Analysis of Brain Areas Activated while Using Strategies to Improve the Working Memory Capacity

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Abstract. Improvement of the working memory capacity is expected to enhance the reasoning task and reading comprehension abilities. The aim of this study was to investigate effective methods for improving the working memory capacity. We used the reading span test (RST) as a task and examined the types of strategies that can be used to process tasks as well as strategies that may improve working memory capacity. In this experiment, we used functional magnetic resonance imaging to observe the brain areas activated in subjects during RST. We examined the high-span subjects (HSS) in the preliminary RST and found that the HSS used a scene imagery strategy when performing RST. The low-span subjects (LSS) were trained to learn the same strategy that was used by HSS. We observed that the similar brain areas as those in HSS were activated in LSS and their RST scores were improved.

Keywords: Brain, fMRI, Working Memory, Reading Span Test, Anterior Cingulate Cortex, Strategy.

1 Introduction

In our daily life, people perform two types of processing simultaneously: information processing and maintaining information temporarily. During conversations and when reading, for example, people process information that they have just heard or read and they memorize the information for a short time. The working memory of the brain fulfills this role [1], and this capacity varies among individuals [2]. According to Olesen et al. (2004), the working memory capacity can be improved by training [3]. Improving the working memory capacity is expected to enhance reasoning task and reading comprehension abilities [4], as well as to relieve the symptoms of attention deficit/hyperactivity disorder [5,6]. Therefore, it is important to identify effective methods for improving the working memory capacity.

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In recent years, the neural basis of the working memory capacity has been studied actively, and studies of the working memory are classified into two groups: research into the visual working memory and that into the verbal working memory [7]. The visual working memory capacity has been studied using multiple object tracking tasks, and it has been reported that brain activities involved with capacity constraints occur in the intraparietal sulcus (IPS) of the parietal lobe [8, 9]. For the verbal working memory, the supramarginal gyrus is involved with memorizing phonological information, while Broca's area in the inferior frontal gyrus (IFG) is involved with processing information, according to a previous study using positron emission tomography [10].

Osaka et al. (2003) examined the relationships between the activated brain areas and differences in the verbal working memory capacities of individuals [11]. In their experiment, the reading span test (RST) was used as a task to measure the working memory capacity. They showed that the high-span subject (HSS) group had significant activation in the anterior cingulate cortex (ACC) and the left IFG compared with low-span subject (LSS) group. In another study [12], Osaka and Nisizaki investigated the individual strategies used during RST. This showed that the strategies used by subjects to memorize target words varied among individuals and that these strategies affected the RST scores.

Thus, the results of RST, i.e., the working memory capacity, were affected by the strategy. In this research, we therefore tested whether there were differences in the activated brain areas with different RST strategies to identify the most effective methods for improving the working memory capacity.

2 Working Memory and Reading Span Test

There are several models of the working memory [1, 2, 13]. One of the models comprises three subsystems and the central executive function [14]. The three subsystems are known as the phonological loop, visuospatial sketchpad, and episodic buffer, and the central executive function controls these three subsystems. The roles of each system are as follows.

- The central executive function: an attention control system that adjusts the capacity for resource allocation and directs the attention selectively to input stimuli.
- The phonological loop: an information system that handles verbal data, such as conversation and reading comprehension.
- The visuospatial sketchpad: stores input stimuli temporarily as visual images and processes these images.
- The episodic buffer: gathers and processes data from the phonological loop, visuospatial sketchpad, and long-term memory.

Information is stored in the three subsystems for a short period. The working memory capacity is affected by the manner in which the central executive function allocates resources to the subsystems, while the resource allocation process varies among individuals [7]. The dual-task paradigm is a method used to study the working memory [1]. Typical dual-task paradigms include the operation span test, the counting span test, and RST are, and are used to measure the working memory capacity of the central executive function [15–17]. It has been reported that there is a high correlation between RST scores and language comprehension [18].

