行政院國家科學委員會專題研究計畫　成果報告

運算中的大腦神經機轉：利用功能性磁振影像研究珠心算高手與一般人的比較

計畫類別：個別型計畫
計畫編號：NSC94-2314-B-040-025-
執行期間：94 年 08 月 01 日至 95 年 07 月 31 日
執行單位：中山醫學大學醫學影像技術學系

計畫主持人：吳東信

計畫參與人員：黃詠暉　王澤景　蔡宗孝

報告類型：精簡報告
報告附件：出席國際會議研究心得報告及發表論文
處理方式：本計畫可公開查詢

中　華　民　國 95 年 10 月 12 日

行政院國家科學委員會專題研究計畫 成果報告

運算中的大腦神經機轉：利用功能性磁振影像研究珠心算高手與一般人的比較

計畫類別： 個別型計畫
計畫編號： NSC94-2314-B-040-025-
執行期間： 94 年08 月01 日至95 年07 月31 日
執行單位： 中山醫學大學醫學影像技術學系

計畫主持人： 吳東信
計畫參予人： 黃詠暉 王澤景 蔡宗孝

報告類型： 精簡報告
處理方式： 本計畫可公開查詢

中 華 民 國 94 年10 月 5 日

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, these 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 funciton) 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 than non-experts after intensive training.

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. Recent advances in neuroimaging have helped in mapping the elaborate neural network activation patterns during the performance of cognitive tasks. Therefore, 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 performing 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 neural mechanism of abacus-based mental calculation 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.

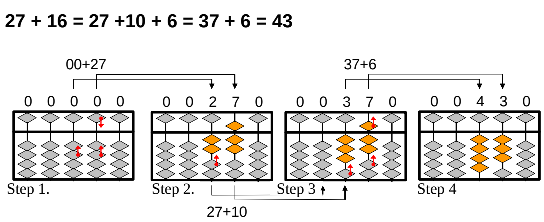

Fig. 1. The calculation steps performed by the *abacus experts.* As an example, adding 27+16 is shown to be accomplished in three steps: in step 1, the abacus shows 27, in step 2, second digit calculation is performed by adding 10, in step 3, first digit calculation is performed by adding 6, and finally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

Recent advances in magnetic resonance imaging (MRI) technology allow high-resolution visualization of cortical activation by utilizing the magnetic properties of deoxyhemoglobin as an endogenous contrast medium [6]. The noninvasive nature of this technique allows hundreds of images to be obtained from an individual subject, making it useful for identifying complex cortical activation patterns during cognitive tasks. 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. 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. Each subject was asked to perform a 30-minute trial having a three–paradigm design: *Covert Reading*, *One-digit Addition*, and *Two-digit Addition*. A typical off-on block design was used in each paradigm. 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 during calculation, 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 participated in the study. There were five males and one female (average age = 34.9). All the abacus experts were certified to at least the 9th-10th 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 and average computation ability as determined by scores on The College Entrance Exam in Mathematics.

2.2. Experimental Design and Cognitive Tasks

Each subject was asked to perform a 30-minute 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, and to perform one-digit number 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 sec, and each slice presentation lasted 2 sec. For paradigm design balance, all subjects pushed a hand-held button while the answer slice was presented.

Mental Calculation Condition. All the subjects were presented with several one-digit and two-digit addition problems. Each problem lasted 20 sec, consisted of nine time-contiguous number additions and one answer slice, and the interval of each slice presentation was 2 sec. To confirm the rate of correct responses, the subjects used a hand-held button to give their answers while the answer slice was presented. To effectively control the error rates of the non-expert subjects in solving *One-digit Addition Problems*, each number was 0 to 9 and the sums were limited to less than 50; and in the *Two-digit Addition Problems*, each number was less than 30 and the sums were less than 250.

2.3. Image Acquisition and Data Analysis

Scanning was performed on a 3 T 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 by 3.9 mm; each slice was 5 mm thick, with a gap of 1 mm between slices; and matrix size was 64 x 64 x 20, and TR/TE/θ= 2000 ms/ 50 ms/ 90°.

Data were analyzed using the general linear model (GLM) [7] for block designs using SPM99 software (Wellcome Department of Cognitive Neurology, London, UK; http://fil.ion.ucl.ac.uk/spm). After all scans were realigned, normalized, time-corrected, and spatially smoothed by an 8-mm full width at half maximum (FWHM) Gaussian kernel, a high-pass frequency filter (cutoff 80 s) was applied to the time series.

