

Neural correlates of serial abacus mental calculation in children: A functional MRI study

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Abstract

Abacus experts have demonstrated extraordinary potential of mental calculation by using an imaginary abacus. But the neural correlates of abacus mental calculation and the imaginary abacus still remain unclear. Here, we report, respectively, the analysis of fMRI images of abacus experts and non-experts in response to the performance of simple and complex serial calculation by visual stimuli as well as the images of the abacus experts with performance of the same tasks by auditory stimuli. We found that activated areas were quite different between two groups. In experts, enhanced activations were mainly observed in fronto-temporal circuit (lateral premotor cortex (LPMC) and posterior temporal areas) in simple addition, but in fronto-parietal circuit (lateral premotor cortex (LPMC) and posterior superior parietal lobe (PSPL)) in complex one. By contrast, in controls, the activated areas were almost similar in both simple and complex tasks, including bilateral inferior parietal lobule, prefrontal and premotor cortices. Furthermore, visual and auditory stimuli generated almost similar activations in experts. These observations reveal that (1) abacus mental calculation induces special patterns of brain response, and simple and complex tasks are sustained by dissociated brain circuits between the temporal and parietal cortices, respectively; (2) the abacus mental calculation may rely on neural resources of visuospatial representations with a super-modal form of abacus beads; (3) the posterior temporal areas and PSPL may be recruited for imaginary abacus. © 2006 Elsevier Ireland Ltd. All rights reserved.

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Abacus mental calculation is a sort of mental calculation based on the principles of manipulating an abacus (Fig. 1), from top digit to low, opposite to the usual algorithm. Abacus experts refer to those who have an extraordinary capacity of manipulating abacus calculation in physical form, as well as in abacus mental calculation by longtime training. When they calculate with an abacus, they push the beads up and down swiftly. Likewise, in abacus mental calculation, they seem to be able to push the imaginary abacus beads in their mind, but the speed is much higher than that of physical form. According to the reports from experts, this skill is based on the imaginary abacus in their mind, a strategy relying on training.

However, little is known about the cognitive mechanisms and the neural correlates of abacus mental calculation. The major

finding for this concern is the importance of visuospatial processing [6,14]. Tanaka et al. and Hanakawa et al. separately indicated that digits working memory and mental calculation of adult abacus experts were associated with enhanced involvement of neural resources for visuospatial information processing [6,14]. Though Hanakawa et al. attempted to explore the neural correlates and to examine the effect of number size on mental abacus operation, no study has been attempted to dissociate the neural correlates underlying simple abacus mental calculation from the complex one in children, and no brain imaging study has been conducted to explore the imaginary abacus even if it has been widely reported by experts.

In the broadest sense, abacus mental calculation is one special method of mental calculations. Many functional neuroimaging studies have been carried out to explore the neural correlate of mental calculation [1–6,9,11,15]. Some support that within the domain of elementary arithmetic, current cognitive models postulate at least two representational formats for number: a

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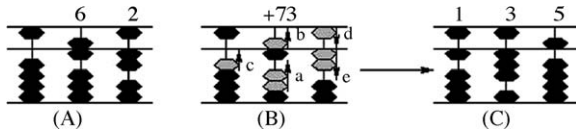


Fig. 1. The principles of manipulating abacus calculation. (A) The left figure represents 62: a bead above the bar is equal to 5 when it is pushed down, and a bead below is equal to 1 when push up. (B) The middle illustrates the process of 62 plus 73, and the lowercases show the steps of manipulation. (C) The final result.

language-based and a language-independent representation; the former is used to store tables of exact arithmetic knowledge, and the latter is for quantity manipulation and approximation relying on visuospatial networks [5]. The triple-code model of number processing predicts that, depending on the task three distinct systems (quantity, verbal and visual) of representation may be recruited [3]. While others indicate that finger counting-based representation is one of the basic numerical learning strategies, and both verbal-based and nonverbal-based strategies are recruited, though the involvement of nonverbal-based strategy depends on different levels of calculation [15]. Furthermore, a number of studies support the determinants of parietal activation in number processing. Especially, Dehaene et al. reviewed that there were three parietal circuits and the bilateral HIPS (horizontal segment of the intraparietal sulcus) have been suggested as potential candidates for number domain specificity [4].

