group. We suggest that these findings may explain why abacus experts can reveal the exceptional computational skills compared to non-experts after intensive training.

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Keywords: FMRI; Computation processing; Abacus; Cognitive brain

1. Introduction

How and where the numbers are processed in brain is an interesting topic and has attracted the attention of many researchers in recent years. Numerous studies on the neural mechanisms underlying mental computation processing have emerged [1,2] and the underlying neural circuitry of math cognition has been clearly established through detailed examination of a range of studies. Cortical activation during mental calculation, however, may be influenced by various individual problem-solving strategies. Abacus-based mental calculation, a feature of Chinese culture, is a unique strategy for mathematical calculation, and the ways of performing abacus-based calculation are quite different (Fig. 1). Abacus experts, through a particular algorithm and long time practice, have acquired specific knowledge of numerical structures and procedures for efficiently encoding and retrieving information using an imaginary abacus, and can perform complex computations mentally at high speed and with high accuracy [3]. Because the problem-solving strategies employed by abacus experts are different, the underlying cortical activation patterns of abacus-based math cognition will never be the same as the well-known activation patterns [1,2]. To date, there have been only two reports of attempts to map the cortical areas involved in calculation in abacus experts [4,5], and the underlying neural mechanism is still poorly documented. The main aim of this study was to gain further insight into the neural processes involved in abacus-based mental calculation.

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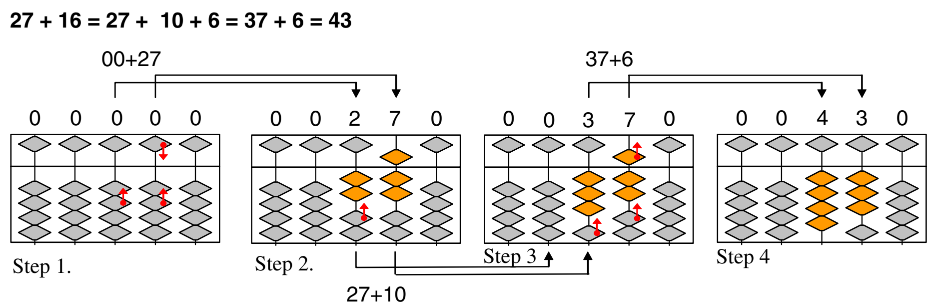

Fig. 1. The calculation steps performed by the abacus experts. As an example, adding 27 + 16 is accomplished in three steps: in step 1, the abacus shows 27, in step 2, second digit calculation is performed by adding 10, in step 3, first digit calculation is performed by adding 6, and finally (step 4) shows the answer of 43. Each upper and lower bead equals 5 and 1, respectively.

Recent advances in magnetic resonance imaging (MRI) technology allow high-resolution visualization of cortical activation [6]. In this study, a 3T MR imaging system and blood-oxygenation-level-dependent (BOLD) contrast sequences were used to investigate the neural basis of math cognitive abilities in non-expert subjects and abacus experts. Each subject was asked to perform a trial having a three-paradigm design: *Covert Reading*, *One-digit Addition*, and *Two-digit Addition*. By comparing brain activation differences between the two groups in the calculation process, the present study focused on the following: (1) what are the brain activation patterns in the abacus experts during calculation; (2) do these patterns have any similarities to those of normal subjects; and (3) what activation areas in abacus experts are unique and correlated to their exceptional computation abilities.

2. Methodology

2.1. Non-expert subjects and abacus experts

Six right-handed abacus experts (five males and one female, average age = 34.9) participated in the study. All the abacus experts were certified to at least the 9th level of calculation ability by the Chinese Abacus Association. The non-expert group contained six right-handed normal subjects, four males and two females (average age = 25.8). All subjects had more than 14 years of formal education.