For individual-subject statistical analysis, GLM was used to test the correlation between fMRI BOLD signal changes and a boxcar function convolved with the canonical hemodynamic response function. In this process, movement parameters derived from realignment corrections were also entered as covariates of no interest. Linear contrast between different conditions (1) *Covert Reading*, (2) *One-digit Calculation versus Covert Reading*, and (3) *Two-digit Calculation versus Covert Reading* were applied to the parameter estimates from GLM, which yielded t-statistic maps (SPM{t}). SPM{t} were then transformed to a normal distribution (SPM{Z}). To explore the effects of interest within each group, within-group analysis was tested in terms of the conjoint effects across subjects. A statistical threshold was set at $P < 0.05$ (corrected for multiple comparisons). To identify activity specific to the abacus expert and non-expert groups during calculation, between-group analysis was performed using two-sample Student's t-test. In this study, we focused only on the differences in brain activations during *Two-digit Calculation versus Covert Reading*. Analysis was performed using a threshold at $P < 0.001$ (uncorrected for multiple comparisons).

3. Results

3.1. Arithmetic Skill Differences

Rate of correct responses to the *One-digit* and *Two-digit Contiguous Additions* was perfect for the abacus experts and 94±0.12% and 75±0.13% for the non-expert subjects, respectively. This rate was significantly lower for the non-expert subjects in the *Two-digit Additions* indicating that in contiguous *Two-digit Additions*, the non-expert subjects found performing complex computations difficult.

3.2. Within-group Analysis

fMRI Results of Non-expert Group

Covert Reading. As shown in Fig. 2A (upper row) and Table 1, we observed activation in some of the brain areas that have been associated with number processing. Our findings indicated that number processing relies on coordination of two different representations of numbers: a visual Arabic form involving the occipital cortex (BA17/18/19) and a verbal form involving language areas (BA44/45) [8]. Activated regions in the medial frontal/cingulate area (BA6/24/32), left superior parietal lobule (BA7), and cerebellum were also detected.

One-digit Calculation versus Covert Reading. To locate the neural network specifically involved in the calculation procedure, we subtracted the results of *Covert Reading* from those of *One-digit Calculation* as shown in Fig. 2A (middle row) and Table 1. We observed a clear left-side predominant pattern, and the brain areas associated with verbal processing (left perisylvian network (BA44/45) and left anterolateral parietal areas (BA39) [9]), visuospatial processing (left frontal area (BA6) and left lateral parietal lobule (BA7/40) [9]), and executive function (prefrontal frontal area (BA9) and anterior cingulate cortex (BA24/32) [2]) were seen.

Two-digit Calculation versus Covert Reading. As shown in Fig. 2A (bottom row) and Table 1, subtracting the *Covert Reading* results from those of *Two-digit Calculation* revealed the similar but larger activation areas associated with the same cognitive function (verbal processing, visuospatial processing, and executive function). Note that more area associated with visuospatial processing in the right hemisphere (the lateral parietal cortex (BA7/40)) was recruited. The result showed that calculation processes activated the brain bilaterally but still with left hemisphere predominance.

fMRI Results of the Abacus Expert Group

Covert Reading. As shown in Fig. 2B (upper row) and Table 1, the symmetrical activation pattern exhibited in the expert group was similar to that of the non-expert group for the same task, including a visual route (BA17/18) and a verbal route (BA44/45). Activated regions in the medial frontal/cingulate area, left superior parietal lobule (BA7), right superior temporal gyrus (BA22), and cerebellum were also detected.

TABLE 1. Within-group analysis.

