Superior digit memory of abacus experts: an event-related functional MRI study

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Abacus experts exhibit superior short-term memory for digits, but the underlying neurophysiological mechanism remains unknown. Using event-related fMRI, we examined the brain activity of abacus experts and non-experts during the memory retention period of a delayed match-to-sample task using digits as stimuli. In controls, activity was greater in cortical areas related to verbal working memory, including Broca's area. In contrast, in experts, activity was greater in cortical areas related to visuo-spatial working memory, including the bilateral superior frontal sulcus and superior parietal lobule. This provides neurophysiological evidence that abacus experts utilize a visuo-spatial representation for digit memory. *NeuroReport* 13:2187–2191 © 2002 Lippincott Williams & Wilkins.

Key words: Abacus; Cognitive expertise; Event-related functional MRI; Spatial working memory; Strategy; Verbal working memory

INTRODUCTION

Studies of the psychological mechanisms underlying domain-specific expertise are numerous, and the research on individuals with exceptional memory has a particularly long history [1]. The neurophysiological mechanism underlying such superior memory capacity, however, remains unknown. In the present study, we investigated the neurophysiological mechanism underlying the superior memory capacity of Japanese abacus experts using fMRI.

The abacus, a traditional tool for mathematical calculation, is still widely used in Asian countries. It is a simple device of beads and rods, and numbers are represented by the spatial locations of beads (Fig. 1a). Highly skilled abacus users can calculate accurate answers to mathematical problems extremely rapidly. Previous behavioral studies demonstrate that abacus experts can remember unusually long sequences of digits. For example, Hatano and Osawa demonstrated that abacus experts can remember sequences of 16 digits forward and 14 digits backward [2]. From evidence showing that their digit memory was disrupted more by concurrent visuo-spatial tasks than verbal tasks, the authors suggested that abacus experts utilize a visuo-spatial mental representation of the abacus in working memory [2–4]. This hypothesis, however, has yet to be examined at a neurophysiological level.

In the present study, we examined the brain areas of abacus experts and non-experts using fMRI while they performed tests of digit-span memory capacity. As the working memory strategies utilized by abacus experts and non-experts were thought to be different, we hypothesized that areas of greatest activity would differ between the two groups.

