# Dissociation of Working Memory Processing Associated with Native and Second Languages: PET Investigation

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Verbal working memory plays a significant role in language comprehension and problem-solving. The prefrontal cortex has been suggested as a critical area in working memory. Given that domain-specific dissociations of working memory may exist within the prefrontal cortex, it is possible that there may also be further functional divisions within the verbal working memory processing. While differences in the areas of the brain engaged in native and second languages have been demonstrated, little is known about the dissociation of verbal working memory associated with native and second languages. We have used H<sub>2</sub><sup>15</sup>O positron emission tomography in 14 normal subjects in order to identify the neural correlates selectively involved in working memory of native (Korean) and second (English) languages. All subjects were highly proficient in the native language but poorly proficient in the second language. Cognitive tasks were a two-back task for three kinds of visually presented objects: simple pictures, English words, and Korean words. The anterior portion of the right dorsolateral prefrontal cortex and the left superior temporal gyrus were activated in working memory for the native language, whereas the posterior portion of the right dorsolateral prefrontal cortex and the left inferior temporal gyrus were activated in working memory for the second language. The results suggest that the right dorsolateral prefrontal cortex and left temporal lobe may be organized into two discrete, language-related functional systems. Internal phonological processing seems to play a predominant role in working memory processing for the native language with a high proficiency, whereas visual higher order control does so for the second language with a low proficiency. © 2002 Elsevier Science (USA)

# **INTRODUCTION**

Working memory (WM) refers to the type of memory that is active and relevant only for a brief period, usually on the scale of seconds. A brain system for WM provides temporary storage and manipulation of the information essential to a wide range of cognitive operations, including linguistic processing. It has been proposed that WM includes the following three components: the central executive, which controls attention and information flow; the visuospatial sketch pad, which sets up and maintains visual images; and the phonological loop, which stores and rehearses verbal information (Baddeley, 1992).

A number of neuropsychological and neuroimaging studies have been performed in order to identify the neural correlates of WM. Several lines of evidence have suggested that the prefrontal cortex, particularly its dorsolateral aspect, is involved critically in WM, though there has been considerable variability across such studies in the areas activated during WM processing. Experimental studies in the monkey have demonstrated that neurons in the dorsolateral prefrontal cortex remain active during delayed periods in tasks demanding active maintenance of an internal representation of a target stimulus (Goldman-Rakic, 1987). The activation of the dorsolateral prefrontal cortex has been found in response to various types of stimuli across functional imaging studies for WM in humans, i.e., dots (McCarthy et al., 1994; Smith et al., 1995; Owen et al., 1996), digits (Petrides et al., 1993a; Smith et al., 1995), faces (Haxby et al., 1995; Courtney et al., 1998), letters (Cohen et al., 1994; Braver et al., 1997), and words (Fiez et al., 1996; Clark et al., 2000). Further, such activation has been found to be common in different task types of WM: spatial (McCarthy et al., 1994; Smith et al., 1995; Owen et al., 1996), object (Smith et al., 1995; Postle et al., 2000), and verbal (Petrides et al., 1993b; Cohen et al., 1994; Fiez et al., 1996). It can be considered, therefore, that there may be multiple domains of WM in the dorsolateral prefrontal cortex that contribute to differential informationprocessing systems. Although such systems share an activation of the dorsolateral prefrontal cortex, it has been suggested that domain-specific dissociations of WM may exist within the prefrontal cortex (Smith et

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*al.,* 1996; Courtney *et al.,* 1996; McCarthy *et al.,* 1996; Belger *et al.,* 1998).

The present study has focused on verbal WM, which plays a significant role in language comprehension and problem-solving. Previous imaging studies have indicated that brain activations accompanying verbal WM are found not only in the dorsolateral prefrontal cortex but also in other regions such as the inferior frontal area, supplementary motor area, premotor area, and parietal cortices (Paulesu et al., 1993; Petrides et al., 1993b: Andreasen et al., 1995: Fiez et al., 1996: Schumacher et al., 1996; Smith et al., 1996; Jonides et al., 1997; Clark et al., 2000). The dorsolateral prefrontal cortex has been interpreted as reflecting the central executive, whereas most other regions have been assumed to serve as the phonological loop for verbal material. The phonological loop, composed of an articulatory store and a subvocal rehearsal system, is necessary for the acquisition and utilization of both native and secondary language vocabulary.

The ability to acquire and use language is fundamental to human life. It is well known that it is difficult to attain ability in a second language learned after puberty equal to the level of the native language. Early lesion studies have suggested that the brain areas engaged in processing a second language are different from those engaged in the native language (Albert and Obler, 1978). These differences have been demonstrated through recent neuroimaging studies for bilingual subjects (Perani et al., 1996, 1998; Weber-Fox and Neille, 1996; Yetkin et al., 1996; Kim et al., 1997; Dehaene et al., 1997). For instance, listening to native language always activated a similar set of areas along the left superior temporal sulcus, whereas listening to a second language activated a highly variable network of left and right temporal and frontal areas (Dehaene et al., 1997).

