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Working Memory Load Can Reduce Task-Irrelevant Processing in Human Fusiform Gyrus*

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How does working memory (WM) load affect concurrent visual selection? A previous study has shown that high WM load increases functional magnetic resonance imaging (fMRI) signals for task-irrelevant information, suggesting that visual selection is impaired with a WM load. In contrast, recent behavioral experiments demonstrated that visual selection can be enhanced if the type of WM load overlaps with distractor processing. Using fMRI, the current experiment extends the previous behavioral findings by demonstrating that loading WM with face images can reduce task-irrelevant face processing in the face-selective cortical region, the fusiform face are (FFA). In Experiment 1, while remembering a famous (low load) or novel (high load) face, participants performed a politician-athlete classification for names overlaid on distractor faces. In Experiment 2, participants remembered one novel face (low load) or three different novel faces (high load) for the WM task. In both experiments, high WM load enhanced target selection. The FFA responses were reduced to face distractors when WM was demanded. We further demonstrated that these results were not driven by load-dependent baseline shifts in the FFA activity in Experiment 3. In conjunction with previous studies, the current findings suggest that WM load can attenuate distractor interference and improve target selection when the contents of WM shares limited-capacity processing with distractors.

Key words : attention, working memory load, cognitive control, Stroop interference, fMRI

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One of the main purposes of cognitive control is to inhibit the processing of task-irrelevant information. Failure to control distractor processing reduces the efficiency of target processing by increasing the load on limited-capacity perceptual systems. Lavie and colleagues (Lavie, Hirst, de Fockert, & Viding, 2004; Lavie & de Fockert, 2005) demonstrated that distractor inhibition was impaired under the loss of cognitive control caused by concurrent WM load. Other studies, however, showed conflicting results wherein a concurrent WM load enhanced distractor inhibition when the contents of that WM load and the distractor properties demanded the same type of processing (Kim, Kim, & Chun, 2005; Park, Kim, & Chun, 2007). These latter findings suggest that the effects of WM load on distractor inhibition could be accounted for not by the load per se, but by whether or not WM overlaps with the perceptual processing of distractors. The current study aims to reveal the neural correlates of such enhanced inhibition of distractors under concurrent WM load when WM load and distractor processing require the same type of processing.

Much of the evidence on cognitive control has been derived from a Stroop paradigm. People are slower to name the ink color of a colored word when the meaning of the colored word is incongruent with its ink color. This phenomenon, known as the Stroop effect, demonstrates that uninhibited task-irrelevant processing affects task-relevant processing. The Stroop effect has been useful to investigate the neural mechanisms underlying cognitive control (Kerns, Cohen, MacDonald, Cho, Stenger, & Carter, 2004; MacDonald, Cohen, Stenger, & Carter, 2000). Importantly, a variant of the Stroop task has been developed to understand how cognitive control is implemented in perceptual processes in visual cortex. For example, previous studies have investigated the role of cognitive control in visual selection by measuring the neural activity of visual cortex related to the target (Egner & Hirsch, 2005) or distractor processing (de Fockert, Rees, Frith, & Lavie, 2001).

Using a name-face Stroop task, de Fockert et al. (2001) demonstrated that concurrent WM load can increase task-irrelevant processing. In their study, participants were asked to categorize famous written names as either pop stars or politicians while ignoring distractor faces that were either congruent or incongr uent to the target name. Participants performed this Stoop task while maintaining in WM either a random order of digits (high load) or a fixed order of digits (low load) on each trial. Higher WM load resulted in greater interference from distractor faces, and was associated with greater neural activities in visual cortex involved in face

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processing. De Fockert et al. argued that WM should maintain stimuli processing priorities, and hence, high WM load would cause the loss of control for prioritizing targets and inhibiting distractors.