MATERIALS AND METHODS

Subjects: Ten male abacus experts (mean ($\pm$s.d.) age 20 ± 2 years) and 13 non-expert controls (seven male and six female, mean age 22 ± 2.6 years) participated in the experiment. All of the subjects were right-handed with no left-handed relatives in their immediate families. Handedness was assessed in accordance with the Edinburgh inventory prior to the experiments [5]. The mean educational level of both groups was at the undergraduate level and there were no significant differences in the academic years between the groups (experts 14.7 ± 2.2 years; controls 15.8 ± 1.5 years; $t(21) = 1.41$, $p = 0.17$). The experts had 8–16 years of abacus training (mean 11.8 ± 2.7 years), and were currently receiving ≥ 1 h of training every day. Their skills ranked from 2 *dan* to 10 *dan* (mean 8 ± 2.8 *dan*). *Dan* are classes for masters and 8 *dan* is considered a grand master. Controls had either no abacus training or negligible experience in abacus use. None of the subjects had a history of psychiatric or neurological illness. Written informed consent was obtained from each subject before testing. The
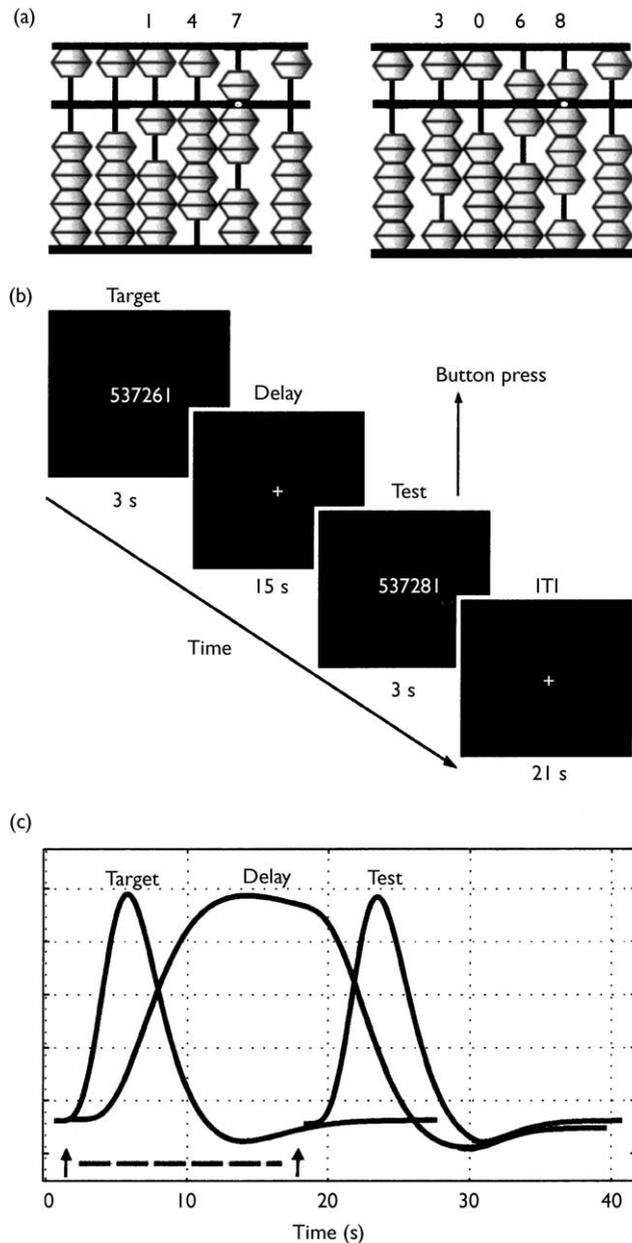
Fig. I. (a) Illustrations of an abacus. An abacus is a rectangular wooden calculator based on the decimal system. Each vertical rod has five sliding beads, one above and four below a middle horizontal bar. Numbers are represented by the configurations of the beads. A bead above the bar is equal to 5 when it is pushed down, and each of the 4 beads below is equal to I when pushed up. For example, the left figure represents I47 and the right represents 3,068. (b) Schematic illustration of I trial of the delayed match-to-sample task. (c) Illustration of the hemodynamic models for each event for statistical evaluation. The arrows indicate the time of presentations of the target and test stimuli, and the dotted bar indicates the delay period.

fMRI experiment was performed in accordance with approval by the local ethics committee of Teikyo University.

Task procedures: Before the functional imaging, all the subjects completed a digit span task to test the digit span memory capacity for each subject. The length of the digit sequence used in the subsequent fMRI experiments was determined separately for each individual based on their performance of the digit span task, thus minimizing possible confounding effects of a difference in task difficulty between the groups during the fMRI experiment.

For the digit span task, a random sequence of digits from 1 to 9 was simultaneously presented on a computer screen for 3 s, and after a delay of 15 s, the subject was asked to recall and report the digit sequence orally. The length of the digit sequence started at 5 digits, increasing by 1 digit each time the subject successfully recalled the sequence. If the subject failed to recall the sequence, another digit sequence of the same length was presented once more. The digit span memory capacity was defined as the maximum length digit sequence that the subject successfully recalled within two trials.

For the fMRI experiments, a delayed match-to-sample task using a digit sequence as the stimulus was employed (Fig. 1b). A target digit sequence was presented simultaneously on the center of a viewing screen for 3 s. The length of the digit sequence used was 2 digits shorter than the individually determined digit span memory capacity. After a 15 s delay period, during which only a fixation cross appeared on the screen, a test sequence of digits was presented for 3 s. The subjects were asked to judge whether the target and test sequences were the same or different, by pressing one of the response buttons with the right index or middle finger, respectively. Following these behavioral events, there was a 21 s intertrial interval (ITI) that allowed the fMRI signal to return to baseline. Each experimental session consisted of 15 trials, and each subject completed two experimental sessions, yielding a total of 30 trials.