Based on prior findings of dissociation of WM processing, further functional subdivisions in verbal WM likely exist. It is unclear, however, if differences in language processing would extend to a functional dissociation of verbal WM associated with native and second languages. In fact, differential features in native and second language processing are closely related to the age of acquisition and/or the level of proficiency in the languages (Kim et al., 1997; Perani et al., 1998). The difference in the proficiency in the languages may in turn be related to differences in performance of some verbal tasks using the languages, which can be considered in the context of the central executive of WM. We hypothesized, therefore, that dissociation of verbal WM processing associated with native and second languages would be presented within the dorsolateral prefrontal cortex engaged in the central executive as well as in areas related to the subsidiary slave systems of WM such as the visuospatial sketch pad and the phonological loop.

It can be testified by examining whether the prefrontal activation pattern of verbal WM, when a second language with a low proficiency is used as verbal material, is identical to that seen when the native language with a high proficiency is used. To address this issue, the present study was designed to compare the regional cerebral blood flow (rCBF) associated with processing WM for different types of materials by using  $H_{2}^{15}O$  positron emission tomography (PET) in normal subjects. The tasks consisted of three sets of the n-back WM conditions requiring subjects to remember the identity and sequence of contrasted types of stimulisimple pictures, English words, and Korean wordsand a control condition of plain focused attention. The goal was to identify the neural correlates involved in verbal WM of native and second language and to elucidate the relationship of each verbal WM to nonverbal WM.

#### **METHODS**

## **Subjects**

We studied 14 healthy right-handed Koreans (7 men and 7 women) who were recruited from the community through newspaper advertisements. Exclusion criteria were any past or present history of neurological, general medical, or psychiatric illnesses, which was screened on an interview session including the Structured Clinical Interview for DSM IV (First et al., 1995). Our study was carried out under guidelines for the use of human subjects established by the institutional review board at Seoul National University Hospital. After complete description of the study to the subjects, written informed consent was obtained. The mean age of the subjects was 24.8 (SD 5.1) years and their mean educational achievement was 15.0 (SD 1.7) years. A mean IQ estimated by the Korean version of the Wechsler adult intelligence scale was 112.1 (SD 10.9).

All subjects had lived exclusively in Korea, were native speakers of Korean, and had learned English at school after the age of 12 years; therefore, that they could be expected to have a low proficiency in the second language. Language proficiency was assessed with a story-reading task, in which the subjects had to read both English and Korean stories. Each of the stories had a balanced quantity of contents that a complete bilingual for the two languages might spend similar times to read. In the preliminary test in order to verify the balance, four complete bilinguals who could speak both languages very fluently spent 119.8 s (SD 15.4) and 121.0 s (SD 11.2), respectively, reading the stories. As expected, our subjects showed significant differences in their reading abilities [189.2 s (SD 45.1) for the English story and 123.9 s (SD 22.5) for the Korean story; t = 2.9, P < 0.05], which would rate them as having a low proficiency in the second language.

# **Cognitive Tasks**

There were three experimental tasks and one control task. As shown in Fig. 1, the experimental tasks were several variants of a sequential object task with a two-back condition in which the subjects were required to continuously monitor a sequence of stimuli and to respond whenever the preindicated material that had been presented before one intervening stimulus was presented again. The experimental tasks required the subjects to keep in mind both the identity and the order of the presented objects and to continuously update the mental record with each subsequently presented stimulus. Thus, we considered them working memory tasks in that they entailed temporary storage and manipulation of information (Cohen *et al.*, 1994; Postle *et al.*, 2000).

Stimuli for the experimental tasks consisted of three kinds of visually presented objects: simple pictures, English words, and Korean words. The preindicated material was a circle for simple pictures and an animal name for English and Korean words. These objects required constant semantic judgment and were chosen to permit comparisons between verbal and nonverbal processing for WM and between native and secondary language in verbal WM processing. The control task was a focused attention task in which the subjects viewed a list of simple pictures and responded whenever a circle was presented. All subjects were given successive study-and-test trials for learning the paradigm in a training session 1 h prior to the PET experiment.

All tasks were designed so that the stimulation and the output were as similar as possible across tasks during PET data acquisition; stimuli were digitally scanned and visually projected on an LCD monitor 40 cm above the nose of the subject for 500 ms at 1.5-s intervals. For the task referred to as WM for simple pictures and for the control task, the stimuli consisted of circles (7 cm diameter), equilateral quadrangles (7 cm long), and equilateral triangles (10 cm long). For the task referred to as WM for English words and for Korean words, the stimuli consisted of English concrete nouns with one to three syllables (1.8 cm high imesmaximum 6 cm long) or Korean concrete nouns with two syllables (1.8 cm high  $\times$  4 cm long). All words were presented only one time during both language tasks and consisted of usual, familiar ones (e.g., animalspig, fox, deer, lion, rabbit, mouse, etc; nonanimalstree, chair, paper, clock, train, school, etc.). Word contents were different between the English and the Korean lists in order to control the length of words, because the same word contents in the two languages corresponded to different syllables. All stimuli were presented as white on a black background.