The WM load, however, does not always impair attentional selection. Previous studies investigating the effect of concurrent WM load on visual search have showed that the efficiency of visual search was not impaired when WM was loaded with a set of colors (Woodman, Vogel, & Luck, 2001) or verbal items (Logan, 1979, 1988). In contrast, visual search interfered with spatial WM load (Oh & Kim, 2004; Woodman & Luck, 2004). These findings suggest that WM load can impair the performance of visual search only when both tasks demand the same type of processing mechanisms. This suggestion fits to the notion that the information processing system is not unitary, but has multiple mechanisms with independent resources (Desimone & Duncan, 1995; Posner & Petersen, 1990; Treisman, 1969).

The multiple resource view allows reinterpretation of de Fockert et al. 's (2001) results. In their name-face Stroop task, the types of WM load (digits) shared more similarity with targets (names) than with distractors (faces). Since WM load demanded the same verbal mechanisms as target processing, high WM load might leave target processing vulnerable to distractor interference. Then, what if the type of WM load is more similar to distractors than targets? Kim et al. (2005) conjectured that high similarity in properties of WM contents and distractors would decrease distractor processing. In fact, that was what they found. In a variant of the Stroop task, distractor interference decreased when WM was loaded with distractor-related information (that is, when processing a verbal/semantic distractor with verbal/semantic WM load). In contrast, distractor interference increased when WM was loaded with target-related information (that is, processing a verbal/semantic target with verbal/semantic WM load), replicating the de Fockert et al. 's (2001). These findings suggest that the effects of WM load on distractor inhibition depend on whether the two processes overlap in processing demands (see also Park, Kim, & Chun, 2007).

Nevertheless, it is not easy to compare de Fockert et al.'s (2001) study directly with Kim et al.'s (2005) because two studies employed different tasks as well as different stimuli. Moreover, de Fockert et al. reported fMRI signals while Kim et al. reported behavioral data. Since fMRI signals in the visual cortex could not distinguish congruent trials from incongruent trials, de Fockert et al.'s hypothesis was focused to the fMRI signal difference

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between distractor-present vs. absent trials. In contrast, Kim et al. tested their hypothesis based on the response time difference between congruent vs. incongruent trials. There was no distractor-absent condition in Kim et al.'s design. Therefore, we aimed to provide both neural (comparing distractor-present vs. absent trials) and behavioral (comparing congruent vs. incongruent trials) within a single experiment, both evidencing that WM load can decrease distractor processing when both processes demand the same mechanisms.

Three experiments in the current study closely resembled de Fockert et al.'s (2001) experiment,