Volume (cm^3)	Anatomical localization of maximum voxel	Coordinates(mm) x	y	z	*Z* score
	Non-expert group				
Covert reading					
0.9	M frontal/cingulate area (BA24,32)	-3	0	64	5.53
12.6	L prefrontal area (BA6,9,44,45)	-51	-6	40	Inf.
5.9	R prefrontal area (BA6,9)	57	3	36	Inf.
2.3	L superior parietal lobule (BA7)	-30	-60	48	7.08
6.2	L occipital area (BA17,18,19)	-33	-93	-20	7.38
1.7	R occipital area (BA17,18)	27	-96	-12	7.75
1.2	R cerebellum	30	-81	-36	5.79
One-digit calculation > covert reading					
2.2	M frontal/cingulate area (BA24,32)	-9	9	48	6.55
7.4	L prefrontal area (BA6,8,9,11,44,45)	-51	9	32	7.46
0.3	R prefrontal area (BA11)	33	36	-4	4.79
16.8	L parietal cortex (BA39,40,7)	-45	-39	32	7.45
Two-digit calculation > covert reading					
7.2	M frontal/cingulate area (BA24,32)	6	21	40	6.44
19.1	L prefrontal area (BA6,8,9,10,44,45)	-51	9	28	Inf.
4.8	R prefrontal area (BA11,46,47)	39	27	-12	6.99
34.4	L parietal cortex (BA39,40,7,19)	-30	-72	44	Inf.
12.3	R parietal cortex (BA39,40,7)	45	-33	40	7.36
	Abacus expert group				
Covert reading					
13.4	M frontal/cingulate area (BA6,24)	-12	-9	64	6.55
9.0	L prefrontal area (BA6,9,44,45)	-48	3	20	Inf.
3.4	R prefrontal area (BA6,8,9,44,45)	51	6	24	6.03
4.2	L superior parietal lobule (BA7)	-27	-69	52	Inf.
0.3	L occipital area (BA18)	-21	-96	-10	5.42
3.3	R occipital area (BA17,18)	30	-87	-12	4.82
4.2	R superior temporal gyrus(BA22,38)	51	9	-4	6.42
0.3	R cerebellum	33	-78	-40	5.85
One-digit calculation > covert reading					
3.3	R precentral gyrus (BA6)	27	-9	48	7.52
3.2	Lprecentral gyrus (BA6)	-24	-6	44	6.47

2.1	R postcentral gyrus, BA2	48	-30	44	5.47
6.4	R parietal cortex (BA7,40,18)	21	-75	48	7.24
12.8	L parietal cortex (BA40,7,18,19)	-33	-60	48	6.90
3.1	R cerebellum	18	-69	-16	5.47
0.1	L cerebellum	-21	-51	-16	4.59
Two-digit calculation > covert reading					
4.2	R precentral gyrus (BA6)	27	-6	52	Inf.
4.6	L precentral (BA6)	-24	-6	44	Inf.
0.8	R postcentral gyrus (BA3,4)	66	-15	28	6.31
5.3	R parietal cortex (BA7,40,2)	45	-42	48	7.64
12.8	L parietal cortex (BA7,40,19)	-30	-60	48	7.59
1.1	R cerebellum	21	-51	-12	5.07
0.1	L cerebellum	-24	-57	-16	4.89

Note: Within these regions, the localization of maxima is based on MNI template. The Z map was threshold at Z_0 =3.09 (P < 0.05, corrected for multiple comparisons) (R, right; L, left; M, median; BA, Brodmann areas)