All stimuli consisted of 80 items, including 28 targets. Frequency and distribution of the targets were matched across all tasks. The subjects' response was to click a left mouse button with their right index finger only when the target stimulus was detected. Behavioral performance was monitored in order to ascertain how well the subjects paid attention to the tasks and to examine the differences among the task conditions. All responses were automatically transferred to a computer file, which was then utilized for calculation of the hit rate. Every task started 30 s prior to injection of the tracer and continued for a total duration of 160 s. To ensure that blood flow would be measured during an intense phase of the cognitive effort, the protocol was designed so that the proportion of targets was relatively high (71.4%) during the 100-s data acquisition time (62.5% of the total task-performing time).

## **Imaging Data Acquisition and Processing**

All subjects underwent four consecutive PET scans for three experimental conditions and one control, the order of which was randomly distributed among the subjects. Scans were obtained using an ECAT EXACT 47 scanner (Siemens-CTI, Knoxville, TN), which had an intrinsic resolution of 5.2 mm full width at halfmaximum (FWHM) and simultaneously imaged 47 contiguous transverse planes with a thickness of 3.4 mm for a longitudinal field of view of 16.2 cm. Before the first injection of the tracer, a 7-min transmission scan was performed for attenuation correction using triple <sup>68</sup>Ge rod sources. Emission scans during the performance of cognitive tasks started after an intravenous bolus injection of 40-50 mCi of H<sub>2</sub><sup>15</sup>O in 5-7 ml saline and continued for 100 s in 20 5-s frames. Acquired data were reconstructed in a 128 imes 128 imes 47 matrix with a pixel size of  $2.1 \times 2.1 \times 3.4$  mm by means of a filtered back-projection algorithm employing a Shepp–Logan filter with a cut-off frequency of 0.3 cycles/pixel. Based on time-activity curves, only 12 frames reflecting the 60 s after arrival at a peak were summed. Injections were repeated at intervals of about 15 min.

Spatial preprocessing and statistical analyses were performed using SPM 99 (Institute of Neurology, University College of London, UK) implemented in Matlab (Mathworks, Inc., Sherborn, MA) (Friston et al., 1994, 1995b). All reconstructed images were realigned and transformed into a standard stereotactic anatomical space to remove the intersubject anatomical variability (Talairach and Tournoux, 1988; Friston et al., 1995a). Affine transformation was performed in order to determine the 12 optimal parameters to register the brain on a standard PET template. Subtle differences between the transformed image and the template were removed by a nonlinear registration method using the weighted sum of the predefined smooth basis functions used in discrete cosine transformation. Spatially normalized images were smoothed by convolution with an

## TABLE 1

receivated regions during morning mentors for simple recurse	Activated Regions	during	Working	Memory	7 Tasks	for	Simple	Pictures
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Region (Brodmann area)		Coordinates	Maximal Z	Voxel number	
Right middorsolateral frontal, caudal (8)	38	20	50	5.09	837
Right middorsolateral frontal, deep (8)	28	8	28	3.37	173
Left middorsolateral frontal, deep (8)	-20	20	28	2.77	61
Left frontal pole (10)	-28	62	-6	3.36	383
Right inferior parietal (40)	58	-36	44	3.73	173
Left superior parietal (7)	-52	-64	46	3.01	68
Left lateral occipital (19)	-46	-78	8	3.18	87

isotropic Gaussian kernel with 16 mm FWHM in order to increase the signal-to-noise ratio and accommodate the subtle variations in anatomical structures.

#### **Statistical Analysis**

Within-subject subtraction of relevant injections was performed and followed by across-subject averaging of the subtraction images. For each voxel in stereotactic space, the analysis of covariance generated a conditionspecific adjusted mean rCBF value and an associated adjusted error variance. The analysis of covariance permitted comparison of the means across conditions on a voxel-by-voxel basis using the *t* statistics of the rCBF changes. For easy interpretation, resulting *t* values were then transformed to *Z* scores in the standard Gaussian distribution.

Subtractions were chosen to make comparisons across conditions. The statistical analyses to identify the specific brain regions related to each material for WM consisted of three subtractions; those to subtract the condition of focused attention to simple pictures from WM conditions for simple pictures, English words, and Korean words. Only areas showing increased rCBF in the WM tasks, compared with the control task, were considered activated regions. The first set of comparisons was carried out to establish the areas activated during WM for simple pictures. The second and third comparisons carried out were intended to address a question of how differently native and second languages affect WM. Moreover, in order to identify activations common to WM conditions between simple pictures and verbal materials, we applied a conjunction analysis (Price and Friston, 1997) for the first comparison with the second one and for the first comparison with the third one.

In addition, further subtractions were made to identify language-related areas where the WM components were relatively less involved; subtractions of WM for simple pictures from WM for English words and for Korean words and conjunction analysis for the two subtractions were done to search the regions common to both on the one hand, and a direct comparison between the two language tasks was done to search the relatively specific brain regions related to the semantic processing of the two languages on the other.

Data are reported in the tables by showing the anatomical location of the cluster with significant changes of rCBF; the *x*, *y*, and *z* Talairach coordinates' and the *Z* value of the voxel with the highest significance in the cluster; and the voxel number (*k*) of the cluster. The threshold of significance for the clusters was defined as an uncorrected *P* level of 0.005. Although most areas reported as "significant" in the tables exceeded the stricter threshold, 0.001, we applied this less harsh one in order to inspect a general trend. Instead, in order to reduce the accidental findings due to a Type I error by multiple comparisons, we chose only the cluster containing at least 50 contiguous voxels with the predefined significant *P* values.