In RST, a few sentences are displayed continuously and subjects are required to read them while simultaneously remembering target words in the sentences. Thus, subjects are required to execute two processes simultaneously during RST: reading and comprehending sentences and memorizing the target words. Therefore, RST facilitates the identification of differences in the verbal working memory capacity of individuals. The RST scores are also affected by the strategy used to memorize the target words. According to Osaka and Nisizaki [12], subjects in the HSS group always adopted strategies such as chaining, word images, and scene images, whereas many subjects in the LSS group adopted no such strategies. Figure 1 shows the major strategies used during RST. In a previous study [7], differences in the verbal working memory capacity among individuals and their brain network correlations were investigated using RST. According to this study, the central executive functions were recognized in ACC, dorsolateral prefrontal cortex (DLPFC), and superior parietal lobule (SPL), while Osaka et al. [19] found that the verbal working memory interacts with ACC, DLPFC, SPL, and language area, including the left IFG. Figure 2 shows a model of the verbal working memory.

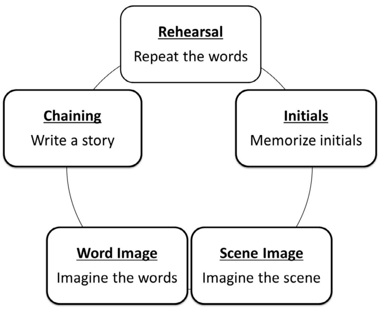


Fig. 1. Strategies used during RST

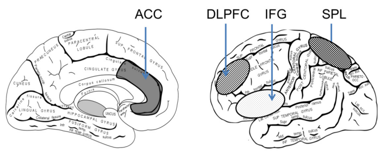


Fig. 2. Model of the verbal working memory in the brain

3 Methods

3.1 Experimental Overview

Using fMRI, we have examined the relations between improving working memory capacity and the activation areas of brain when using an appropriate strategy to the RST.

First, we classified subjects into HSS and LSS groups on the basis of their preliminary RST scores, and interviewed each subject and determined the strategy they used during RST before comparing their activated brain areas based on previous studies. Second, HSS and LSS participated in the fMRI experiment. Third, we trained some of the subjects in the LSS group to use the strategy applied by the subjects in the HSS group, before investigating whether the brain area activated changed after learning the strategy. Finally, we also trained some other subjects in the LSS group to learn the strategy used by the subjects in the HSS group, and they repeated RST.

3.2 Subject and Experimental Design

In the preliminary experiment, 26 healthy university students (age, 19-22 years) performed RST. Based on the results of this preliminary RST experiment, we selected seven right-handed subjects, four of whom were assigned to the HSS group and the other three were assigned to the LSS group. These 7 subjects participated in the fMRI experiment.

The fMRI experiment was designed based on previous research. The sentences displayed in the fMRI experiment were also formed after referring to a previous study [19]. Figure 3 shows the fMRI experiment process, which comprised two sessions. Each session involved the following sequence.

1. RST: The subject judged whether each sentence was semantically correct and memorized the target word in each sentence simultaneously (five sentences in total).
2. Recognition: The subject recalled the target words in order and identified each of the target words from three candidate words. If there was a target word among the candidate words, the subject pressed the button for the corresponding word, otherwise they pressed a button with a cross sign.
3. Rest: A star was displayed randomly on each side of the screen, and the subject pressed the left or right button, which corresponded to the side where the star appeared.
4. Read: The subject only judged whether the sentence was semantically correct.
5. Rest: Repeat stage 3. The subject pressed the left or right button corresponding to the side where the star appeared on the screen.

Stages 1-5 were repeated four times during each session. The order of the stages was varied in subsequent sessions: 4 and 5 were processed first, followed by 1-3. When the experiment was complete, the subjects were interviewed, and they reported the strategies they used in RST. Next, two subjects from the LSS group were trained in the scene imagery strategy for approximately 30 min before they repeated the fMRI experiment. We also conducted the following experiment to study the relationship between the improvement in the working memory capacity and the strategy used during RST. Three subjects were selected from the group who used no strategies in the preliminary experiment. After training in the scene imagery strategy, they repeated RST, which was similar to the preliminary experiment.