Then, there are some questions arising: does the abacus mental calculation have the same neural correlate as the traditional mental calculation? Is the simple one associated with a verbal resolution, while the complex one with a visual resolution? Are the HIPS potential candidates for number domain specificity too? And how does imaginary abacus play an important role? Whereupon, in the study we let abacus experts and non-experts perform both simple serial addition (SSA) and complex serial addition (CSA) by visual stimuli and simultaneously measured their brain activities with fMRI. Additionally, we asked the experts to perform same tasks by auditory stimuli, and then compared the results of two modalities. We hope the findings of the present study would help us enrich the theories of number cognitive processing, and provide a solid foundation for and a direction to future researches.

Eight right-handed healthy abacus experts (four female, 11.75 ± 1.39 years) and eight right-handed healthy non-experts (four female, 12.29 ± 0.38 years) participated. All experts had kept practicing abacus operation and abacus mental calculation for about 4–6 years (mean 5.5 years) and about 0.5–1 h every day. The controls had no experience in both. One of the subject's data of each group was deleted due to head motion. All subjects volunteered to participate in this study with informal written consent by their parents. The fMRI experiment was performed with the approval of the local ethics committee of Zhejiang University.

In the preliminary session, the controls practiced serial addition with three different difficulty levels (problems with single-digit numbers, two-digit numbers consisting of 1–5, and two-digit numbers consisting of 5–9), while problems practiced by the experts were single-, three-, four-, and five-digit num-

Table 1

Activation in experts and non-experts as revealed by fixed effect analysis

Area (BA)	Cluster voxels	T score	SPM coordinates		
			X (mm)	Y (mm)	Z (mm)
Expert group					
A: SSA vs. control task					
R GFs (6)	40	4.71	14	6	66
GTm (21)	129	4.47	64	−44	0
GTi (37)		4.40	60	−58	−4
GTm (37)	15	4.04	50	−58	4
L GTi (20)	102	5.79	−66	−28	−16
		3.92	−54	−22	−18
GTs (22)	108	5.10	−64	−52	12
GTm (21)		4.38	−62	−58	0
GF (37)	57	4.89	−54	−48	−18
B. CSA vs. control task					
R GFm (6)	340	6.36	24	2	54
		5.62	18	4	66
PSPL (7)	72	5.62	18	−60	66
L PSPL (7)	381	6.93	−28	−62	64
GFm (6)	515	10.19	−28	2	64
GH (30)	272	5.00	−6	−38	0
C. CSA vs. SSA					
R GFm (6)	235	6.25	24	2	54
PSPL (7)	469	8.14	20	−58	68
PCu (7)		5.74	16	−72	52
GL (18)	725	7.75	20	−98	−6
GF (19)		6.76	24	−84	−14
L GFm (6)	318	6.86	−28	2	60
PCu (7)	1363	9.27	−16	−72	52
PSPL (7)		9.01	−20	−68	58
GL (17)	1024	8.47	−22	−96	−10
GF (18)		7.45	−26	−86	−16
Cu (18)	111	4.85	−4	−90	16
Non-expert control group					
A. SSA vs. control task					
R GFs (6)/ACC	70	4.74	0	12	50
LPi (40)	173	5.10	46	−36	54
L GFm (6)	33	4.37	−36	−2	56
LPi (40)	983	7.96	−44	−40	54
GPoC (2)		7.18	−54	−26	48
B. CSA vs. control task					
R GFs (6)/ACC	1106	8.68	0	14	52
		6.83	4	28	40
ACC (33/24)	84	4.69	0	14	22
		4.61	2	4	24
R LPi (40)	404	6.65	48	−38	58
GPoC (4)		4.74	56	−24	48
L GFm (6)	1262	7.16	−30	4	60
GFi (9)		6.90	−50	14	26
GFi (45)	277	4.95	−32	24	0
GFi (46)	102	5.12	−46	40	18
GH (19)	78	4.71	−16	−52	−6
LPi (40)	1898	10.47	−48	−34	50
AG (40)		5.35	−32	−58	48
		5.00	−32	−56	40
C. CSA vs. SSA					
R GFm (6)	12	4.19	28	12	60
ACC (32)	353	5.09	2	28	42
		4.62	0	16	50
PCu/PSPL (7)	28	4.33	26	−62	38
L GFm (6)	148	5.73	−28	4	62
GFi (9)	239	5.62	−54	12	24