### RESULTS

#### **Behavioral Data**

The subjects performed well all four of the experimental and control tasks. For WM for the simple pictures, they made on average 27.8 hits and 0.4 misses, and the mean correct response rate based on all 80 items was 99.3% (SD 1.0). For WM for English words, they made on average 26.8 hits and 0.9 misses, and the mean correct response rate was 97.4% (SD 5.0). For WM for Korean words, they made on average 27.5 hits and 0.4 misses, and the mean correct response rate was 98.9% (SD 1.4). Finally, for the control task, they made on average 27.9 hits and 0.1 misses, and the mean correct response rate was 99.8% (SD 0.5). An analysis of variance indicated that there was no significant difference in the correct response rates (F = 2.03; df = 3, 52; P = 0.12).

#### **Activations during WM for Simple Pictures**

The results of subtracting the control condition from WM for simple pictures are presented in Table 1. Activated areas during WM for simple pictures were distributed mainly in the frontal lobe. As seen in Fig. 2A, the most marked activation occurred in the dorsolat-



FIG. 1. Examples showing the course of events and the target in working memory tasks. The stimuli consisted of three sets of visually presented objects, such as simple pictures (circles, equilateral quadrangles, and equilateral triangles), English concrete nouns with one to three syllables, and Korean concrete nouns with two syllables. The meanings of the Korean words in the sequence correspond to "hippopotamus," "rabbit," "train," and "mirror," in order. Subjects were requested to respond whenever the preindicated material that had been presented two steps earlier was presented again. The preindicated material was a circle for simple pictures and an animal name for English and Korean words. Frequency and distribution of the targets were matched across all tasks.

eral prefrontal cortex: the caudal portion of the right middle frontal gyrus [Talairach coordinates +38/+20/+50; Brodmann area (BA) 8]. Moreover, both sides of the middle frontal gyri were symmetrically activated in the deep portions, the locations being +28/+8/+28 in the right and -20/+20/+28 in the left. A large activation also occurred in the left frontal pole (-28/+62/-6). Beyond the frontal lobe, the right inferior parietal, left superior parietal, and left lateral occipital cortices were activated.

# Activations during WM for English Words

Significantly activated areas identified in the subtraction of WM for English words minus the control condition are shown in Table 2. Compared with WM for simple pictures, it was striking that there were similar activations in the frontal lobe. As illustrated in Figs. 2A and 2B, the right dorsolateral frontal location (+30/+16/+58) and the left frontal pole location (-30/+70/-4) were homologous in position to the right middle frontal activation (+38/+20/+50) and the left frontal pole location (-28/+62/-6) during WM for simple pictures. As shown in the lower part of Table 2, overlap of these regions in the two WM conditions was confirmed in the conjunction analysis.

While activation in the deep portion of the prefrontal cortex was not found, an additional activation was found in the right frontal pole (+34/+52/+10). Contrary to WM for simple pictures, the posterior part of the brain was more activated than the anterior part. The biggest activation occurred in the posterior portion of the left inferior temporal gyrus (-46/-62/-20). Additional activations were observed in the right inferior temporal gyrus, the right motor area, the right fusiform gyrus, the left lateral occipital cortex, and the left cerebellum.

## **Activations during WM for Korean Words**

Significantly activated areas found in the subtraction of WM for Korean words minus the control condition are shown in Table 3. The general pattern of activation in WM for Korean words was different from that seen in WM for English words. Compared with two frontal areas—the right dorsolateral prefrontal cortex and the left frontal pole—identified to be commonly engaged in WM for simple pictures and English words, activation in the right dorsolateral

Region (Brodmann area)		Coordinates	Maximal Z	Voxel number	
Right middorsolateral frontal, caudal (8)	30 16 58			3.17	113
Right frontal pole (10)	34	52	10	2.91	129
Left frontal pole (10)	-30	70	-4	3.29	181
Right motor (4)	50	-2	62	4.06	254
Right inferior temporal, posterior (37)	55	-55	-15	3.00	154
Left inferior temporal, posterior (37)	-46	-62	-20	3.13	497
Left fusiform gyrus (18)	-22	-92	-12	2.70	51
Left lateral occipital (19)	-44	-78	6	3.25	168
Left cerebellum	-10	-80	-30	2.88	53
Con	njunction with we	orking memory f	or simple picture	25	
Right middorsolateral frontal, caudal (8)	46	12	60	3.61	78
Right inferior frontal (47)	32	46	8	3.32	293
Left frontal pole (10)	-32	66	12	3.37	355
Right fusiform gyrus (18)	34	-78	-20	3.50	324
Left fusiform gyrus (18)	-44	-78	-28	3.45	194

