

Functional MRI Study on Working Memory of Orthography

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ABSTRACT

The purpose of this fMRI study was to investigate the neural substrates related to the working memory of orthography. The question may be asked as to whether handling orthographic information should be considered as to a verbal or a visuospatial stimulus, because this information can be employed as a shape or as a location for visuospatial stimuli, even though it falls within the category of verbal information. Ten Korean native speakers were imaged using a 1.5T MR scanner while performing a one-back working memory task in orthography (OTH), phonology (PHO) and figures (FIG). The brain areas commonly activated in OTH and PHO were found to be in the bilateral, frontal and parietal cortices, which is consistent with previous working memory studies. Among these areas, the regions where the MR signal was found to be higher in OTH than in PHO were located in the inferior frontal gyrus and superior parietal lobule. When the figure was subtracted from orthography, inferior frontal gyrus was activated as well. Therefore, dealing with orthographic information seemed to activate a similar network of brain areas as for spatial information. However, considering that the additional activation in the inferior frontal gyrus was observed only in OTH, we can also conclude that dealing with orthography differed somewhat from the process of handling figures. This observation confirms the unique property of dealing with orthography, distinct from the process of handling figures.

Key words: functional magnetic resonance imaging, working memory, orthography, phonology, figure, inferior frontal gyrus

INTRODUCTION

This study was performed to examine the neural substrates underlying the working memory process of managing orthographic information. Orthographic information generally refers to the visual representation of the speaker's utterances using the standard spelling of a given language. One of the previous

studies related to orthographic information suggested that copying letters or accessing visual representations of words was involved with the inferior parietal lobe and the parieto-occipital area (Matsuo et al., 2000). Nakamura and colleagues (Nakamura et al., 2000) provided evidence that the left posterior inferior temporal cortex played an important role in writing Kanji through the retrieval of visual graphic images. Based on these previous studies, we may consider that the characteristics of orthography are similar to those of visuospatial information, and that orthographic processing is related to visuospa-

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tial processing. Then, the question may be asked as to whether handling orthographic information should be considered as to a verbal or a visuospatial stimulus, because this information can be employed as a shape or as a location for visuospatial stimuli, even though it falls within the category of verbal information.

The purpose of the current study is to examine this issue in detail. We attempt to compare orthography with figures and phonology, in order to discover to which of these processes it is more related. Specifically, we used identical material consisting of Korean letters in order to diminish the possibility of confusion derived from using different stimuli.

MATERIALS AND METHODS

Subjects

Informed consent was obtained from ten volunteers (five female, five male). All of them spoke Korean as their first language. The average age was 20.2 years (range, 19~23). All participants were right handed and fully informed about the nature of the study.

Experimental procedure

All of the stimuli used for the orthographic and phonologic tasks were drawn from Korean words consisting of two, three or four syllables. These words were divided into two sets of nouns, verbs, and non-words and each set contained fifteen words. A total of 6 sets were presented to each subject once only. Figure stimuli consisted of a sequence composed of two, three or four figurines. Each figure stimulus was composed of a small figure located inside of a big figure. Three sets of different figure stimuli were repeated twice. Each set contained fifteen different shapes.

Each subject performed orthographic, phonologic and figure tasks related to 'one-back' working memory. All of the tasks were composed of an activation epoch set between the two baseline conditions. In the orthography task (OTH) (Fig. 1A), subjects compared the locations of the second consonant between the one back presented word and the currently presented word. They then generated a silent Yes/No response as to whether the syllable-

by-syllable pattern was identical (In Korean, each letter represents a syllable, consisting of either 1st consonant-vowel or 1st consonant-vowel-2nd consonant letter combinations). In the phonology task (PHO) (Fig. 1B), subjects were instructed to rehearse subvocally the word presented one stimulus previously and then read the currently shown word silently. In the figure task (FIG) (Fig. 1C), the subjects evaluated where the small figures were positioned in a sequence and compared their location between the one back and the currently presented stimulus. They responded to positional identity with a silent Yes/No response. In the corresponding baseline task (BASE), subjects