2.2. Experimental design and cognitive tasks

Each subject performed a 30-min trial having a three-paradigm design involving contiguous *Covert Reading*, contiguous *One-digit Number Additions*, and contiguous *Two-digit Number Additions*. A typical off-on block design was used in each task. In the 'ON' condition, all the subjects were asked to read a number covertly, or to perform one-digit or two-digit number additions. In the 'OFF' condition, the subjects were asked to relax by looking at a screen. Stimuli were presented on a PC monitor using STIM (Neurosoft Inc., El Paso, TX, USA). Each session consisted of 14 alternating, 10-scan epochs between the 'ON' and 'OFF' conditions.

Covert Reading Condition: All the subjects were presented with one- or two-digit Arabic numerals and had to read them covertly during slice presentation. Each reading stimulus contained nine time-contiguous number slices and one answer slice, all procedures lasted 20 s.

Mental Calculation Condition: All the subjects were presented with several one- and two-digit addition problems. Each problem lasted 20 s, consisted of nine time-contiguous number additions and one answer slice. To confirm the rate of correct responses, the subjects used a hand-held button to give answers while the answer slice was presented.

2.3. Image acquisition and data analysis

Scanning was performed on a 3T Bruker MedSpec S300 system (Bruker Instruments, Karlsruhe, Germany). The functional images were obtained using a T2*-weighted gradient-echo planar imaging (EPI) sequence, with an in-plane resolution of 3.9 mm $\times$ 3.9 mm; each slice was 5 mm thick, with a gap of 1 mm between slices; and matrix size was $64 \times 64 \times 20$, and $TR/TE/\theta = 2000\,ms/50\,ms/90°$.

Data were analyzed using the general linear model (GLM) [7] with SPM99 software (Wellcome Department of Cognitive Neurology, London, UK; http://fil.ion.ucl.ac.uk/spm). Because covert reading of numbers is required in performing calculation, statistical comparison of data in the two situations is needed to reveal the neural networks specifically subserving the process of mental calculation. Hence, linear contrast between different conditions: (1) *Covert Reading*; (2) *One-digit Calculation* vs. *Covert Reading*; and (3) *Two-digit Calculation* vs. *Covert Reading* were applied to the parameter estimates from GLM, which yielded *t*-statistic maps (SPM$\{t\}$). To explore the effects of interest within each group, within-group analysis was tested in terms of the conjoint effects across subjects (threshold was set at $P<0.05$, corrected for multiple comparisons). To identify activity specific to each group during calculation, between-group analysis was performed using two-sample Student's *t*-test ($P<0.001$, uncorrected for multiple comparisons). In this study, we focused only on the activations differences during *Two-digit Calculation* vs. *Covert Reading*.

3. Results

3.1. Arithmetic skill differences

Rate of correct responses to the *One-* and *Two-digit Contiguous Additions* was perfect for the abacus experts vs. $94 \pm 0.12\%$ and $75 \pm 0.13\%$ for the non-expert subjects, respectively. In the *Two-digit Additions*, the rate was lower for the non-expert subjects indicating that the non-expert subjects found performing complex computations difficult.

3.2. Within-group analysis

3.2.1. fMRI results of non-expert group

Covert Reading: As shown in Fig. 2(A) (upper row), our findings proved that number processing relies on coordination of two different representations of numbers: a visual Arabic form (BA17/18/19) and a verbal form (BA44/45) [8]. Activated regions in the medial frontal/cingulate area (BA6/24/32) and left parietal lobule (BA7) were also detected.

One-digit Calculation vs. *Covert Reading*: In Fig. 2(A) (middle row), we observed a clear left-side predominant pattern, and the brain areas associated with verbal processing (left BA44/45 and left BA39), visuospatial processing (left BA6 and left BA7/40) [9], and executive function (BA24/32) [2] were seen.

Two-digit Calculation vs. *Covert Reading*: As shown in Fig. 2(A) (bottom row), it revealed the similar but larger activation areas associated with the same cognitive function (verbal, visuospatial and executive function). Note that more area associated with visuospatial processing in the right hemisphere (BA7/40) was recruited.