Table 1 (Continued)

Area (BA)	Cluster voxels	T score	SPM coordinates		
			X (mm)	Y (mm)	Z (mm)
GFi (45)		4.15	−54	18	4
PSPL (7)	484	5.88	−22	−62	50
LPi (40)	72	4.46	−44	−32	38
Cu (18)	11	4.06	−14	−102	−2

L, left; R, right; BA, brodmann area; GFs, superior frontal gyrus; GFm, medial frontal gyrus; GTi, inferior temporal gyrus; GTs, superior temporal gyrus; GTm, medial temporal gyrus; GF, fusiform gyrus; GH, parahippocampal gyrus; PSPL, posterior superior parietal lobule; LPi, inferior parietal lobule; GPoC, postcentral gyrus; PCu, precuneus; GL, lingual gyrus; Cu, cuneus; AG, angular gyrus; ACC, anterior cingulate cortex. ($P < 0.0001$, uncorrected).

bers as addends. We chose single-digit numbers as the SSA for groups (controls, 92.8% correct; experts, 96.5% correct), four-digit numbers as the CSA for the experts (90.3% correct), and two-digit numbers consisted of 1–5 for the controls (88.6% correct).

In visual, tasks began with the presentation of a prime stimulus of red crisscross for 2 s, followed by a task period of 20 s,

then an equal sign for 2 s. (a) In control task, 10 seven-digit random numbers were presented with the rate number/2 s and the subjects were required to keep gazing at numbers without calculation. (b) In SSA task, 10 one-digit random numbers were presented with the same rate and subjects were instructed to keep looking at numbers and adding them in turn without reporting the result. (c) In CSA task, four- or two-digit numbers were adopted to replace one-digit numbers but other conditions remained the same as in (b). In auditory version for the experts, tasks began with a cue of prime stimulus of “**attention**”, and the design was nearly the same as that in visual version, except that there were six numbers in control, eleven numbers in SSA, and eight numbers in CSA task. Each task lasted 30 s with identical audio frequency and volume. Subjects heard numbers through an earphone. It should be noted that we chose seven-digit numbers as control because the task was so difficult for children that it would frustrate their attempt to fulfill it. Images were projected to the mirror above subjects via an LCD screen. The visual angle was 3.5 in horizontal and 2.7 angle in vertical dimension. The timing and sequencing of stimuli were controlled by a personal computer.