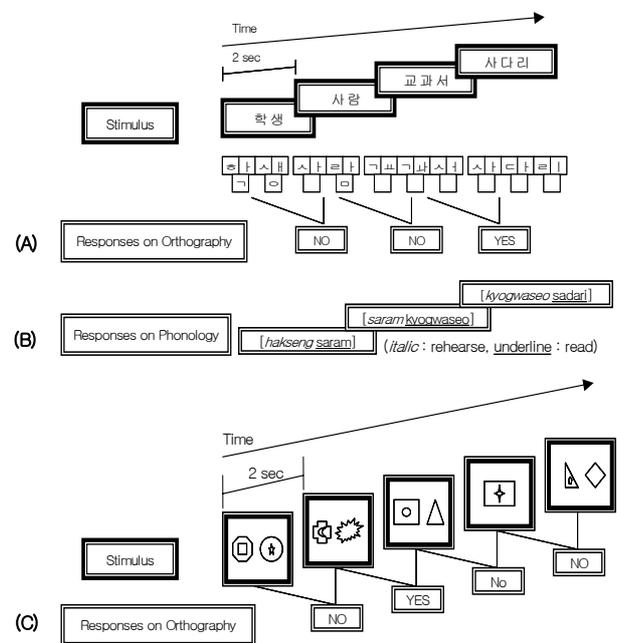


Fig. 1. (A) The exemplar paradigm of OTH. When 학생 is shown for 2 secs, subjects judge where the 2nd consonant is located. In case of 학생, two consonants (ㄱ, ㅇ) are positioned in both letters. When 사람 appears, they compare the position of the 2nd consonant between one-back (학생) and current stimulus (사람). Since only right letter has the last consonant (ㅁ) in 사람, subjects respond 'no'. The same process applies to all the stimuli. (B) The exemplar paradigm of PHO. Subjects read 학생 for 2 secs until the next stimulus appears. When 사람 is presented, subjects rehearse 학생 and then read 사람 within 2 secs. When 사람 disappears, 교과서 appears and they should rehearse 사람 and then read 교과서. After 교과서 disappears and 사다리 is shown, they rehearse 교과서 and read 사다리. (C) The exemplar paradigm of FIG. Subjects should compare the position of the small figure located in a big figure. The first stimulus has two small figures (□ ☆) while the second stimulus has only one small stimulus (□) in the left. In this case, subjects say 'no' subvocally. The same paradigm applies to all the stimuli.

were required to watch the fixation mark of the two baseline conditions starting before and after the activation epoch.

Each experimental run consisted of a 30s block of the memory task between two 30s baseline conditions, repeated 6 times. The stimulus presentation time was 2s.

Image acquisition and data analysis

A 1.5 T GE Signa whole-body scanner with echo planar imaging capability was used for image acquisition. The standard RF coil provided with the scanner was used. Based on a scout image of the midline sagittal plane, 20 slices were positioned parallel to the AC-PC line. T1-weighted images were first obtained and then T2*-weighted functional images were acquired at the same slice locations using an interleaved EPI gradient echo sequence (TR 3 sec, TE 60 msec, flip angle 90°, FOV 24 cm, matrix size 64×64, slice thickness 5 mm separation). Using SPM99 (Wellcome Department of Cognitive Neurology, University College London), the brain volumes were aligned, normalized according to the Talairach and Tournoux space for pooling across subjects (after normalization, 4×4×4 mm voxel size, 28 slices in dz coordinates ranging from -28 mm to 80 mm from the inter-commissural plane),

and convolved with a three-dimensional Gaussian kernel (7 mm FWHM). The images were aligned using AIR (Automated Image Registration, version 3.0) package (Woods et al., 1993), and smoothed and normalized according to Talairach and Tournoux coordinates (Talairach and Tournoux, 1988) using SPM99 (Statistical Parametric Mapping, 1999 version). The statistical analysis was then performed with SPM99 on pooled data by setting up a contrast (Friston et al., 1995). The resulting z-maps were then thresholded by the criteria of z-score height ($p < 0.001$, corrected) and cluster size ($p < 0.05$) (Friston et al., 1995). In order to evaluate variation in activation across subjects, a kind of variance map was also constructed by thresholding individual maps at $p < 0.001$, uncorrected, and then counting voxelwise the number of subjects who showed activations. This map was made by superimposing all of the subjects' MR images so that every activation pattern could be easily compared, and the number of subjects was represented by the color bar.