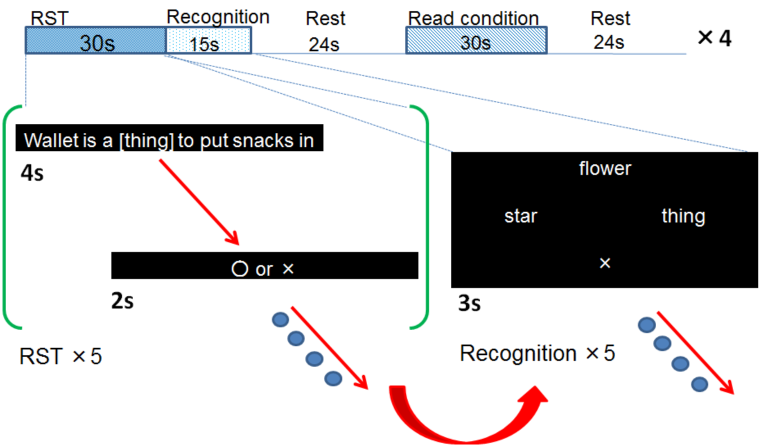


Fig. 3. Design of the fMRI experiment

3.3 Data Acquisition and Analysis

Whole brain image data were acquired using a 1.5 Tesla MRI scanner (Echelon Vega; Hitachi Medico) with a head coil. The button that the subjects used to select the target words was supplied by Cambridge Research Systems Ltd (fORP 932 Subject Response Package).

For functional imaging, we used a gradient-echo echo-planar imaging sequence with the following parameters: the repetition time (TR) was 3000 ms, echo time (TE) was 55 ms and the flip angle was 90, the field of view (FOV) was 192 192 mm. In one experimental session, 174 contiguous images, 20 slices with a 5 mm thickness, were obtained on the axial plane for each subject.

Data were processed using SPM8 software (Wellcome Department of Imaging Neuroscience, Institute of Neurology, University College London, London, UK). Five initial images of each scanning session were discarded from the analysis. All functional images were realigned to correct for head movement and slice-time corrected. After realignment and slice timing, the anatomical image was co-registered to the mean functional image for each participant. Functional images were then normalized with the anatomical image and spatially smoothed using a Gaussian filter (8-mm full width at half-maximum). For the individual analysis, the fMRI time series of each subject was correlated with a boxcar reference function.

4 Results

4.1 RST Results

Table 1 shows the percentages of recalled target words and the strategies used by the subjects. Subject D was removed from the following analysis because subject

Table 1. Percentages of correct answers in RST

Group	Subject	Percentages of correct answers [%]	Strategy
HSS	A	95.0	Scene Image
	B	90.0	Rehearsal
	C	87.5	Chaining
	D	77.5	Scene Image
LSS	E	77.5	Word Image
	F	70.0	None
	G	60.0	None

D belonged to the HSS group but had the same score as the subject in the LSS group. The target word recall scores differed significantly between the HSS and LSS groups (Student's t-test, $p < 0.05$).

4.2 Activated Brain Areas in the HSS and LSS Groups

To focus on the allocation of information resources by the central executive function, the activated brains areas described below were identified on the basis of a comparison of the data captured during RST and reading conditions. ACC, DLPFC, IFG, and SPL have been reported to be involved with the central executive functions of the verbal working memory. Therefore, Fig. 4 shows the number of subjects in the HSS and LSS groups who had activated ACC, DLPFC, IFG, and SPL regions. Figures 5 and 6 show the activated areas in subjects from the HSS group and subjects from the LSS group. Table 2 summarizes the regions significantly activated during RST relative to the read condition among ACC, DLPFC, and SPL.

As shown in Fig. 4, the activated areas differed in the HSS and LSS groups. The activation areas also varied among individuals in each group, as shown in Figs. 5 and 6. Figure 6 shows that the activated areas were similar in subjects F and G, who had no strategies.