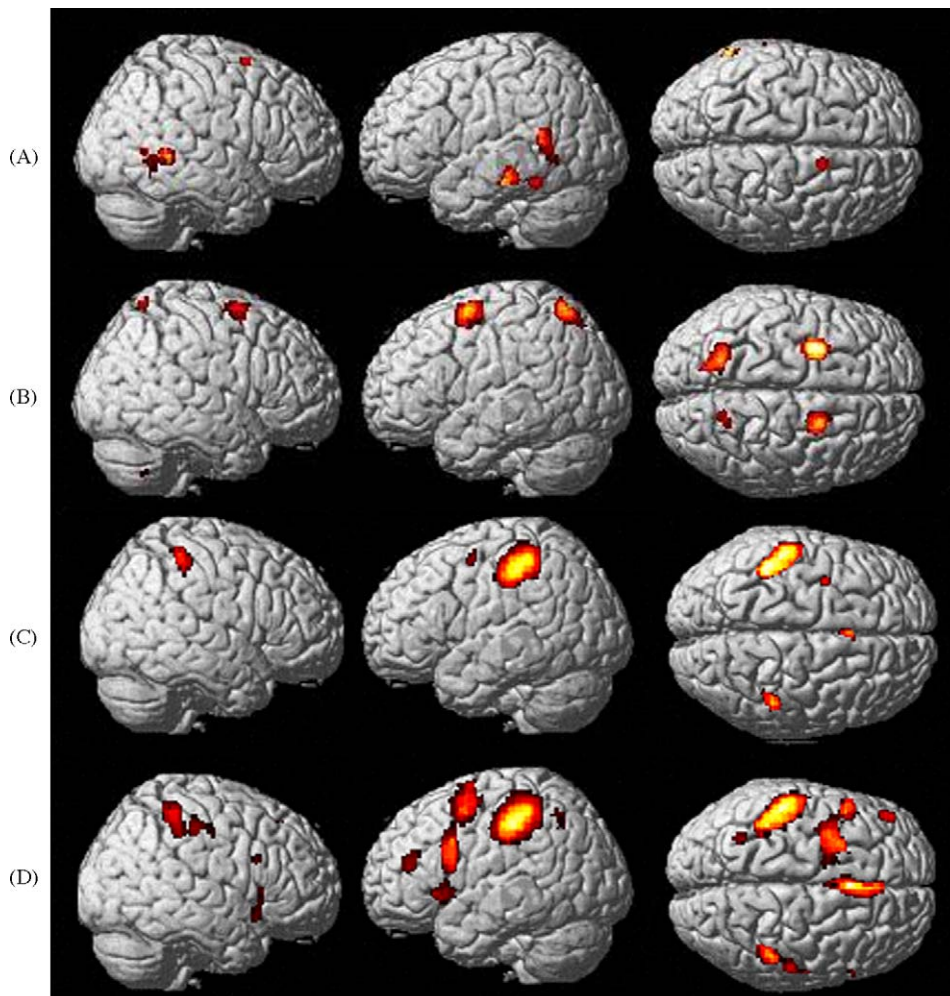


Fig. 2. The fMRI activation in SSA and CSA by visual stimuli. (A) Activation revealed in SSA vs. control task in experts. (B) CSA vs. control task in experts. (C) CSA vs. control task in non-experts. (D) CSA vs. control in non-experts. R, right; L, left. ($P < 0.0001$, uncorrected).

Imaging data were collected with a 1.5 T MR scanner (Marconi, USA) with a standard circularly polarized head coil. Foam cushions were to minimize head motion. Anatomical imaging included a T1-weighted sequence (500/12 ms [TR/TE], flip angle 90°, FOV 23 cm × 23 cm, matrix 192 × 256, slice thickness/gap 6/1 mm, number of slices 21). For fMRI, a whole brain echo-planar imaging (EPI) sequence (2000/40 ms [TR/TE], flip angle 90°, FOV 23 cm × 23 cm, matrix 64 × 64, slice thickness/gap 6/1 mm, number of slices 21) was adopted, in parallel to the anatomical slices. The data analysis was performed with SPM99 [<http://www.fil.ion.ucl.ac.uk/spm>]. The EPI data were realigned and normalized into Talairach space [13]. Next, the resultant image volumes were spatially smoothed with a Gaussian kernel of 7.5 mm × 7.5 mm × 13 mm FWHM. The smoothed data were analyzed voxel by voxel with fixed effects analysis (FFX). We made group analysis using three different contrasts to reveal cortex activation by the following different pairs of conditions: SSA versus control task, CSA versus control task and CSA versus SSA task. Group activation maps were depicted with a significant activation ($P < 0.0001$, uncorrected, minimal cluster size, 5 voxels), and the loci were determined by corrected $P < 0.05$.

Brain activation of each group in visual is shown in Table 1 and Fig. 2. For the experts, the SSA task induced activation in the right lateral premotor cortex (LPMC) and bilateral posterior temporal areas. Activation was also observed in the left LPMC, but it did not reach significant level. The CSA task induced activation bilaterally in the LPMC, posterior superior parietal lobule (PSPL), and parahippocampal gyrus. And no activation was observed in classical language areas of the left hemisphere. In contrast, for the controls, simple and complex tasks induced almost the same activation areas. Activities were found in the

bilateral inferior parietal lobule (LPi), left LPMC and right supplementary motor area (SMA) including the anterior cingulate cortex (ACC) in both SSA and CSA tasks. Moreover, significant activation was also found in the left inferior frontal gyrus (GFi) (BA 9, 45, 46) in CSA; and the region in LPi including HIPS extending anteriorly to the postcentral gyrus and laterally into the angular gyrus (AG). During CSA versus SSA task, both experts and controls showed activation areas primarily in the LPMC and PSPL (including the vicinity of precuneus). However, the occipital areas (BA 17, 18, 19) were significantly activated in experts while the GFi, ACC and cuneus showed increasing activation in controls. In auditory stimuli, the brain activation mapping closely corresponded to the similar activation in visual stimuli except that superior temporal cortices were significantly observed in CSA against SSA task contrast (Fig. 3). In this contrast, as Fig. 3 illustrated, there was no between-hemisphere difference in terms of the comparison of the peak activations obtained for both hemispheres in both stimuli.