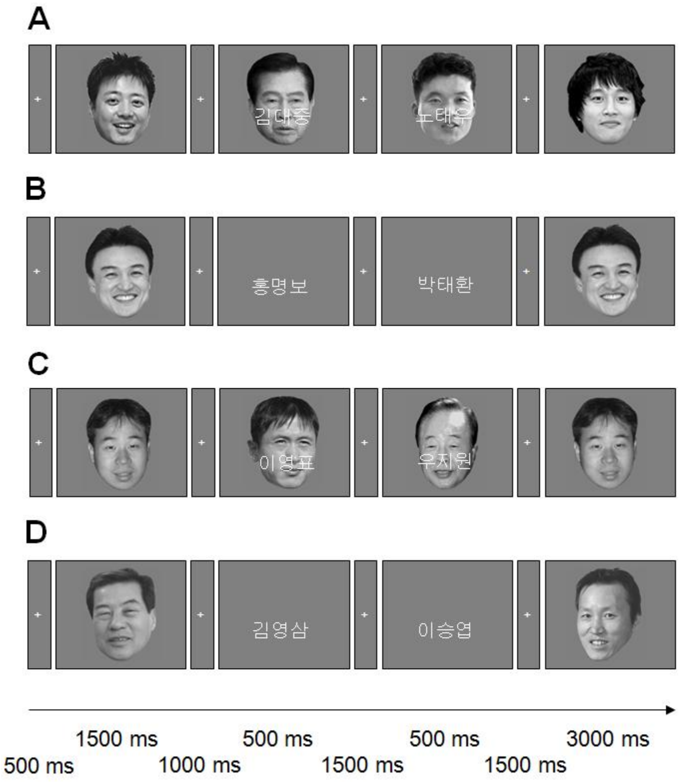

Fig. 1. Trial structure in Experiment 1. Participants performed a dual task consisting of a face delayed match-to-sample task and a name-face Stroop task. In each trial, participants memorized a face of a famous actor or of an unknown person following initial fixation and then categorized a series of names into either an athlete's and a politician's. After two to four such displays (here only two displays), participants decided whether or not the memory probe was the same as or different from the face held in the WM. A. Example of distractor-present trials with low WM load. B. Example of distractor-absent trials with low WM load. C. Example of distractor-present trials with high WM load. D. Example of distractor-absent trials with high WM load.

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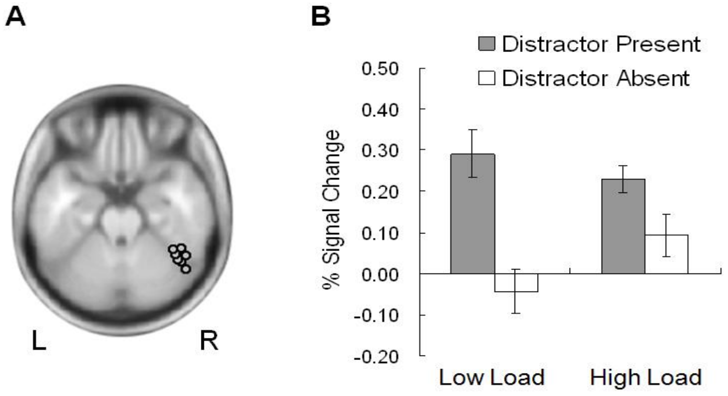

Fig. 2. Results of FFA ROI analysis in Experiment 1. A. Illustration of individuals' FFA regions of interest. B. The fMRI signal changes as a function of distractor presence and WM load. Error bars indicate within-subject standard error.