fMRI and data analysis: fMRI was conducted using a 1.5 T MRI scanner (LX scanner, General Electric Medical Systems, WI). Stimuli were presented using a liquid crystal display (LCD) projector onto a custom viewing screen, and subjects viewed the screen though a mirror. The visual angle of each digit used as a stimulus was ~1°. Functional images were acquired using T2*-weighted echo planar imaging (TR 3000 ms, TE 50 ms, flip angle 90°, 3.75×3.75 mm in-plane resolution, 6 mm slice thickness, 21–23 axial slices covering the whole brain). For each experimental session, 217 functional images were collected. The first 7 images were discarded to allow for stabilization of the magnetization. T1-weighted structural images were acquired using a 1.5 T MRI scanner (SIGNA Horizon scanner, General Electric Medical Systems, WI) and a 3D-spoiled gradient recalled sequence (TR 33 ms, TE 3 ms, field of view 24 cm, flip angle 30°, 0.95×0.95 mm in-plane resolution, 1.3 mm slice thickness, 124 axial slices covering the whole brain).

SPM99 software (Wellcome Department of Cognitive Neurology, London, UK) was used for image processing and analysis [6]. For the spatial preprocessing, the functional images were realigned to the first functional image, coregistered to the structural image, and normalized to the standard stereotaxic space [7]. Then, the images were spatially smoothed using an isotropic Gaussian kernel of 6 mm full-width half maximum (FWHM).

For within-subject statistical analysis, we used a general linear model [6]. The responses during the presentations of the target and test sequences and the delay period were modeled separately using 3 boxcar functions convolved with a canonical hemodynamic response function (Fig. 1c). The epoch length was 3 s each for the presentations of the target and test sequences, and 15 s for the delay period. A slow baseline drift by the aliasing effects of the physiological factors such as cardiac and respiratory fluctuations was removed using a high-pass filter with a cut-off period of 84 s. To increase the signal-to-noise ratio, a low-pass filter derived from a Gaussian kernel of 6 s FWHM was employed. After these procedures, individual contrast images were calculated using the β value representing the correlation between the observed response and the modeled response.

Within-group analysis was performed using a random effect model [8]. Activation maps were created using a one-sample Student's t-test comparing the contrast images of each event and the baseline for each group separately. To identify activity specific to the abacus expert group, we also used a two-sample Student's t-test to compare between the two groups. Only the voxels showing significantly increased activity in abacus experts ($p < 0.001$ without correction for multiple comparisons) were included in the analysis. The voxels were thresholded at a p value of 0.001 (within-group analysis: $t = 3.93$ for controls, and 4.30 for experts; between-group analysis: $t = 3.53$) and the resulting clusters were estimated in terms of the probability of the spatial extent (i.e., number of contiguous voxels). The final threshold was set to a p value of 0.05 with a correction for multiple comparisons. The present report focuses on the brain activity associated with memory retention and thus the data collected during the delay period of the match-to-sample task is presented.

RESULTS

Behavioral data: The mean digit-span memory capacity of experts (12.2 ± 1.55 digits) was significantly ($t(21) = 6.71$, $p < 0.001$) greater than controls (8.5 ± 1.13 digits), supporting previous data indicating that abacus experts have greater digit span memory capacity. During the fMRI sessions, there were no significant differences between groups in the percentage of correct responses (experts, $90 \pm 4.0\%$; controls, $93 \pm 6.9\%$; $t(21) = 1.00$, $p = 0.33$) or the mean reaction time (experts 1580 ± 292 ms; controls 1542 ± 286 ms; $t(21) = 0.32$, $p = 0.75$). Thus, it appeared that the effects of differences in task difficulty were minimal.