It is the first time, to our knowledge, that neural correlates during simple and complex abacus mental calculation in children abacus experts have been reported. The pattern of cerebral activations in experts was quite different from those in controls and in previous imaging studies of mental calculation [1,2,5,9,15].

The posterior temporal regions were activated during SSA task in experts. These brain regions, the fusiform and the inferior temporal gyrus in particular, were known to be involved in objects recognition and more generally in the encoding and retrieval of the figurative properties of visual representations [10]. However, in our analysis, by visual stimuli, SSA task was contrasted to control task. Thus, it is unlikely that the activation reflects the visual number form itself. Additionally, significant activation was also observed during the auditory stimuli. To

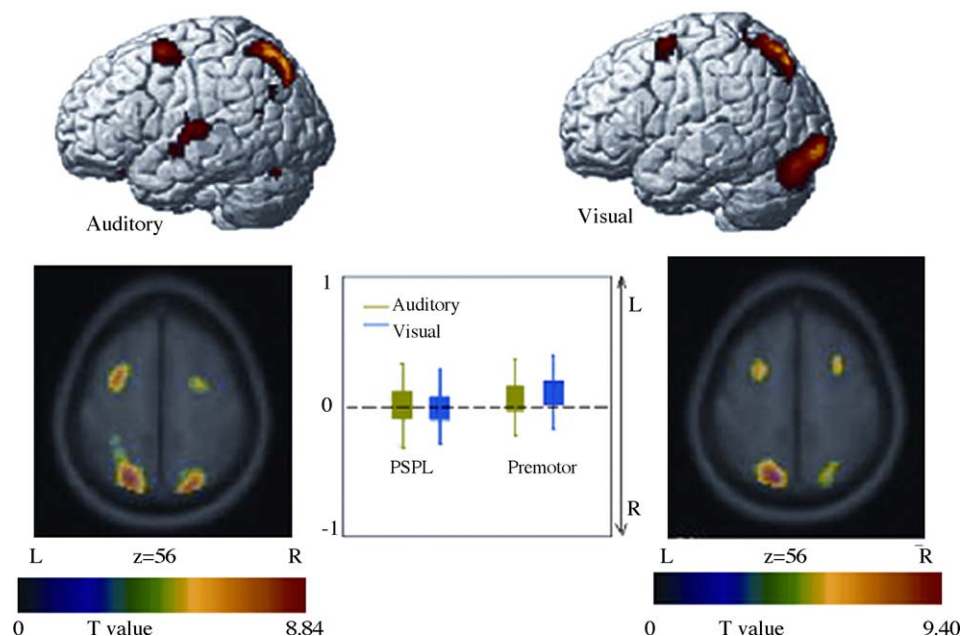


Fig. 3. The fMRI activation by visual and auditory stimuli in CSA vs. SSA. (A) Top, group activation in the left hemisphere ($P < 0.0001$, uncorrected), rendered onto a standard brain. (B) Middle of the bottom, laterality of activation for the premotor and PSPL. Estimated mean signal increase (SI) at the most significantly activated single voxel was computed in each area in each individual and then was used to calculate a laterality index (LI), that is SI for left minus SI for right, divided by the sum of SI for both. (C) Bottom, axial views in Talairach space, superimposed on the standard T1 image.

experts, the SSA task was too easy, and the processing did not need much actually operation of calculation. These areas may constitute a circuit involved in visuospatial-dependent encoding and retrieval of imaginary abacus.