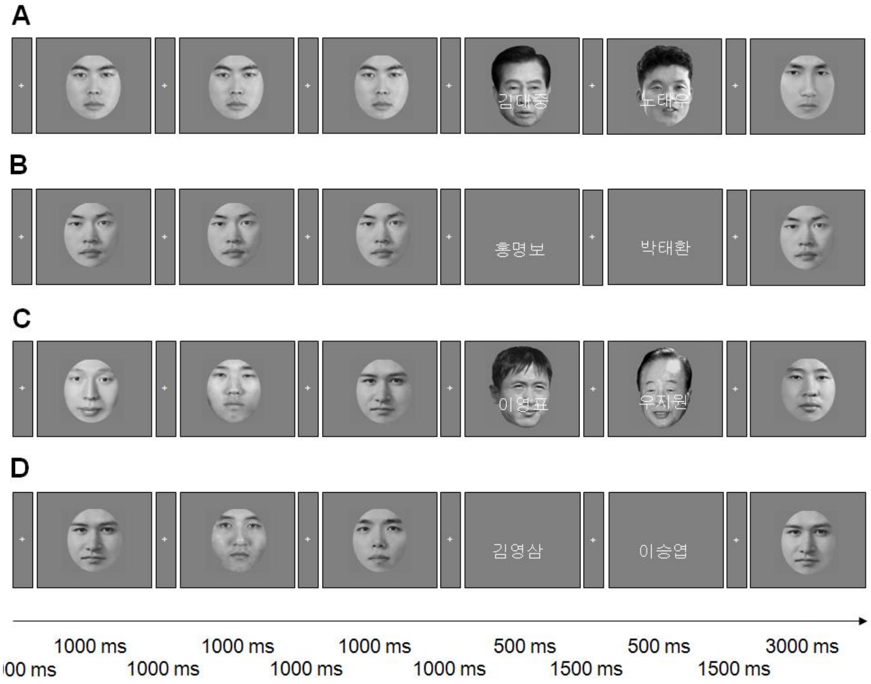

Fig. 3. Trial structure in Experiment 2. In each trial, participants memorized three identical faces or three different faces and then categorize a series of names into either an athlete's and a politician's. Other aspects of the task were the same as those in Experiment 1.A. Example of distractor-present trials with low WM load. B. Example of distractor-absent trials with low WM load. C. Example of distractor-present trials with high WM load. D. Example of distractor-absent trials with high WM load.

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except that the concurrent WM load consumed resources associated with distractor processing, not target processing. In Experiments 1 and 2, participants performed a name-face Stroop task while maintaining face stimuli in WM (Fig. 1 and 3). We predicted that if neural resources related to face processing is depleted by WM load, processing of distractor faces would decrease in face-selective cortical regions. We tested this prediction by probing the a priori-defined region of interest (ROI), the fusiform face area (FFA; Kanwisher, McDermott, & Chun, 1997). In the last experiment, we attempted to exclude an alternative interpretation of the findings in the first two experiments. FFA activation changed not only with the presence of face distractors, but also with increased WM load. Such confounding effects could potentially overshadow a true pattern of task-irrelevant face processing. Thus, we tested if a WM load alone could have produced the patterns of results in Experiments 1 and 2.

Experiment 1

In the scanner, participants performed a name-face Stroop task while maintaining a face stimulus in WM for a delayed match-to-sample (DMS) task. The WM load was manipulated by requiring participants to maintain either a famous or novel face in WM. Two previous behavioral studies have shown that famous faces were easier to retain in visual WM than novel faces (Eng, Chen, & Jiang, 2006; Jackson & Raymond, 2008). Thus, we expected the WM load (and a face-specific perceptual system) to be more demanding when maintaining a novel face, as opposed to a famous face.

Methods

Participants Fifteen college students participated in the experiment for monetary compensation (4 females, mean 25.07 years old). Four subjects did not show significant face-selective activity along the right fusiform gyrus and were excluded from further analyses. All participants were neurologically intact and showed right-handed preference as measured by the Edinburg Handedness Inventory (Raczkowski, Kalat, & Nebes, 1974). Informed consent was obtained from all participants in accordance with guidelines outlined by the Yonsei University Institutional Review Board.

Stimuli All stimuli were projected on an LCD screen mounted on a head-coil. Face stimuli were photos of frontal view faces in grayscale. The faces had either neutral or smiling expressions with visible hair, neck, and ears. The name-face Stroop task consisted of 40 politicians, 40 athletes, and 40 unknown persons. The WM

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task consisted of 60 movie stars and 60 unknown persons. Politicians, athletes and movie stars were all Korean celebrities. Each face was projected at the center of a light-gray background and subtended approximately 2° horizontally and 2.3° vertically. Names consisting of white Korean characters were presented 0.2° below the center of the screen and subtended between 0.6° and 0.9° horizontally and 0.3° vertically. A white fixation cross was projected at the center of the screen during inter-stimulus intervals.

Design and procedure During the first four functional runs, participants performed the main experiment, in which several trials of the name-face Stroop task were incorporated in a trial of the DMS task. This dual-task structure was almost identical to those used in de Fockert et al.'s (2001) study, except that faces, not digits, were used as materials for WM load. Four conditions from a 2 (WM load: high vs. low) x 2 (distractor presence: present vs. absent) design were tested in four separate blocks during each run. The block order was counterbalanced between participants.