Imaging data: Brain activity observed during the delay period in each group is shown in Fig. 2a and Table 1. Overall, activity was lateralized to the left hemisphere in controls, and was more bilateral and symmetrical in experts. In controls, activity was observed in the left inferior frontal cortex (Broca's area: BA44, 45), medial frontal cortex (BA32), and insula (BA13); bilaterally in the ventral prefrontal cortex (BA47) and inferior parietal lobule (BA40); and more predominately in the right cerebellum. The active region including Broca's area extended to the precentral gyrus (BA6). In contrast, in experts, activity was observed bilaterally in the superior frontal sulcus (BA6), inferior
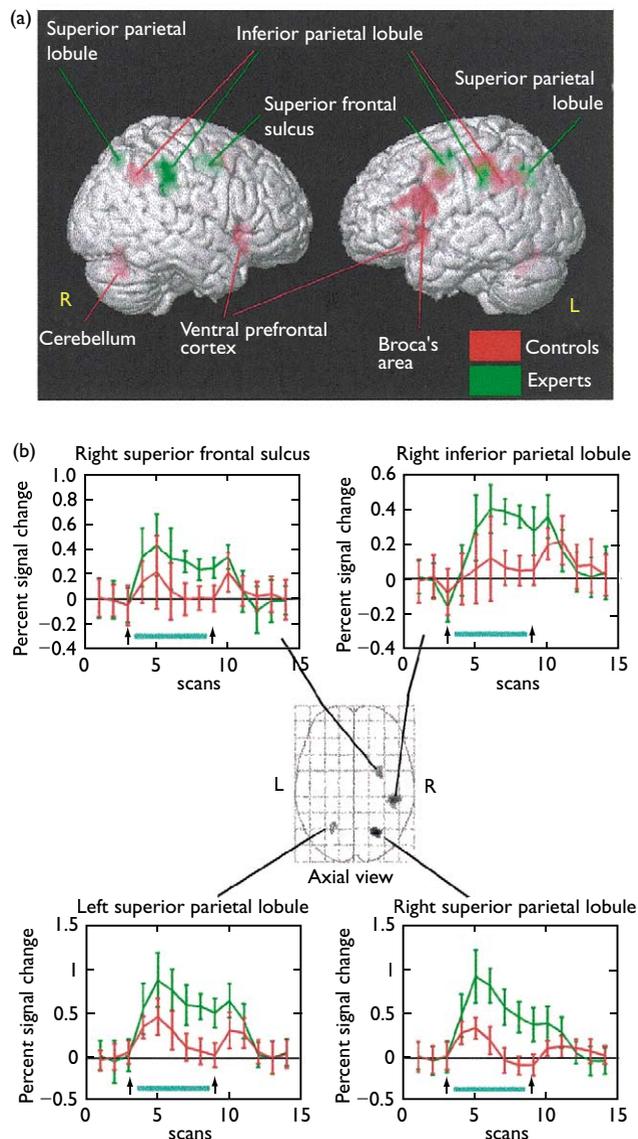

Fig. 2. (a) Activity during the delay period of the delayed match-to-sample task relative to the baseline in controls (red) and experts (green). (b) Active areas during the delay period specific to the abacus experts (center panel). Only statistically significantly different activity is shown. The averaged time courses in both controls (red) and experts (green) were plotted (upper and lower panels). The vertical axis indicates the mean percent signal change relative to the baseline, which was defined as the mean intensity of the two time points immediately prior to the presentation of the target stimulus. The horizontal axis indicates the peri-stimulus time (3 s/scan). The error bars represent s.d. across subjects. The arrows indicate the time of presentations of the target and test stimuli, and the blue bar indicates the delay period.

parietal lobule (BA40), superior parietal lobule (BA7), and cingulate gyrus (BA24). Because the ratio of males to females was not balanced between the groups, we also performed additional analysis restricted to the male subjects in the control group. Activity was observed predominately in the left hemisphere (e.g., $t = 8.54$ in Broca's area, $t = 0.76$ in the corresponding area in the right hemisphere). This was consistent with analysis including both sexes.

Table I.   Areas exhibiting activity during a delayed match-to-sample task in abacus experts and non-expert controls.