RESULTS

All subjects reported successful performance in all offline tests.

Table 1 listed the coordinates of the activated re-

Table 1.

Scan-condition*	Activated area	BA	Coordinates [†]			z-score [‡]	p< [‡]	k [§]
			X	Y	Z			
OTH>BASE	L IFG	9	-52	4	28	8<	0.000	993
	R PreCu	19	28	-76	40	8<	0.000	621
	R MFG	8	48	12	32	8<	0.000	814
OTH>PHO	R IFG	45	48	12	20	8<	0.000	208
	L SPL	7	-36	-64	52	8<	0.000	42
	R MFG	6	28	8	60	8<	0.000	22
PHO>OTH	L IFG	32	-32	24	8	6.83	0.000	12
	L PreC	6	-56	-8	36	7.75	0.000	46
	L MFG	6	-28	-4	60	7.42	0.000	17
	L MTG	39	-44	-68	20	7.05	0.000	41
OTH>FIG	L SMG	40	-52	-52	28	6.56	0.000	23
	L IFG	9	-56	16	28	8<	0.000	102
FIG>OTH	R IFG	47	44	16	-4	7.14	0.000	15
	MOG	18	32	-84	12	6.39	0.000	29

L: left, R: right, IFG: inferior frontal gyrus, MFG: middle frontal gyrus, PreCu: precuneus, SPL: superior parietal lobe, MOG: middle occipital gyrus. *Definition of scan-condition: OTH (orthography task), PHO (phonology task), FIG (figure task). [†]Coordinates are of the voxel with the maximum z-score in each contiguous activation. The numbers represent the distance in mm from the AC along x, y, and z axes, as defined by Talairach and Tournoux (1988). Positive numbers refer to the right, anterior, and above locations, respectively. [‡]See Frackowiak et al, (1997) for detailed descriptions on the equations and assumptions involved in the calculation of z-score and the probability (P) associated with it. [§]k refers to the number of contiguous voxels (2×2×2 mm³), which is above 10 ($p < 0.05$, corrected).

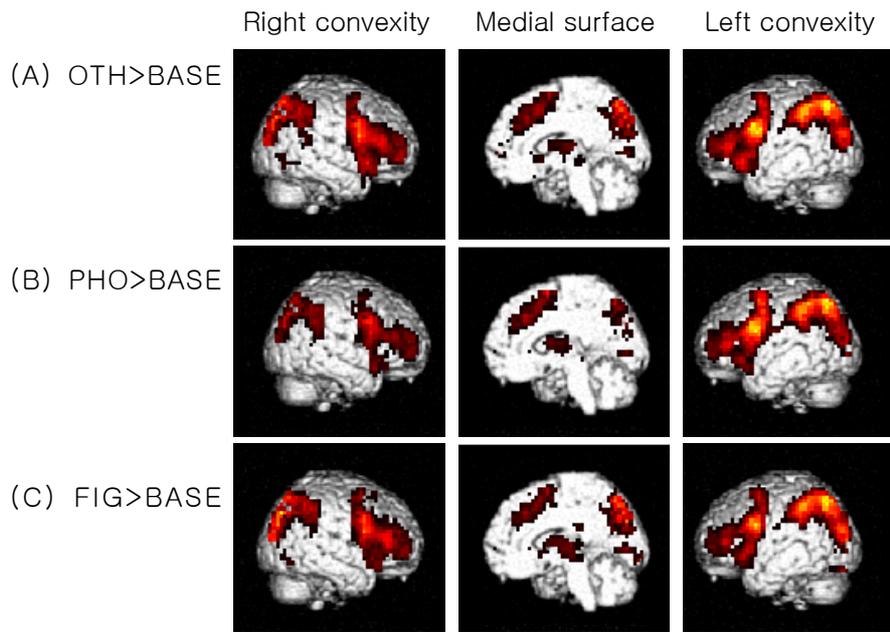


Fig. 2. Activation maps are shown for each task compared with baseline. MR signal images were obtained by group analysis ($p < 0.05$ corrected).