 TABLE 2

 Activated Regions during Working Memory Tasks for English Words



**FIG. 2.** Statistical parametric maps displaying increased regional cerebral blood flow during three sets of working memory conditions: simple pictures (A), English words (B), and Korean words (C). Significantly activated areas (P < 0.005, k > 50) in each condition are shown on 3D-rendered MR images. Note that working memory tasks for simple pictures and English words activate homologous positions in the posterosuperior portion (Brodmann area 8) of the right dorsolateral prefrontal cortex and the left frontal pole, whereas working memory tasks for Korean words activates the anteroinferior portion (Brodmann area 46) of right dorsolateral prefrontal cortex. Beyond the frontal lobe, the posterior portion of the left inferior temporal gyrus is engaged in English words, whereas the posterior portion of the left superior temporal gyrus is engaged in English words, whereas the posterior portion of the left superior temporal gyrus is engaged in English words.

prefrontal cortex occurred in a different location (the middle and lower part of the middle frontal gyrus), which can be assigned as BA 46 (+30/+42/+16), and activation in the left frontal pole was not identified

(see Fig. 2C). As shown in the lower part of Table 3, activation in the right dorsolateral prefrontal cortex was also identified in the conjunction analysis of WM for Korean words with WM for simple pictures.

Activated Regions during Working Memory Tasks for Korean Words									
Region (Brodmann area)		Coordinates	Maximal Z	Voxel number					
Right middorsolateral frontal, middle (46)	30	42	16	3.26	80				
Left supplementary motor (6)	-6	4	62	2.96	142				
Left premotor area (6)	-46	0	52	2.83	98				
Left superior temporal, posterior (22)	-60	-38	12	2.96	51				
Left fusiform gyrus (19)	-30	-84	-6	3.57	425				
Right cerebellum	36	-66	-30	3.04	69				
Con	junction with wol	rking memory fo	r simple picture	5					
Right middorsolateral frontal, deep (46)	26	40	20	3.53	107				
Right cerebellum	34	-72	-30	3.01	65				

**TABLE 3** 



**FIG. 3.** Statistical parametric maps showing relatively specific brain regions related to the semantic processing of English and Korean words. Relative activation was obtained in the subtraction of working memory task for Korean words from working memory task for English words. Clusters with a positive significance were referred to as the areas specific to English words (A), whereas clusters with a negative significance were referred to as the areas specific to Korean words (B). Significantly activated areas (P < 0.005, k > 50) are displayed on three orthogonal sections of the average T1-weighted MR image. Cross hairs indicate that activation of the semantic processing area in the posterior visual region is relatively specific to English words (A), whereas internal phonological process activating the primary auditory cortex occurs specifically to Korean words (B).

It was also characteristic that the activated areas included motor-related cortices such as the left supplementary motor area (SMA) and the left premotor area. In contrast with activation of the left side of the secondary visual cortex, i.e., the posterior portion of the left inferior temporal gyrus, during WM for English words, the activation within the temporal lobe during WM for Korean words occurred in the left side of the secondary auditory cortex, i.e., the posterior portion of the secondary auditory cortex, i.e., the posterior portion of the superior temporal gyrus (-60/-38/+12). Additionally, as seen in WM for English words, activations in the fusiform gyrus and the cerebellum were also observed in WM for Korean words, but

there were differences in the pattern of hemispheric dominance between the two conditions.

# Language-Related Areas

Language-related areas were identified in the subtractions between WM tasks and are listed in Table 4. Areas related to semantic processing were defined by increased regional CBF during WM tasks for words, compared with WM for simple pictures, and noted mainly in the posterior portion of the brain. Characteristically, the left fusiform gyrus was very strongly activated during semantic processing of both English and Korean words.

Areas with Increased Regional CBF during Working Memory Tasks for Words, Compared with Working Memory for Simple Pictures

**TABLE 4** 

Region (Brodmann area)	Coordinates			Maximal Z	Voxel number
English words					
Right fusiform gyrus (18)	32	-90	-4	3.68	310
Right fusiform gyrus (18)	58	-68	-16	3.07	224
Left fusiform gyrus (18)	-20	-94	-8	4.07	1171
Left fusiform gyrus (19)	-44	-72	-18	3.31	174
Korean words					
Left fusiform gyrus (18)	-28	-86	-6	4.39	1580
Right calcarine cortex (17)	22	-92	-10	3.13	58
Conjunction: English words with Korean words					
Left fusiform gyrus (18)	-12	-98	-2	4.40	1351

## TABLE 5

Region (Brodmann area)		Coordinates		Maximal Z	Voxel number
English words					
Right middle temporal, posterior (37)	62	-54	-10	3.38	103
Right lateral occipital (18)	34	-80	2	2.88	71
Right cerebellum	34	-38	-34	3.72	59
Korean words					
Right superior frontal (9)	12	52	44	3.21	55
Right orbitofrontal (11)	30	24	-24	3.12	165
Left posterior cingulate (31)	-2	-48	34	3.79	538
Right Heschl's gyrus (41)	36	-26	16	3.10	188
Left middle temporal, middle (21)	-44	-34	-14	3.33	218
Right inferior temporal, middle (20)	20	-10	-36	3.22	115
Left putamen	-26	8	-4	3.06	99

Relatively Specific Areas for the Semantic Processing of English and Korean Words, Which Were Obtained by a Direct Comparison between Working Memory Tasks for the Two Languages

As seen in Table 5, differences between English and Korean words were more authentic in the direct comparison between them. Similar to the activation pattern observed in the analyses for the WM components as described above, both languages revealed quite different activation patterns in the temporal lobe. Figure 3 shows that English words were related to the visual association cortex such as the posterior portion of the right middle temporal gyrus (62/-54/-10), whereas Korean words were associated with the right primary auditory cortex (36/-26/16). In addition, the regions relatively specific to English words were limited to the posterior visual regions, whereas the regions specific to Korean words were observed in multiple areas, including the right superior frontal and orbitofrontal cortices, the left posterior cingulate, the middle portions of the right inferior and left middle temporal gyri, and the left putamen.