The stimulus sequence in a trial is depicted in Fig. 1. When a trial began, a face was presented for 1500 ms as a memory sample. Participants needed to memorize this sample face in order to match it with a probe face at the end of the trial. WM load was manipulated by the familiarity of faces. Sample and probe faces were those of famous people in the low WM load condition whereas they were those of non-famous people in the high WM load condition. A memory face was followed by a 1000-ms fixation period. Then, two to four name displays were presented, each of which showed a name for 500 ms either with or without a distractor face in the background. Participants were required to judge if a given name was that of an athlete or a politician and to respond by pressing a button as quickly as possible. Distractor faces were equally likely to be athletes, politicians, or non-famous persons. Name responses could be congruent, incongruent, or neutral with the distractor faces. After the name displays, a probe face was presented for 3000 ms. Participants then reported if this probe face was the same as or different from the sample face. Each block had 5 DMS trials and presented 15 name displays. The number of name displays was varied in a trial, with the expectation that participants were to actively rehearse sample faces during an unpredictable delay.

In the fifth functional run, a one-back repetition detection task was conducted to localize the FFA ROI for each individual. This run consisted of eighteen 20-sec stimulation blocks. Half of the blocks presented faces while

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the other half presented scenes. During these blocks, face or scene images were sequentially presented every second at the center of the screen (200 ms inter-stimulus interval). Two or three images per block were repeated in a row, to which participants gave untimed responses by pressing a button. Face and scene blocks were alternated, the order of which was counterbalanced between participants.

Imaging data acquisition A 3T magnetic resonance imaging (MRI) scanner (ISOL Forte, Korea) with a standard birdcage head coil was used to acquire functional data using an echo planar imaging blood oxygen level dependent (EPI-BOLD) sequence. Each functional volume [repetition time (TR), 3000 ms; echo time (TE), 30 ms; flip angle, 70°; 5 mm thickness with no gap]was comprised of 28 slices (27 for one participant) orthogonal to the brain stem, covering the entire brain. The first four functional runs acquired 460 volumes for the main experiment. The fifth run acquired 136 volumes for the FFA localizer.

Imaging analysis Preprocessing and statistical analyses were conducted using a statistical parametric mapping package (SPM2, Wellcome Department of Cognitive Neurology, London UK). The first five volumes of each functional run were discarded to allow for equilibration effects. The remaining volumes were then corrected for slice timing, realigned to the first volume to correct for head motion, and co-registered to the co-planar anatomical image in the same session. The T1 anatomical volume was normalized to the standard Montreal Neurological Institute (MNI) brain template and the resulting transformation parameters were applied to each of the co-registered functional volumes. Normalized functional volumes were further re-sampled (voxel size, 2 x 2 x 2 mm) and smoothed (Gaussian kernel, 8 x 8 x 8 mm). A high-pass frequency filter (cutoff, 128 s period) and auto-correlation correction were applied to the time series.

The face-selective ROI was then localized for individual participants. Blocks of faces and scenes were separately modeled by canonical hemodynamic response functions (HRFs) with six movement parameters as covariates of no interest. A statistical parametric map of t-statistics was generated from the linear contrast between face and scene blocks. Due to the well-known laterality of face processing in the right hemisphere (Kanwisher, McDermott, & Chun, 1997; Puce, Allison, Asgari, Gore, & McCarthy, 1996), the maximally face-selective voxel was identified from the right lateral fusiform gyrus for each participant and used as the gravity of a spherical ROI (4 mm radius). The mean Talairach coordinates of the right

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FFA (x = 42, y = -49, z = -18) were similar to those of previous studies (Grill-Spector, Knouf, & Kanwisher, 2004; Yi, Turk-Browne, Flombaum, Scholl, Kim, & Chun, 2008).