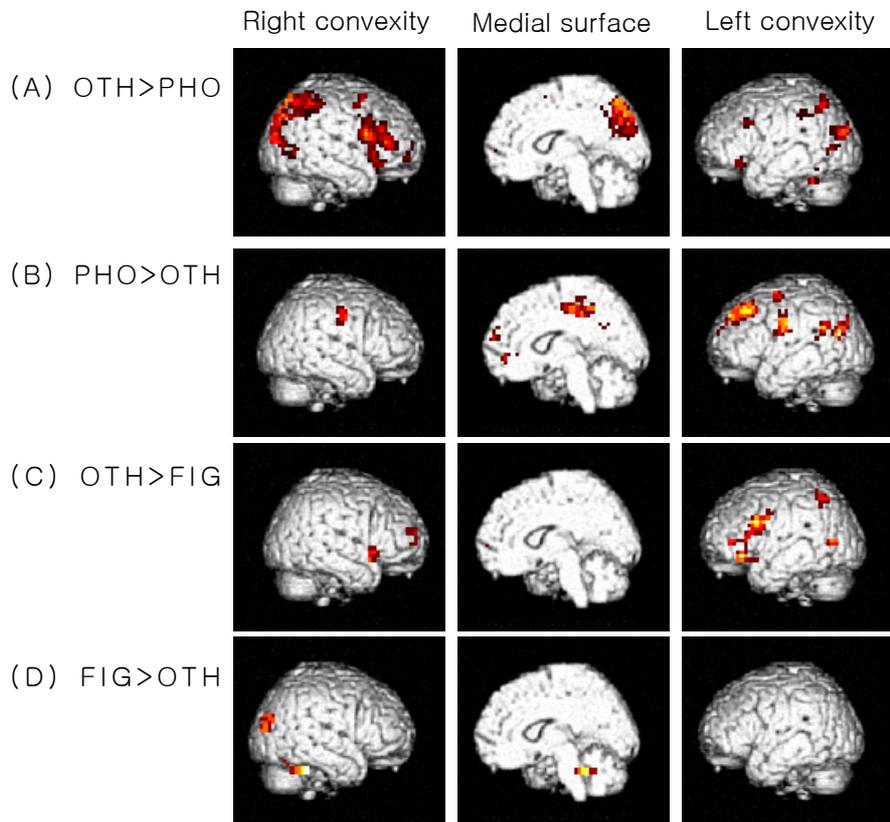


Fig. 3. Activation maps are shown for regions of activity associated with each contrast. MR signal images were obtained by group analysis ($p < 0.05$ corrected).

gions for each task in the Talairach and Tournoux space (Talairach and Tournoux, 1988).

The areas shown in Fig. 2 referred to the activated brain regions compared with baseline in OTH, PHO and FIG. It overlays areas with significant signal changes ($p < 0.05$, corrected) on the brain surface images provided in SPM99 with the method of group analysis. In A, B and C, the left inferior frontal gyrus, right precuneus and right middle frontal gyrus were commonly activated. These activation areas confirmed the results of previous studies in that the process related to the activity of working memory was involved with the frontal and the parietal cortices (Petrides et al., 1993a, b; Swartz et al., 1994).

The regions where OTH provided more activation than PHO were shown in Fig. 3A. Extensive MR signals were presented in the right inferior frontal gyrus (BA 45). The left inferior frontal activation, the superior parietal lobe (BA 7) and the right middle frontal gyrus were also activated. In particular, the inferior frontal gyrus and superior parietal lobe showed higher signals than any other regions in OTH.