## DISCUSSION

## **Dissociation of the Prefrontal Activations**

A central question addressed in the current study was whether there would be any differences in the activation pattern within the dorsolateral prefrontal cortex when native (Korean) and second (English) languages were used as the materials of WM. To reduce the involvement of any confounds, factors other than those directly related to the type of stimulus material were controlled and the monitoring requirements of the two tasks were carefully matched. The results demonstrate that WM tasks for native and second languages activate different regions within the right dorsolateral prefrontal cortex. The right predominance of the dorsolateral prefrontal activation is consistent with the findings of previous WM studies that activation in the dorsolateral prefrontal cortex is stronger on the right than on the left (Petrides et al., 1993a; McCarthy *et al.*, 1994; Fiez *et al.*, 1996). The dissociation within the right dorsolateral prefrontal cortex is a new finding proving our hypothesis of further subdivisions of verbal WM. It is clear from some pictures in Fig. 2 that the performance of the WM task for English words results in increased activity in the posterior portion of the dorsolateral prefrontal region (BA 8), whereas the performance of the WM task for Korean words leads to increased activity in the anterior portion of the dorsolateral prefrontal region (BA 46). This observed difference does not seem to be confounded by a difference in the degree of difficulty or effort required to perform the tasks, since there is no significant difference in the behavioral performance.

The focus of activation within BA 8 in WM for English words lies in a position homologous to the area activated in nonverbal WM for simple pictures. This area is close to the frontal eye field, which is linked anatomically and physiologically with the visual and oculomotor systems (Bruce and Goldberg, 1985; Fox et al., 1985; Shanton et al., 1989). In the monkey, lesions of BA 8 result in the severe impairment of the performance of conditional tasks in which the appropriate visual stimuli must be chosen depending on the particular visual cues presented (Halsband and Passingham, 1982; Petrides, 1985), suggesting that this area plays an important role in the selection of specific visual stimuli. In neurophysiological studies, BA 8 encompasses various other physiologically defined regions that exert higher order control over visual behavior (Schall, 1991). Therefore, the failure on visual conditional tasks following lesions of BA 8 in the monkey may reflect the loss of this visual higher order control (Petrides et al., 1993a). Likewise, activation in BA 8 of the right hemisphere during the performance of WM task for simple pictures in the current study is probably related to visual nonverbal higher order control for WM or to a frontal control site for the visuospatial

sketch pad of WM. It is important to note that, in the current study, a similar area within BA 8 was activated during the performance of WM for English words, but not during the performance of WM for Korean words. This can be interpreted in terms of language proficiency; that is, the performance of tasks in which subjects must use a second language with low proficiency seems to readily rely on encoding and retrieval of visual nonverbal forms, just like the processing in shape judgment, and this aspect of visual processing may have placed greater demands on BA 8.

In contrast to WM for English words, WM for Korean words induced a significant increase of rCBF in BA 46 of the right hemisphere. The focus of this increase was located in the lower part of the middle frontal gyrus, just above the inferior frontal sulcus. This region participates in retrieval by virtue of its role in the online monitoring, within WM, of the output from long-term memory (Petrides *et al.*, 1995). Such online processing affects the performance of WM for familiar stimuli. Thus, it is rational that WM for Korean words as a native language activates BA 46, which is consonant with the activation of BA 46 in prior verbal WM studies of English native speakers (Petrides *et al.*, 1993b; Fiez *et al.*, 1996)

Another impressive prefrontal dissociation in the current study is identified in the left frontal pole where the activation pattern is similar to that seen in the right dorsolateral prefrontal cortex; WM tasks for English words and simple pictures activated the identical area, while WM task for Korean words did not activate that area. Although activation in this area is not observed frequently in processing WM, unlike the dorsolateral area, it has been reported in several other WM studies. For example, Petrides et al. (1993a) found a prominent increase in rCBF of the frontal pole yielded in externally ordered tasks in which subjects had to monitor carefully the auditory input generated by the experiment. Considering that the polar region was strongly connected with auditory cortical areas of the superior temporal cortex (Petrides and Pandya, 1984; Barbas and Mesulam, 1985), they suggested that it might be involved in mnemonic processing involving auditory input. Activation of the left frontal pole in the current visual WM study, however, is not likely to be related to such auditory mnemonic processing, because it was found only in the WM tasks for simple pictures and English words and not in the WM task for Korean words, which was possibly more likely to include internal phonological processing. Another suggestion was made by Salmon et al. (1996), who also found activation of the frontal pole and interpreted it as being related to the specific storage function of the central executive or to the coordination function between short-term and long-term memory. Similar to the dissociation in the right dorsolateral activation, that observed in the left frontal pole needs to be considered to reflect a strategic difference in the central executive of WM.