The fMRI data from the main experiment were analyzed in two ways: the ROI analysis and the voxel-wise whole brain analysis. For the ROI analysis, the mean time course was extracted from the FFA ROI localized in each individual, using the MarsBar toolbox (Brett, Anton, Valabregue, & Poline, 2002). Parameter estimates of block-related activity were obtained using the general linear model for the four conditions, each of which was modeled by canonical HRF. Six movement parameters were also included as covariates of no interest. The amplitudes of the fitted HRFs for the four conditions were entered into statistical analysis as percentage signal change. For the voxel-wise whole brain analysis, the same general linear model was applied to each voxel across the entire brain. Then, two-level analysis was performed for the obtained parameter estimates. In the first level, linear contrasts of interest were calculated to generate contrast maps for each participant. Afterward, the ensuing contrast images of the first level were submitted to the second level for random effects group analysis by using a one-sample t-test, to obtain statistical parametric maps of the t-statistics for each voxel. Resulting SPMs of the t-statistic (df = 10) at each voxel were thresholded at $p < .001$ (uncorrected, cluster threshold $k = 5$).

Results

Behavioral results For both the name-face Stroop task and the DMS task, the data were submitted to a 2 X 2 repeated-measures analysis of variance (ANOVA), with WM load (low vs. high) as one factor and distractor presence (present vs. absent) as the other factor. Response times (RTs) and error rates for all conditions are shown in Table 1. In the DMS task, participants showed better WM maintenance for famous faces than for non-famous faces. When a distractor face was present, mean error rates was 4% for famous faces and 7% for non-famous faces. When there was no distractor face, mean error rates was 2% for famous faces and 4% for non-famous faces. A main effect of WM load was significant, $F(1, 10) = 7.042$, $p < .05$. However, a main effect of distractor presence and a two-way interaction were not significant, $p > .05$.

In the name-face Stroop task, mean RTs showed a significant main effect of distractor presence, $F(1, 10) = 21.848$, $p < .05$. However, mean RTs were not affected by WM load. Neither a main effect of WM load nor a two-way interaction was significant, $p > .05$. The same pattern of results was found in error

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Table 1. Mean RTs and error rates in Experiments 1, 2 and 3.

			low load		high load	
			Distractor present	Distractor absent	Distractor present	Distractor absent
Exp 1	WM task	RT (SE)	1297 (27)	1127 (18)	1379 (27)	1194 (24)
		%E (SE)	4 (1)	2 (1)	7 (2)	4 (1)
	Name-face Stroop task	RT (SE)	1030 (14)	924 (16)	1058 (16)	927 (14)
		%E (SE)	14 (1)	7 (1)	15 (2)	7 (2)
Exp 2	WM task	RT (SE)	1366 (29)	1121 (26)	1526 (29)	1329 (14)
		%E (SE)	9 (1)	2 (2)	20 (1)	15 (2)
	Name-face Stroop task	RT (SE)	903 (10)	766 (13)	897 (6)	795 (9)
		%E (SE)	14 (1)	7 (1)	15 (2)	9 (1)
Exp 3	WM task	RT (SE)	1324 (26)	1191 (21)	1448 (16)	1355 (27)
		%E (SE)	11 (1)	6 (2)	19 (1)	15 (2)
	Name-face Stroop task	RT (SE)	1020 (18)	887 (7)	991 (9)	873 (15)
		%E (SE)	17 (2)	9 (2)	18 (2)	9 (2)

Note. RT: mean reaction time (in mm), %E: percentage error rate, SE: standard error

rates. Only a main effect of distractor presence was significant, $F(1, 10) = 7.974$, $p < .05$ while a main effect of distractor presence and an interaction were not, $p > .05$.

To reveal the effect of WM load on distractor processing, the data in distractor-present blocks with correct DMS responses were separately submitted to a 2 x 2 repeated-measures ANOVA, with WM load (low vs. high) as one factor and congruency between names and background faces (congruent vs. incongruent) as the other factor. Mean RTs and mean error rates are shown in Table 2. Mean RTs showed significant main effects, $F(1, 10) = 8.127$, $p < .05$, for WM load, and $F(1, 10) = 40.574$, $p < .05$, for congruency. There is no significant interaction between WM load and congruency, $p > .05$. Mean error rates showed only a significant main effect of congruency, $F(1, 10) = 5.432$, $p < .05$.