The regions where PHO yielded higher MR signals compared to OTH were indicated in Fig. 3B. PHO was associated with a predominantly left-late-

ralized network of brain areas, including the frontal, the temporal and the parietal lobe. The frontal activation was evident in both the left and right precentral gyrus (BA 6). The parietal activation was maximal in the supramarginal gyrus (BA 40). The left temporal activation was distinctly found in the middle temporal gyrus (BA 39).

Little activation was observed in the subtraction of FIG from OTH, except for the inferior frontal gyrus (Fig. 3C). No areas except for the occipital gyrus were found to be significantly activated in the subtraction OTH from FIG (Fig. 3D).

Fig. 4 is a variance map that provided individual differences and the color bar denoted the number of subjects. In A, broadly activated areas were displayed in almost every subject in the frontal and parietal lobe. Clear differences of activation pattern between OTH and PHO appeared in A and B with the identical z coordinates. C and D depicted the comparison between OTH and FIG. The inferior frontal gyrus was activated in almost all subjects in OTH, while specific activations in FIG were scarcely noticeable.

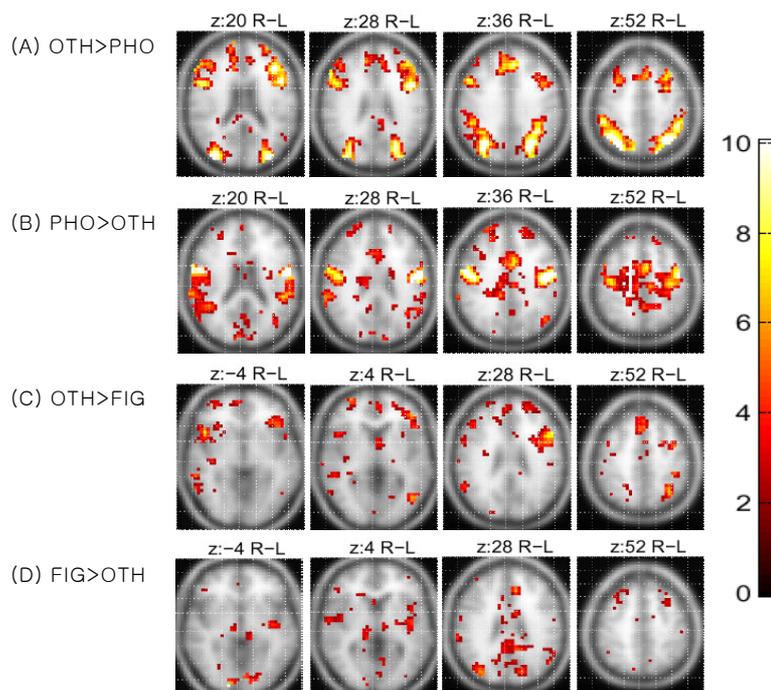


Fig. 4. Individual-difference map presents several regions meeting the criteria of subject-wise significance ($p < 0.01$ uncorrected). Color scale bar denotes the number of subjects.

DISCUSSION

As stated earlier, the question should be asked as to what are the characteristics of orthography from the point of view of processing verbal or visuospatial information. The current study provided interesting results regarding this question. First of all, when OTH, PHO and FIG were compared with BASE, we observed broad activation in the frontal and parietal cortices, regardless of stimulus and task. These areas have previously been considered to be related to working memory tasks (Cohen et al., 1994; Henson et al., 2000). Considering that our tasks were based on a one-back memory task, these activated areas seem to be related to working memory.

OTH provided more activated areas in the superior parietal lobe than PHO. Many functional neuroimaging experiments concerning the parietal lobe suggested that handling spatial information, such as mental rotation or variation in spatial attention, caused activation in the parietal lobe (Jonides et al., 1993, 1997; Carpenter et al., 1999). As regards the mechanism used for OTH, the subjects had to judge if the ending consonant of the current word was located in the same position as the last one. This process must have obliged the participants to process spatial information. According to this interpretation, the activation in the superior parietal lobe must have occurred due to the process of spatial information. Consequently, we suppose that manipulating orthographic information led to the use of almost identical neural substrates as when processing visuospatial information such as figures.