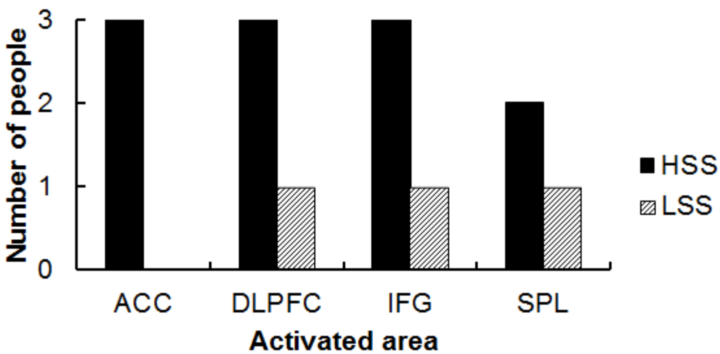
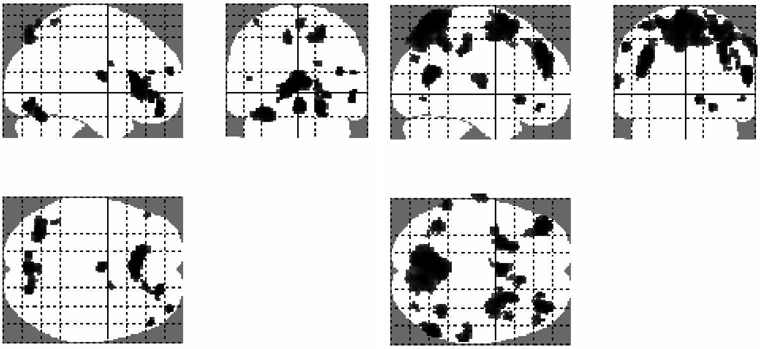
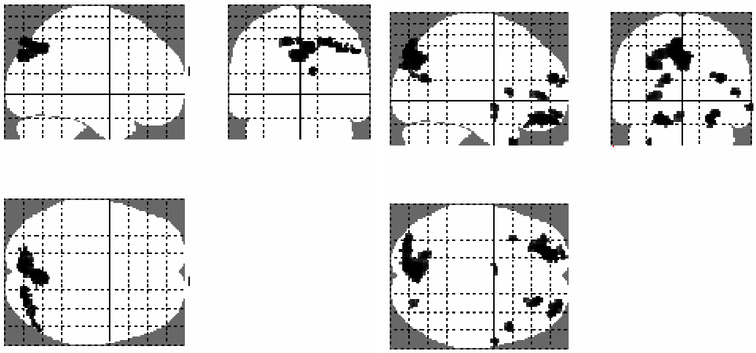


Fig. 4. Number of people activated brain areas in the HSS and LSS groups



(a) Subject A (b) Subject B

Fig. 5. Brain area activated in the HSS group



(a) Subject F (b) Subject G

Fig. 6. Brain area activated in the LSS group

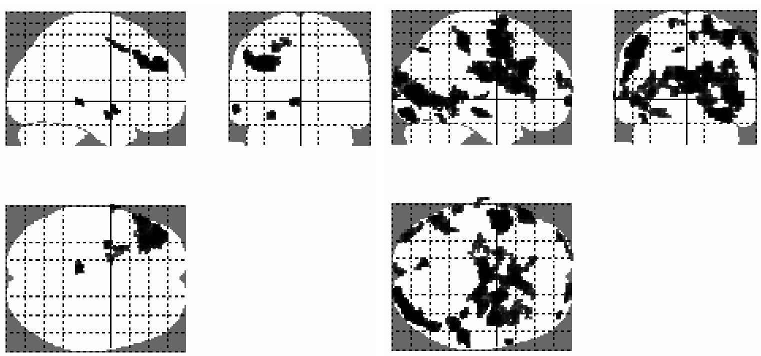
4.3 Changes in the Activated Areas after Learning the Strategy

To investigate whether the activated brain areas changed after learning the strategy, subjects F and G, who had no strategies, were trained how to use the scene imagery strategy during RST for approximately 30 min before they repeated the fMRI experiment. The changes in the correct target word recall scores of subject F were from 70.0 % to 72.5 %, and those of subject G were from 60.0 % to 65.0 %. Figure 7 shows the brain areas activated after subjects F and G received training, and Table 3 summarizes the areas significantly activated during RST relative to the read condition.