3.2.2. fMRI results of the abacus expert group

Covert Reading: As shown in Fig. 2(B) (upper row), the symmetrical activation pattern exhibited in the expert group was similar to that of the non-expert group for the same task.

One-digit Calculation vs. *Covert Reading*: As shown in Fig. 2(B) (middle row), it disclosed a symmetrical activation region associated with the involvement of visuospatial/visuomotor imagery processing [9,10]. The areas occupy the bilaterally precentral gyrus, and parietal area (BA7/40/19). Other areas were in the right postcentral gyrus (BA2).

Two-digit Calculation vs. *Covert Reading*: As shown in Fig. 2(B) (bottom row), a pattern identical to that detected by the *One-digit Calculation* vs. *Covert Reading* comparison was shown, except for the addition of postcentral gyrus (BA3/4) activation. Note that the pattern is more focused.

3.3. Between-group analysis

Abacus Experts vs. *Non-experts*: As shown in Table 1, activity in the right dorsal premotor area (BA3/4), was greater in experts than non-experts. This area is claimed to be involved in the visuomotor imagery processing [10].

Non-experts vs. *Abacus Experts*: As shown in Table 1, the non-experts demonstrated hyperactivity in the frontal-subcortical area. It has been suggested that this circuit is associated with executive functions such as the ability to initiate, coordinate a sequence of processes and place them in the appropriate order [11].

4. Discussion and conclusion

4.1. Within-group analysis

As expected, our results in the non-expert group during calculation (Fig. 2(A), middle, bottom row) approximate

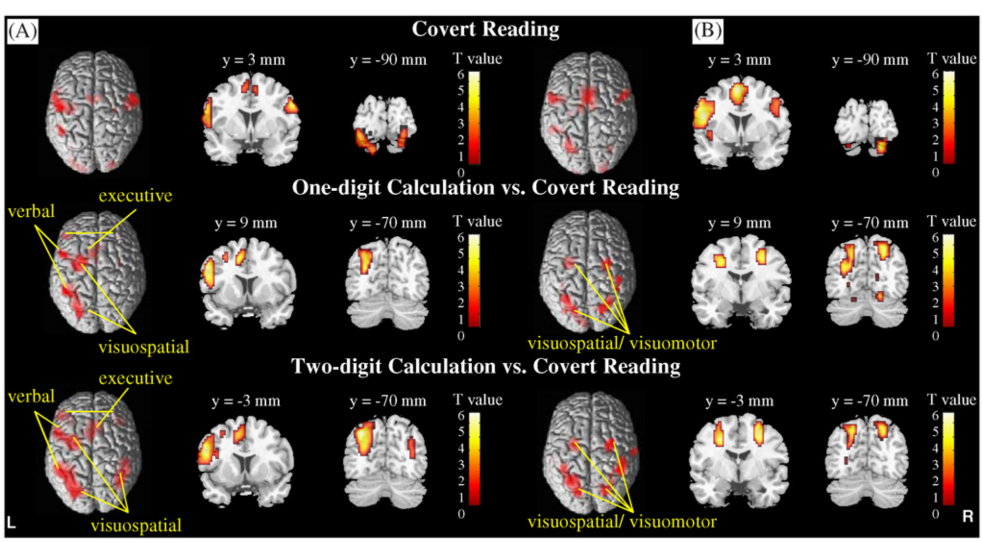

Fig. 2. Comparison of the non-expert (A) and abacus expert group (B) for the covert reading (top row), one-digit calculation vs. covert reading (middle row), and two-digit calculation vs. covert reading (bottom row) condition. Areas of significant BOLD response (within-group conjunction analysis, $P<0.05$ corrected for multiple comparisons) are shown on a surface-rendered brain and coronal slices (L, left and R, right).