# **Strategic Difference for Performing WM**

In fact, most WM studies for letters, digits, words, shapes, and faces have been reported to produce an activation of the dorsolateral prefrontal cortex, so that the area has been related to the core component of WM, the central executive. The central executive is theoretically approximate to a supervisory attentional control system that is responsible for strategy selection and for coordination of the various processes (Baddeley, 1986). The dorsolateral prefrontal cortex has been activated during the performance of verbal and nonverbal random generation tasks, which are generally considered to place significant demands on the central executive (Petrides et al., 1993a,b). This area has also been observed to be activated bilaterally under a dual-task condition requiring the allocation and coordination of attentional resources that are equivalent to the central executive of WM (D'Esposito et al., 1995).

Although a number of neuroimaging studies have attempted to identify the neural substrates of visual WM in humans and have consistently reported that the prefrontal cortex is critically devoted to the monitoring of information within WM, there have been controversies regarding the existence of domain specificity within the prefrontal cortex. In the case of spatial versus object WM, for example, some groups have reported impressive dissociations of anatomical regions within the prefrontal cortex between them (Smith *et al.*, 1996; Courtney *et al.*, 1996; McCarthy *et al.*, 1996; Belger *et al.*, 1998), whereas others have failed to find domain-specific differences in the prefrontal cortex (D'Esposito *et al.*, 1998; Owen *et al.*, 1998; Postle *et al.*, 2000).

Such findings of previous WM studies are, in part, dependent on the activation paradigm applied. Increased activity in the dorsolateral areas has been observed during the performance of a delayed facematching task, but not during the performance of a delayed location-matching task (Courtney et al., 1996). Performing spatial WM tasks has been reported to predominantly activate the ventrolateral frontal cortex in one study (Jonides et al., 1993) and the middorsolateral frontal cortex in another study (McCarthy et al., 1994). As suggested by Owen et al. (1998), who observed similar patterns of frontal activation during visual spatial and nonspatial WM tasks that had been matched in terms of the difficulty of their monitoring requirements, activation areas may be variable, depending on the precise executive processes that were called on by the performed tasks. It was also demonstrated by another recent report (Stern et al., 2000) that executive processing rather than stimulus type

may be the critical factor in determining where activity would be increased within the prefrontal cortex.

The observed difference between native and second languages in the current study is likely to be related to a difference in the central executive that is attributed to the proficiency of the languages. In general, in order to achieve a high performance in some task using a language with a low proficiency equal to the performance of another task using a language with a high proficiency, a different strategy would need to be engaged in the processing. Based on our findings, visual WM performance of a native language with high proficiency predominantly uses silent reading or internal phonological processing, whereas that of a second language with low proficiency predominantly uses visual scanning.

These differences may be accounted for in terms of a distributed neural circuit, including the prefrontal cortex and other regions. As demonstrated in all neuroimaging studies, performing WM does not produce activations confined only to the prefrontal cortex, but involves multiple regions, including even the sensorymotor cortex. Some researchers have reported that domain-specific visual WM processing may not be mediated by the prefrontal cortex but by posterior regions associated with domain-specific sensory processing (Postle et al., 2000). Distinctions between functions such as spatial versus nonspatial WM may be a matter of the degree of participation of different regions in a widely distributed system rather than the discrete parcellation of different functions to different modules (Haxby et al., 2000). Along this line of reasoning, we can consider that distributed neural circuits are influenced differently by the verbal WM strategies determined by language proficiency.

Alternatively, these differences may reflect differential patterns of interaction between verbal WM and phonological representation. Although word processing and verbal WM have been investigated largely as separate domains, the two systems can be considered to have an interactive relationship in that word recognition includes feedback processes from the lexical to the phonemic level and, therefore, word processing is closely related to short-term memory (Martin et al., 1999). That is, they share temporary storage of multilevel linguistic representations and underlying processes that regulate activation of the linguistic representations (Martin, 2000). From this view, it is predicted that different patterns of linguistic representations would be connected to different features of the interactive WM processes.

Here it should be noted that interpretation is mainly dependent on results of a fixed-effect analysis by the conventional subtraction method despite focusing on interaction. The results in the current study could still be explicable by a combination of WM material and processing. In fact, to address a question such as "how different languages affect WM" and to disambiguate the effects of material and processing, a factorial design with an interaction analysis would be required. This problem seems to be a major limitation of our study, and more optimal design will be necessary to demonstrate patterns of interaction in the follow-up study.

# Language-Related Areas

We feel that the most critical difference in WM tasks for native and second languages in the current study seems to be the phonological representation. It is still unclear why there is a relative deficiency of internal phonological processing during the performance of the WM task for second language. A difference in the cortical representation between native and second languages in the current study eventually seems to be ascribed to a difference in the time of life at which language is acquired. All of our subjects learned the second language after puberty and have a low proficiency. There is difficulty in learning a new language after puberty, whereas it is easier before puberty (Johnson and Newport, 1989; Flege et al., 1995). Brain imaging studies have consistently suggested that the age of acquisition or proficiency level is critical in determining the different patterns of cortical responses between native and second languages (Kim et al., 1997; Perani et al., 1998). More specifically, while the lexicon seems to be acquired with greater ease, the phonological components seem relatively deficient when a second language is learned after puberty (Perani et al., 1998).