Regions (Brodmann area)	Laterality	Size of cluster	x	y	z	t-value
Within-group analysis						
Controls						
Ventral prefrontal cortex (47)	L	111	−31	22	−12	5.76
	R	154	36	16	−5	6.08
Inferior parietal lobule (40)	L	811	−38	−29	39	7.11
	R	138	34	−58	32	8.20
Cerebellum	L	327	−4	−71	−16	7.02
	R		19	−65	−32	6.26
Inferior frontal cortex (Broca:44, 45)	L	691	−45	6	25	8.60
Precentral gyrus (6)	L		−44	−3	38	8.28
Medial frontal gyrus (32)	L	286	−45	6	25	9.60
Insula (13)	L	116	−40	6	−4	7.38
Experts						
Superior frontal sulcus (6)	L	268	−31	−3	47	9.96
	R	183	26	−11	45	8.33
Inferior parietal lobule (40)	L	212	−48	−32	28	7.29
	R	499	40	−36	31	10.00
Superior parietal lobule (7)	L	251	−15	−64	33	6.77
	R	88	22	−69	42	7.26
Cingulate gyrus (24)	L	90	−8	3	47	6.47
Between-group analysis						
Experts > controls						
Superior parietal lobule (7)	L	44	−22	−54	47	4.40
	R	65	26	−63	52	6.96
Superior frontal sulcus (6)	R	37	30	−2	42	4.41
Inferior parietal lobule (40)	R	164	44	−29	37	5.61

Size of cluster represents the number of contiguous voxels. Coordinates are based on the Talairach and Tournoux atlas [19].

A direct comparison of activity observed during the delay period between the two groups is shown in Fig. 2b. Activity in the right and left superior parietal lobule and the right superior frontal sulcus and inferior parietal lobule was significantly greater in experts than in controls. The time course of activity in these areas was sustained throughout the delay period in abacus experts, remaining statistically significantly increased compared to controls, in which activity in these areas was phasic in response to the presentations of the stimuli.

DISCUSSION

The results of the present study show that brain activity in abacus experts during the memory retention period of a delayed match-to-sample task was more symmetrically distributed in areas implicated in visuo-spatial working memory [9–11] than in non-expert control subjects, in which activity was more predominant in the left hemisphere in areas related to verbal working memory [12]. Activity in abacus experts was observed in the right superior frontal sulcus, inferior parietal lobule, and the bilateral superior parietal lobule, whereas that in controls was observed in Broca's area, precentral gyrus, and inferior parietal lobule. There were no significant behavioral differences between the groups in either response accuracy or reaction time. Therefore the difference in activity cannot be attributed to a difference in task difficulty between the groups. Analysis restricted to males was also consistent with that including both sexes. Thus, the results cannot be accounted for solely by differences in the ratio of males to females in the two groups. We conclude that the differences in brain activity probably reflected differences in working memory strategies utilized by each group.

The present findings are consistent with previous behavioral studies [2,3] and a previous fMRI neuroimaging study in which bilateral activity in the premotor cortex and parietal lobules was observed during mental calculations in abacus experts [13]. It is possible that a spatial representation of numbers is developed through abacus practice, which involves rule–based visuo-motor processing, and utilized in the digit span memory task, because it may be more efficient to mentally manipulate large numbers using a spatial representation than a sequentially organized phonological representation. It may be that these processes involve the bilateral frontal–parietal areas, which have important roles in visuo-motor processing [14].

Another possibility is that subjects achieving a high degree of abacus experience have inherently greater ability for spatially based cognitive tasks. Some behavioral evidence, however, may agree against this possibility [15]. In this previous study, five groups of abacus operators differing in expertise were compared using a digit span task. The authors found that a concurrent verbal task had a greater confounding effect on the memory performance in less skilled subjects than in experts, while a concurrent visuo-spatial task had a greater confounding effect in experts than in less skilled subjects. These results suggest that the digit memory of mental abacus operators becomes more visuo-spatial in nature as they gain expertise. Longitudinal studies may clarify this issue.

Recently, Pesenti *et al.* studied a calculating prodigy using positron emission tomography and reported that his calculation ability involves brain areas related to long-term memory, such as the right prefrontal and medial temporal areas [16]. The results of the present study suggest that abacus experts utilized spatial representation of numbers during the digit memory tasks, and this involved the

bilateral frontal–parietal areas. One commonality between the two studies is that the experts used brain areas that are not used by non-experts. These neurophysiological results support psychological theories that cognitive expertise is achieved by developing novel strategies not used by non-experts [17,18].

CONCLUSION

Using event-related fMRI, the results of the present study indicate that brain activity in abacus experts during the memory-retention period of a digit span memory task involved the bilateral frontal–parietal area. This result is consistent with previous behavioral results showing that abacus experts utilize visuo-spatial representations of digit sequences during digit span memory tasks and that this strategy increases their digit span memory capacity.

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