The parietal areas were both observed in visual and auditory stimuli in experts during the CSA. Moreover, the activations in parietal areas were found in controls and repeatedly reported in previous imaging studies of mental calculation [6,11,15]. It is noteworthy that in experts parietal activation is mainly in PSPL, including the vicinity of precuneus, whereas in controls the activation areas focus on HIPS extending anteriorly to the postcentral gyrus and laterally into AG. Dehaene et al. had considered that the bilateral HIPS might be potential candidates for number domain specificity; the bilateral PSPL is considered to support attentional orientation on the mental number line [4]. However, we failed to agree that the notion of Dehaene et al. fit abacus mental calculation. Firstly, HIPS is not peculiar to number domain in abacus mental calculation, for no activation was observed in this area. Secondly, PSPL might play a more important role. Rather it plays somewhat curial roles in a variety of visuospatial tasks including reaching, grasping, eye and/or attentional orientation, spatial working memory, and visuo-motor processing [4,12,14]. First and foremost, the PSPL activation in our study cannot be attributed to eye and/or hand movement, because the CSA and the control tasks were matched in stimuli, and no hand movement was observed. In contrast, it may be attributed to attentional orientation and imaginary abacus representation of number and its operation. Here, imaginary abacus is akin to a mental number line, but it is a vivid map of two dimensions. Through years' practice, abacus experts could transform the serial numbers into a super-modal form of abacus beads, and transform the operation of abacus into quick internal change of imaginary abacus. Thus, under such especial strategy, they could encode storing, updating and retrieving intermediate results quickly and effectively manipulate calculation of large numbers. Based on the sound analysis, our results suggest that in complex abacus mental calculation, the HIPS is not the potential candidates for number domain specificity, while the PSPL is the crucial one, indicating imagery abacus and reflecting the visuospatial processing.

Hence, there arise several questions—how can we convince people that experts perform additions using an imaginary abacus rather than other usual direct ways? Why are there different circuits involved between SSA and CSA, though visuospatial representation and imaginary abacus emerge in mind in both tasks? From the experts' reports to the first question, we are convinced that imaginary abacus makes calculation much easier and with higher speed even in simple task. And the experts preferred using strategy of imaginary abacus to using traditional one. To the second question, it is likely that the simple operations are sufficiently familiar to have their own distinct, static representation. Here, the processing focuses on the beads self, being akin to retrieval in traditional calculation. However, more complex operations must be recapitulated by visualizing a series of movements or visuospatial relationships, and to some degree, this is an action-oriented object representation [8] of imaginary abacus, emphasizing the integrated group effect.

Activation patterns were quite different between two groups. One probable explanation of the discrepancy is that the influence of cognitive strategies. Data from Burbaud et al. [2] indicates that cognitive strategies will influence the cortical activation. Obviously, abacus mental calculation is language-independent, even in single-digit additions. While, visual-based strategy is employed, and visual mental imagery rather than numbers and/or language plays a crucial role. Though, abacus mental calculation is one kind of mental calculation, it fails to agree with the neural correlates of traditional one and models of current cognitive number processing mentioned before. Our results imply that representation of number and strategy of calculation are associated with training and degree of practice rather than genetic gift. The PSPL rather than HIPS plays a much crucial role in abacus mental calculation.

Then, another areas, the lateral premotor areas, filled a role in both SSA and CSA tasks. However, these areas are not exclusively in abacus mental calculation, but in motor tasks and other cognitive contexts [7,10]. It was also suggested that the LPMC was important in the rule-based association of symbolic cues and responses in both motor and nonmotor behaviors [7]. The development of abacus mental calculation is natural and inner transitions form a motor skill to a nonmotor cognitive skill. So, the neural activation of these areas in our study may reflect for metal imagery of abacus, for movement of “carry” operation and for working memory. On the other hand, there areas might sustain cognitive control or executive functions, allocating resources and organizing the processing stages sustained by parietal or temporal areas. And it might be ‘control core’ of abacus mental calculation.

Last enhanced finding was that the brain activation mapping was closely similar in visual and auditory for experts. As showed in Fig. 3, the direct comparison of the activation between the two modalities did not yield significant differences in these areas. It confirmed the veracity of our results and farther verified imaginary abacus; on the other hand, it proved that the neural correlate of abacus mental calculation depended on the nature of the task rather than on the nature of the stimulus, and farther supported that the activation did not reflect the visual input itself.