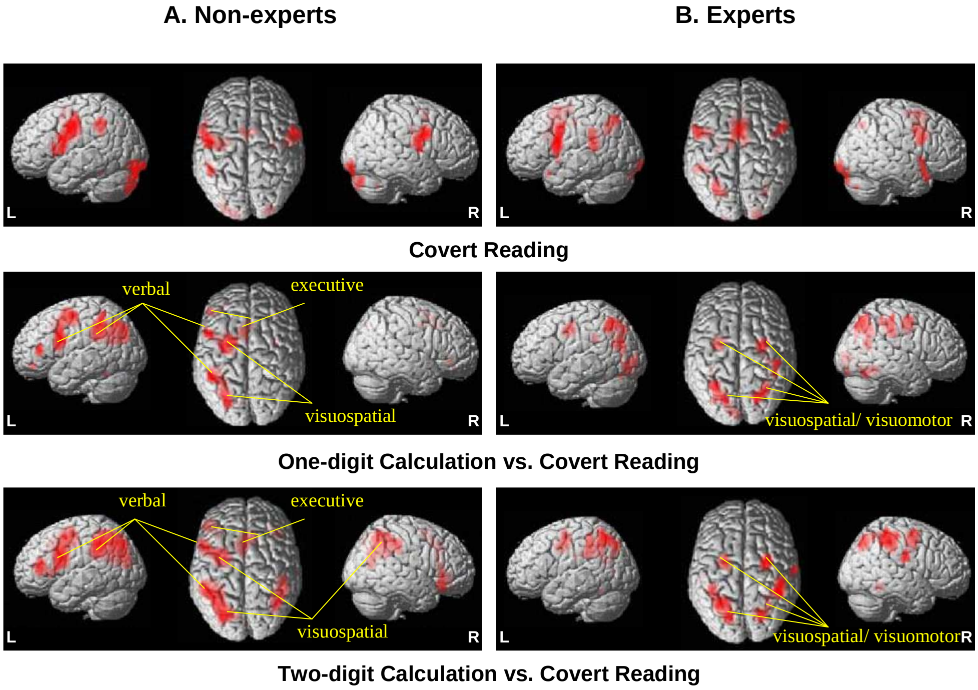

Fig. 2. Comparison of the non-expert (A) and abacus expert group (B) for the covert reading (top row), one-digit calculation > covert reading (middle row), and two-digit calculation > covert reading (bottom row) condition. Areas of significant BOLD response (within-group conjunction analysis, P < 0.05 corrected for multiple comparisons) are overlaid on a surface-rendered ‘template’ brain supplied with SPM99. (L, left; R, right)

One-digit Calculation versus Covert Reading. As shown in Fig. 2B (middle row) and Table 1, subtracting the results of *Covert Reading* from those of *One-digit Calculation* 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 activated areas were in the right postcentral gyrus (BA2), and bilateral cerebellum.

Two-digit Calculation versus Covert Reading. As shown in Fig. 2B (bottom row) and Table 1, subtracting the results of *Covert Reading* from those of *Two-digit Calculation* revealed a pattern identical to that detected by the *One-digit Calculation versus Covert Reading* comparison, except for the addition of postcentral gyrus (BA3/4) activation. Note that the pattern is more focused.

3.3. Between-group Analysis

Abacus experts versus Non-experts. As shown in Fig. 3A and Table 2, activity in the right dorsal premotor area, including the postcentral gyrus (BA3/4), was greater in experts than non-experts. This area is claimed to be involved in the visuomotor imagery processing [10].

Non-experts versus Abacus experts. As shown in Fig. 3B and Table 2, the non-expert group demonstrated hyperactivity in the medial thalamus, the bilateral middle frontal gyrus and medial frontal gyrus. It has been suggested that this frontal-subcortical circuit is associated with executive functions such as the ability to plan, initiate, coordinate a sequence of processes and place them in the appropriate order, monitor, and generate novel verbal or non-verbal information [11]. Moreover, the medial thalamus is also thought to be involved with attention [12].

TABLE 2. Between-group comparisons

Volume (cm^3)	Anatomical localization of maximum voxel	Coordinates(mm) x	y	z	Z score
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
0.14	R thalamus	12	-12	-8	3.67

Note: Within these regions, the anatomical 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; BA, Brodmann areas).

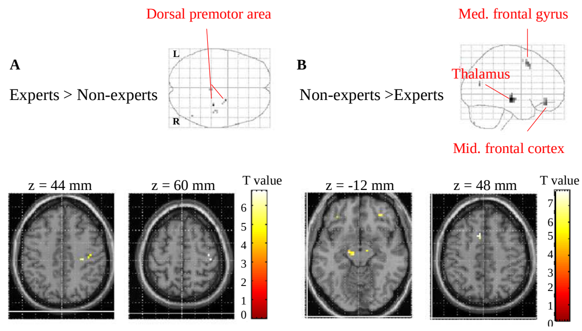

Fig. 3. Between-group comparisons. Projections rendered as glass brain projections and transverse slices (bottom row) with voxel significant thresholds of P < 0.001 uncorrected (between-group analysis). (A) Area recruited more in the abacus expert group than non-expert group was mainly in one cluster in the right frontal cortex (dorsal premotor area, Brodmann area 3/4). Slices are taken at z = 44 and 60 mm. (B) Activity exhibited more in the non-expert than abacus expert group is shown and implies involvement of frontal-subcortical circuit (medial and prefrontal cortex to thalamus). Slices are taken at z = -12 and 48 mm.