Figures 6 and 7 also illustrate the changes in the activated areas before and after learning the strategy. Tables 2 and 3 show that ACC and DLPFC were activated after learning the strategy, whereas SPL was activated before learning the strategy. Thus, the activated brain areas changed depending on the strategy used during RST.

Table 2. Significant activation (uncorrected, $p < 0.001$), the peak Z scores, and the number of activated voxels based on MNI coordinates, pre training strategy

Subject	Brain region	Broadman area	x	y	z	z score	Voxels
F							
	ACC						
	DLPFC						
	L SPL	7	− 14	− 82	46	3.78	47
G							
	ACC						
	R DLPFC	9/46	36	58	16	4.28	48
	L SPL	7	− 6	− 84	44	5.07	732



(a) Subject F (b) Subject G

Fig. 7. Brain area activated in the LSS group (after learning the strategy)

Table 3. Significant activation (uncorrected, $p < 0.001$), the peak Z scores, and the number of activated voxels based on MNI coordinates, post training strategy

Subject	Brain region	Broadman area	x	y	z	z score	Voxels
F							
	L ACC	32	− 16	− 2	52	3.33	13
	L DLPFC	9/46	− 38	46	34	4.35	600
	SPL						
G							
	R ACC	32	6	18	20	4.72	1144
	L DLPFC	9/46	− 50	6	− 6	5.38	596
	R SPL	7	48	− 42	62	3.29	174

4.4 Effects of the Learning Strategy

To study the relationship between the improvement in the working memory capacity and the use of an appropriate strategy, three subjects who lacked strategies in the preliminary experiment practiced the scene imagery strategy and then repeated RST.

The changes in the correct target word recall scores of subject H were from 12.0 % to 68.0 %, subject I were from 28.0 % to 48.0 %, and subject J were from 40.0 % to 68.0 % The target word recall scores differed significantly between pre-training and post-training the strategy (Student's t-test, $p < 0.05$).

5 Discussion

According to Osaka et al. (2004), for both HSS and LSS groups, the fMRI signal intensity increased in ACC and IFG during the RST condition compared to that under the read condition [20]. In the present study, however, we found those areas activated in all of the subjects in HSS group, but not all in the LSS. The activated areas varied among subjects in the HSS and LSS groups, as shown in Figs. 5, 6, and 7 Thus, the working memory capacity cannot be analyzed simply by classifying subjects into HSS and LSS groups, and they should be studied separately. After the subjects in the LSS group learned the scene imagery strategy, their RST scores increased and their working memory capacity improved. Furthermore, the brain areas activated in the subjects from the LSS group were similar to those in the subjects from the HSS group. Thus, the activated brain areas were affected by learning the strategy, which also improved the working memory capacity.

The scene imagery strategy is a memorization method that classifies verbal information into visual images and phonological information, before associating them with the long-term memory, thereby memorizing a word. Subject A had the best RST score and used the scene imagery strategy in which the central executive function performs the processes mentioned above. Figure 5(a) shows that the number of activated brain areas was low in subject A, although significant local activation was observed, particularly in ACC. This suggests that ACC functions as the central executive system. The working memory capacity of subject A appeared to be high, which also suggests that only a specific domain should be used and other domains should be repressed to avoid excess information handling. On the other hand, activation of ACC is an indicator of a better working memory capacity because brain activation was observed in ACC in all of the subjects in the HSS group and any in the LSS group.

6 Conclusion

This research investigated the effects of using an effective RST strategy on the working memory capacity and changes in the activated brain areas. The results showed that ACC, DLPFC, SPL, and the left IFG were significantly activated in the HSS group. Subjects in the LSS group then learned the strategy used by the subjects in the HSS group, and similar brain areas were activated when they repeated RST. Thus, effective strategies can improve the working memory capacity.

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