To sum up, the findings of the present study have indicated that children abacus experts primarily share the underlying dissociated neural correlates – the fronto-temporal circuit and the fronto-parietal circuit – respectively, in simple and complex serial abacus. Our results suggest that abacus mental calculation puts emphasis on visuospatial-specific representations, and relies on the posterior temporal areas and posterior superior parietal lobe (PSPL) in which imaginary abacus can be generated by transforming the serial numbers into a super-modal form of abacus beads. Unfortunately, to date, there is no lesion study in abacus experts to support these hypotheses. To explore further understanding of the functional neuroanatomy in abacus experts, future studies will be warranted.

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References

- [1] P. Burbaud, O. Camus, D. Guehl, B. Bioulac, J.M. Caillé, M. Allard, A functional magnetic resonance imaging study of mental subtraction in human subjects, *Neurosci. Lett.* 273 (1999) 195–199.
- [2] P. Burbaud, O. Camus, D. Guehl, B. Bioulac, J.M. Caillé, M. Allard, Influence of cognitive strategies on the pattern of cortical activation during mental subtraction. A functional imaging study in human subjects, *Neurosci. Lett.* 287 (2000) 76–80.
- [3] S. Dehaene, L. Cohen, Towards an anatomical and functional model of number processing, *Mathem. Cogn.* 1 (1995) 83–120.
- [4] S. Dehaene, M. Piazza, P. Pinel, L. Cohen, Three parietal circuits for number processing, *Cogn. Neuropsychol.* 20 (2003) 487–506.
- [5] S. Dehaene, E. Spelke, P. Pinel, R. Stanescu, S. Tsivkin, Sources of mathematical thinking: behavioral and brain-imaging evidence, *Science* 284 (1999) 970–974.
- [6] T. Hanakawa, M. Honda, T. Okada, Y. Yonekura, H. Fukuyama, H. Shibasaki, Neural correlates underlying mental calculation in abacus experts: a functional magnetic resonance imaging study, *Neuroimage* 19 (2003) 296–307.
- [7] T. Hanakawa, M. Honda, N. Sawamoto, T. Okada, Y. Yonekura, H. Fukuyama, H. Shibasaki, The role of rostral brodmann area 6 in mental-operation task: an integrative neuroimaging approach, *Cereb. Cortex* 12 (2002) 1157–1170.
- [8] L. Jancke, R. Loose, K. Lutz, K. Specht, N.J. Shah, Cortical activations during paced finger-tapping applying visual and auditory pacing stimuli, *Brain Res. Cogn. Brain Res.* 10 (1–2) (2000) 51–66.
- [9] R. Kawashima, M. Taira, K. Okita, K. Inoue, N. Tajima, H. Yoshida, T. Sasaki, M. Sugiura, J. Watanabe, H. Fukuda, A functional MRI study of simple arithmetic—a comparison between children and adults, *Cogn. Brain Res.* 18 (2004) 225–231.
- [10] E. Mellet, N. Tzourio, F. Crivello, M. Joliot, M. Denis, B. Mazoyer, Functional anatomy of spatial imagery generated from verbal instructions, *J. Neurosci.* 16 (1996) 6504–6512.
- [11] T.C. Rickard, S.G. Romero, G. Basso, C. Wharton, S. Flitman, J. Grafman, The calculating brain: an fMRI study, *Neuropsychologia* 38 (2000) 325–335.
- [12] O. Simon, J.F. Mangin, L. Cohen, D.L. Bihan, S. Dehaene, Topographical layout of hand, eye, calculation, and language-related areas in the human parietal lobe, *Neuron* 33 (2002) 475–487.
- [13] J. Talairach, P. Tournoux, *Co-Planar Stereotaxic Atlas of the Human Brain*, Thieme, New York, 1988.
- [14] S. Tanaka, C. Michimata, T. Kaminaga, M. Honda, N. Sadato, Superior digit memory of abacus experts: an event-related functional MRI study, *NeuroReport* 13 (2002) 2187–2191.
- [15] L. Zago, M. Pesenti, E. Mellet, F. Crivello, B. Mazoyer, N. Tzourio-Mazoyer, Neural correlates of simple and complex mental calculation, *Neuroimage* 13 (2001) 314–327.