Neuroimaging data In the whole brain analysis, subtraction of the low WM load condition from the high WM load condition revealed significant activation in the right inferior frontal gyrus and the left insula. In contrast,

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Table 2. Congruency effects in the name-face Stroop task in Experiments 1 and 2.

		low load		high load	
		Congruent	Incongruent	Congruent	Incongruent
exp 1	RT (SE)	963 (16)	1073 (13)	1030 (11)	1090 (12)
	%E (SE)	7 (3)	16 (2)	10 (2)	20 (3)
exp 2	RT (SE)	837 (13)	923 (9)	875 (10)	928 (15)
	%E (SE)	9 (2)	14 (2)	14 (3)	15 (2)

Note. RT: mean reaction time (in mm), %E: percentage error rate, SE: standard error

subtraction of the high WM load condition from the low WM load condition revealed significant activation in the right orbitofrontal cortex, the right superior temporal gyrus and the left thalamus. Table 3 summarizes the results of comparisons between the high WM load condition and the low WM load condition. Greater activation observed in the prefrontal area during the high WM load condition validated our WM load manipulation.

To observe the WM load effect on neural processing of face distractors, we searched for voxels which showed a significant two-way interaction, or in other words, a greater difference in activity between the presence and absence of face distractors in low WM load compared to high WM load. As shown in the fourth contrast of Table 3, the contrast revealed voxels in the right FFA, indicating reduced face distractor processing with higher WM load ($p < .001$).

The results from the FFA ROI further evidenced reduced distractor processing with WM load. Fig. 2b shows percent signal changes of the four conditions. There was no main effect of WM load, $F(1, 10) = 0.653$, $p > .05$, but a significant main effect of distractor presence, $F(1, 10) = 9.035$, $p < .05$. More importantly, a significant two-way interaction was found, $F(1, 10) = 5.237$, $p < .05$, indicating that the difference between distractor present and absent conditions was smaller in the high WM load condition than in the low WM load condition. Paired t-tests revealed a significant difference between distractor-present versus distractor-absent conditions in the low WM load condition, $t(10) = 3.283$, $p < .05$, and not in the high WM load condition, $t(10) = 1.808$, $p > .05$.

Discussion

De Fockert et al. (2001) claimed that WM load impairs cognitive control and that distractor interference should increase with any type of

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Table 3. Coordinates, peak *t* values, and labels of brain areas revealed in contrasts.

Cortical area	Talairach coordinates			*t* value
	x	y	z	
(High-Low)				
R inferior frontal gyrus	38	9	29	3.49
L Insula	-46	10	3	3.62
(Low-High)				
R superior temporal gyrus	51	11	-7	3.87
R obitofrontal cortex	34	35	-8	3.75
L thalamus	-2	-2	2	3.41
(High/Present - High/Absent) - (Low/Present - Low/Absent)				
L middle temporal gyrus	-36	15	31	3.58
(Low/Present - Low/Absent) - (High/Present - High/Absent)				
R fusiform gyrus	34	-72	-10	3.22
L middle occipital gyrus	-38	-77	6	3.34
R post-central gyrus	34	-27	42	3.45
L post-central gyrus	-53	-15	15	3.58
R middle temporal gyrus	51	-59	16	4.04
L middle temporal gyrus	-44	-33	-2	4.09
R pre-cuneus	18	-53	23	3.26
L pre-cuneus	-20	-65	27	3.36
R posterior cingulate	14	-50	12	3.81
R thalamus	28	-29	11	3.61
R parahippocampal gyrus	24	-50	3	3.87

Note. L: left hemisphere, R: right hemisphere.