Another activated area in OTH is the inferior frontal gyrus. This region is known to be in charge of the classical language process and of verbal working memory. The widely known role of the inferior frontal gyrus is processing syntax or semantics in sentence comprehension (Dapretto et al., 1999). However, the precise role of this area in language-related behaviors remains controversial (Mohr et al., 1978; Goodglass, 1993; Zatorre et al., 1996). One of the previous studies done by Leigh and his colleagues questioned the role of the inferior frontal gyrus (Leigh et al., 2000). Their study, in which subjects performed a three-back working memory task with letters versus spatial locations, revealed more

activation in the inferior frontal gyrus for the spatial task than for the letter task. In our study, the inferior frontal gyrus demonstrated extensive activation even when FIG was subtracted from OTH. Given this uncertainty as to the exact role of the inferior frontal gyrus, we attempted to establish a hypothesis explaining the relationship between the orthographic process and the activation in the inferior frontal gyrus. From the model of the reading process by Caplan (1998), a visually presented word is first perceived at the level of 'abstract letter identities (ALI)'. ALI is the representation of letters in a form that is independent of size, font and other aspects of words. In accordance with ALI, we propose that orthographic knowledge is involved with abstract letter categories, which are distinct from the visual properties of the input. Consequently, the additional activation in the inferior frontal gyrus may well be due to processes involved in retaining or comparing the Korean equivalent of ALIs. When we perform tasks of both OTH and PHO, we go through the process of managing ALI, since reading automatically takes place whenever literal stimuli are offered. However, paying particular attention to the location of a letter (orthography) seems to be more involved with handling ALI than with simply rehearsing verbal information (phonology), because orthography is much more concerned with visual information than phonology. Further study is necessary in order to investigate the precise role of the inferior frontal gyrus with regard to the handling of orthographic information.

In this study, one interesting observation, obtained from the contrast between OTH and PHO, was that the activated cortical areas in charge of visuospatial (OTH) and verbal (PHO) working memory were distinct from each other. As we mentioned above, while the precentral, middle temporal and supramarginal gyrus were activated in PHO, the bilateral inferior frontal gyrus and superior parietal gyrus produced higher MR signals in OTH. The precentral gyrus seems to be activated owing to subvocal articulation, because its function has been known to be involved in motor aspects of speech planning and execution, even though no overt speech was performed during this experiment (Lee and Lee, 1997). The observed activation in the temporal gyrus indicates the use of inner speech. According to

MacSweeney and his colleagues, the activation of auditory areas during silent speech involved similar brain regions of the auditory cortex as when listening to overt speech (MacSweeney et al., 2000). The higher MR signals observed in the supramarginal gyrus may result from the involvement of verbal information management, such as short-term phonological storage. In view of the results so far discussed, we suppose that the process of orthography and phonology is recruited in discriminative brain areas.

Moreover, the fact that each activated area was related to distinctive tasks with identical stimuli, explains the notion of task-dependent working memory. In other words, not stimuli but processes play a critical role in yielding dissimilar neural circuits. If the stimuli had a significant effect on the diverse neural substrates, OTH and PHO would have activated almost the same cortical areas regardless of the task. In this study, we obtained almost identical results for OTH and FIG, regardless of stimulus type. This leads us to the question of the two currently competing theories, 'domain-specific' and 'process-specific.' Domain-specific theory supposes that different regions within the frontal cortex process different types of information (Goldman-Rakic, 1998). The alternative, process-specific theory, assumes that the functional difference between some areas of the cortex is located not in the type of stimulus being maintained but in the type of processes operating on that stimulus (Petrides, 1994). Inasmuch as our study touches upon these two approaches, the current study may be seen to support the point of view of the process-specific theory.

CONCLUSION

Our findings demonstrate that handling orthographic information uses similar processes to those used for dealing with visuospatial information. Orthography, discriminated from phonology and figures, activated principally the inferior frontal gyrus. In addition, this study provides evidence supporting the theory that different neural substrates are employed depending on the requirement of the task at hand, regardless of the identity of the to-be-maintained stimulus.

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