Table 1
Between-group comparisons

Volume (cm^3)	Anatomical localization of maximum voxel	Coordinates (mm)			Z-score
		x	y	z	
Experts > Non-experts					
0.144	R postcentral gyrus, (BA3,4)	39	−21	44	3.82
Non-experts > Experts					
0.18	R middle frontal gyrus (BA11)	30	42	−16	3.67
0.14	L middle frontal gyrus	−33	42	−8	3.30
0.29	L medial frontal gyrus (BA8)	−6	12	52	3.59
0.47	L thalamus	−9	−15	−8	4.08

Note: The localization of maxima is based on MNI template. The Z map was threshold at $Z_0 = 3.09$ ($P < 0.001$, uncorrected for multiple comparisons) (R, right; L, left; and BA, Brodmann areas).

the results of earlier studies [1,2]. The observed activation regions related to verbal and visuospatial processing support the notion that verbal processing for retrieving rote arithmetic facts is coordinated with a back-up visuospatial strategy for mental visualization of the arithmetic procedure when rote knowledge is not available [12]. The engagement of an executive function also helps coordinate the sequencing of the above cognitive processing in the appropriate order, and detects errors [2].

In abacus expert group, we found that the recruited regions are related to visuospatial and visuomotor processing (Fig. 2(B), middle, bottom row). Therefore, we suggest that the generation of virtual abacus image and subsequent imagery bead movement may rely on this network. Because all the procedure is performed on this virtual abacus image, all that is needed to obtain the final result is read the final bead position, which surely shortens the computation time.

The calculation procedure adopted by non-experts facing problems with various degrees of difficulty is mediated by coordination of several neural networks with different weights. Thus, in comparing the results during both calculation conditions (Fig. 2(A), middle, bottom row), we could notice normal subjects tend to shift to a visuospatial strategy for helping solving increasingly complicated problems. Moreover, the more distributed activation pattern observed especially during complex computation may imply that the neural network is not effectively connected and thus more areas must be involved (Fig. 2(A), bottom row).

On the other hand, unlike the recruiting of several networks in non-experts, experts simply use the visuospatial/visuomotor strategy to perform calculation, and the more focused pattern also implies that the network is more effectively linked (Fig. 2(B), middle, bottom row). Therefore, we suggest that experts' exceptional abilities may be correlated with such acceleration of existing visuospatial process.

Although in both groups similarities exist in activation areas involved in visuospatial processing (which is thought to process information very quickly as images), in non-experts these areas need to act in concert with areas doing other sequentially organized cognitive processes to perform calculation. In sequentially organized processing, information is processed one bit at a time, and therefore it is a fairly time-consuming activity. This might explain why abacus experts can perform complex computations mentally faster and more accurately than non-experts.

4.2. Between-group analysis

Different from previous works [4,5], we found more involvement of the right dorsal premotor cortex during mental calculation in abacus expert group (Table 1). This area has often been associated with visuomotor processing, supporting the existence of mental manipulation of abacus beads on a virtual abacus. On the contrary, more frontal-subcortical area involvement was found in the non-expert group (Table 1). The involvement of these areas is related to the global workspace executive function, suggesting that these areas may play an important role in launching fairly time-consuming sequentially organized processes, such as coordination of verbal processing and back-up visuospatial strategies. From the combination of the above between-group results (Table 1), we suggest that solution of computation-based problems involves more visuomotor imagery processing and very low level use of executive function in the abacus expert group than the non-expert group. These interesting findings reflect that the experts tended to use fewer and more effective strategies through local modulation of activations to deal with arithmetic operation, which may account for the exceptional computational skills of experts.

In conclusion, this study provides demonstration of the ability of the brain to change with intensive training and practice. It shows that brain plasticity facilitates connection of the neural pathways in the experts and thereby achieves their exceptional computation abilities. From this study, fMRI imaging does extend our understanding of regional blood flows in the brain and provide a valuable tool for cognitive brain function study.

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