Discussion and conclusion

Within-group Analysis

As expected, our results in the non-expert group during both calculation paradigms (Fig. 2A, middle and bottom row) approximate 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 [13]. Additionally, the engagement of an executive function helps coordinate the sequencing of the above cognitive processing in the appropriate order, holds intermediate results in working memory, and detects errors [2].

Owing to the nature of abacus-based arithmetic procedure, we anticipate a spatial representation of numbers is developed through abacus practice. Therefore, unlike the recruiting of several networks performed by the non-expert group to carry out arithmetic operations, our data shows that the abacus experts recruited regions simply related to visuospatial and visuomotor processing (Fig. 2B, middle and bottom row) , which are essentially consistent with sites found in previous studies [4,5]. The findings may suggest that the rule-based calculations performed by imagining the pushing of beads on an imaginary abacus relies on the visuospatial/visuomotor system thought to be involved in the generation and subsequent analysis of the virtual image [14]. In another word, through this network, all the intermediate and final results can be processed and retrieved on this virtual abacus image, all that is needed to obtain the final result is read the final bead position on the virtual abacus, and therefore shorten 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 *Two-digit Calculation vs. Covert Reading Condition* (Fig. 2A, bottom row) with the *One-digit Calculation vs. Covert Reading Condition* (Fig. 2A, middle row), we could notice normal subjects tend to shift to a visuospatial strategy for helping solving increasingly complicated problems, reflecting that arithmetic rote knowledge is not available to the verbal strategy. 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. 2A, bottom row)**.** On the other hand, the calculation procedure utilized by experts is simply executed by visuospatial/visuomotor processing, and the more focused pattern lends support to the notion that the network is more effectively linked (Fig. 2A, middle and 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.

Furthermore, in *Covert Reading Condition*, basic and complex cognitive processes observed in the two groups were fairly consistent (Fig. 2A, B, top row), indicating that they all utilize similar routes to represent, hold and manipulate these numbers [8]. Thus, it is possible to infer that intense abacus training does not change the representation of numbers but build up more effective visuospatial representation of numbers corresponding to the position of beads on a virtual abacus and in turn implements rule-based visuomotor imagery processing during calculation.

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 (Fig. 3A). This area has often been associated with visuomotor processing, supporting the existence of mental manipulation of abacus beads on a virtual abacus, which is the characteristic of mental abacus operations. On the contrary, more frontal-subcortical area involvement was found in the non-expert group (Fig. 3B). 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, including coordination of verbal processing and back-up visuospatial strategies. We suggest from the combination of the above between-group results (Fig. 3) 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 speed and high accuracy of the complex computational skills of abacus 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.

Acknowledgment

The study was financially supported by the Program for National Research Program for Genomic Medicine (NSC94-3112-B010-010) and the grant (NSC94-2314-B-040-025) of the National Science Council of Taiwan.

References

[1] Gruber, P. Indefrey, H.Steinmetz, et al., Cerebral Cortex 11 (2001) 350.
[2] S. Dehaene, L. Naccache, Cognition 79 (2001) 1.
[3] T. Hatta, T. Hirose, K. Ikeda et al., Applied Cognit. Psychol. 3 (1989) 23.
[4] S. Tanaka, C. Michimata, T. Kaminaga, et al., Neuroreport 13 (2002) 2187.
[5] T. Hanakawa, M. Honda, T. Okada, et al., Neuroimage 19 (2003) 296.

[6] S. Ogawa, D.W. Tank, R. Menon, et al., Proc Natl Acad Sci USA 89 (1992) 5951.
[7] K.J. Friston, A.P. Holmes, K.J. Worsley, et al., Hum. Brain Mapp. 2 (1995) 189.
[8] M. McCloskey, Cognition 44 (1992) 107.
[9] O. Simon, J.F. Mangin, L. Cohen, et al., Neuron 33 (2002) 475.
[10] S.P. Wise, E.A. Murray, Trends Neurosci. 23 (2000) 271.
[11] S. Tekin, J. Cummings, An update J. Psychosom. Res. 53 (2002) 647.
[12] J. Newman, Consciousness and Cognition 4 (1995) 172.
[13] N. Molko, A. Cachia, D. Riviere, et al., Neuron 40 (2003) 847.
[14] E. Formisano, D.E.J. Linden, F. Di Salle, et al., Neuron 35 (2002) 185.