As shown in Table 3, significant increases in rCBF during the performance of the WM task for native language were detected in multiple areas beyond the prefrontal cortex, such as the left SMA, the left premotor area, the left superior temporal gyrus, the left fusiform gyrus, and the right cerebellum. Such findings are remarkably in contrast to those for a second language, in which the posterior portion of the left inferior temporal gyrus was the most prominent area beyond the prefrontal cortex with significantly increased rCBF. These multiple activation foci in native language are similar to those of other verbal WM studies. For example, Paulesu et al. (1993) reported that verbal WM induces bilateral activations in the SMA, Broca's area, the supramarginal gyrus, the superior temporal gyrus, the insula, and the cerebellum. Salmon et al. (1996) also reported similar activations in the left side of the premotor cortex, superior temporal gyrus, and supramarginal gyrus, as well as in both sides of the insula and sensory cortex. These reported areas seem to be involved in the phonological processing that verbal tasks include rather than in memory load itself.

In particular, the superior temporal gyrus, primarily acting on the auditory association area, has been observed to be activated in auditory tasks such as aurally presented word comprehension (Wise et al., 1991; Binder et al., 1997) and phonetic discrimination (Zatorre et al., 1992) and even in visual recognition tasks for verbal materials such as passive word presentation (Petersen et al., 1988; Paulesu et al., 1993). This seems to be possible because visually presented words are transformed into a phonological code and access an articulatory loop through the subvocal rehearsal system, even in the absence of direct auditory stimulation. On the other hand, activations of the SMA and premotor area can be related to motor aspects of speech planning and execution. Similar activation in the SMA has been found in other verbal memory studies (Paulesu et al., 1993; Petrides et al., 1993b; Fiez et al., 1996). It appears to be activated because memory tasks in the studies are performed through the generation of high-level internal motor representations. In addition, given that greater activation of the SMA is found in a verbal WM task than in a silent rehearsal task (Fiez et al., 1996), the degree of activation of the SMA may be affected by the memory load.

Paulesu *et al.* (1993) have suggested that multiple regions constitute the functional anatomy of the phonological loop and, more specifically, that the left supramarginal gyrus and Broca's area are the primary locations of the phonological store and articulatory rehearsal process, respectively. Although these two regions are not found in the current study, increases in rCBF in the superior temporal gyrus and motor-related areas still provide evidence of activation of the phonological loop in the performance of verbal WM tasks for native language. It is interesting that these areas of phonological processing are found only in native language and not in second language.

Instead, the most prominently activated region in WM for the second language was the posterior portion of the left inferior temporal gyrus. Contrary to the superior temporal gyrus, the inferior temporal gyrus contributes to the visual recognition of objects together with the middle temporal and occipitotemporal gyri (Kim *et al.*, 2000). In particular, the posterior portion of the left inferior temporal gyrus is engaged in semantic processing of visually presented words (Price *et al.*, 1994; Puce *et al.*, 1996; Vandenberghe *et al.*, 1996; Kiehl *et al.*, 1999; Kim *et al.*, 1999). This finding is very impressive in that it can be associated with its activation of BA 8 of the prefrontal cortex related to visual higher order control on WM.

This dissociation within the left temporal lobe provides further evidence that internal phonological processing and visual higher order control predominantly contribute to WM for native and second languages, respectively. Such dissociated cognitive processing in the performance of verbal WM tasks for the two languages was ascertained by the direct comparison between them; the specific regions activated in response to Korean words included the auditory region, such as Heschl's gyrus, while the specific regions to English words did not.

Although the phonological component has been mainly discussed, the observed differences might also stem from differences in other components such as semantic knowledge or fluency. Since all these factors eventually constitute the language proficiency, our findings of language-related differences might reflect a difference in the proficiency. Our findings are in contrast to a recent study for bilinguals (Chee et al., 2000), in which the semantic processing of Chinese characters more closely resembled that of English words than pictures. Indeed, direct comparison is difficult because obvious different conditions exist between the two studies. First, our subjects are not complete bilinguals; they have a low proficiency for the second language. Second, Korean words consist of a combination of phonemes with graphemic symbols like English words, so that they are linguistically different from Chinese characters that are based on the combination of meaningful morphemes with graphic units. Third, the task conditions are different between them. It has to be noted here that the overall differences between native and second language in the current study should be interpreted in the context of WM but not generalized to language processing, because WM remains a prevailing component rather than the language itself in our subtractions. This could be a reason why our results differ from those of Kim et al., (1997), that brain activation associated with language comprehension does not differ across languages.

# CONCLUSION

In the present investigation examining the difference in brain activation patterns of verbal WM associated with native and second languages, the results indicate that the prefrontal cortex may be organized into two discrete, language-related functional systems, each supporting WM function, but each preferentially devoted to different strategies of executive control. This functional dissociation within the prefrontal cortex is associated with the dissociation in the left temporal lobe, which is likely to be attributed to a difference in the language proficiency. Internal phonological processing seems to play a predominant role in WM processing for native language with a high proficiency, whereas visual higher order control does so for a second language with a low proficiency. Interaction analysis will be necessary to confirm this conclusion.

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