WM load. However, the current behavioral results failed to support their claim; distractor interference in the low WM load condition did not differ from that in the high WM load condition. In fact, the pattern was numerically opposite. Moreover, the difference in neural activity between distractor present vs. absent conditions was greater under the low WM load condition than under the high WM load condition in face-selective visual cortex. Both whole brain voxel-wise analysis and ROI analysis evidenced that the FFA became more sensitive

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to distractor's presence under the high WM load. These findings are not easily interpreted by de Fockert et al.'s account, but they are well compatible with what Kim and his colleagues have proposed: The effects of WM load on distractor inhibition depend on whether the two processes overlap in processing demands (Kim, Kim, & Chun, 2005; Park, Kim, & Chun, 2007).

Experiment 1 manipulated WM load by requiring participants to maintain either famous faces or non-famous faces in their WM. The behavioral data revealed significant effects of such face type; WM performance was worse for non-famous faces than for famous faces. In addition, our whole-brain analysis revealed voxels of greater activity in high WM load versus low WM load in the right inferior frontal gyrus, which has been associated with nonspatial visual WM in other studies (Baker, Frith, Frackowiak, & Dolan, 1996; Courtney, Petit, Maisog, Ungerleider, & Haxby, 1998; Smith, Jonides, Koeppe, Awh, Schumacher, & Minoshima, 1995). However, previous studies have typically manipulated WM load by the number or complexity of memory items, not by their familiarity. Thus, in Experiment 2, we attempted to replicate the current findings by demanding WM capacity with different number of face identities.

Experiment 2

In the current experiment, WM load was manipulated by the number of different sample faces, not by the familiarity of a sample face. All the WM samples were novel faces. Low WM load blocks presented three identical faces while high WM load blocks presented three different faces. In addition, the current experiment used different stimulus (faces cropped to exclude the ears and hair) for WM from Experiment 1 to enhance the WM load effect.

Methods

Participants Eleven college students were newly recruited for monetary compensation (4 females, mean 22.73 years old).

Stimuli and procedure The current methods were identical to those used in Experiment 1, except a few modifications in a DMS task as follows. To load WM, 200 unknown faces were used. These faces were cropped to exclude the ears and hair in order to minimize peripheral mnemonic cues.

The stimulus sequence in a trial is depicted in Fig. 3. When a trial began, three faces were presented sequentially as memory samples. Each face was presented for 1000 ms, followed by a 1000 ms fixation period. Participants asked to

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memorize these sample faces in order to match them with a probe face at the end of the trial. The WM load was manipulated by varying the number of identity in the sample faces: three faces were identical in the low WM load condition whereas they were all different in the high WM load condition.

Imaging data acquisition and analysis

The same 3T MRI scanner was used. Each functional volume (TR, 2000 ms; TE, 25 ms; flip angle, 90°; 5 mm thickness with no gap) was comprised of 25 slices orthogonal to the brain stem, covering the entire brain. The first four functional runs acquired 940 volumes for the main experiment. The fifth run acquired 190 volumes for the FFA localizer. Statistical analyses were also identical to those in Experiment 1. The mean Talairach coordinates of the right FFA (x = 42, y = -44, z = -23) were similar to those of Experiment 1.

Results

Behavioral results For both the name-face Stroop task and the DMS task, the data were submitted to a 2 X 2 repeated-measures ANOVA, with WM load (low vs. high) as one factor and distractor presence (present vs. absent) as the other factor. RTs and error rates for all conditions are shown in Table 1. In the DMS task, participants showed better WM maintenance with low load than with high load. When a distractor face was present, mean error rates was 9% with low WM load and 20% with high WM load. When there was no distractor face, Mean error rates was 2% with low WM load and 15% with high WM load. Main effects of WM load and of distractor presence were significant, $F(1, 10) = 86.244$, $p < .05$, $F(1, 10) = 9.527$, $p < .05$, respectively. However, the two-way interaction between WM load and distractor presence was not significant. Thus, WM load was properly manipulated in this DMS task.

In the name-face Stroop task, RTs showed a significant main effect of distractor presence, $F(1, 10) = 105.696$, $p < .05$. However, neither a main effect of WM load nor a two-way interaction was significant, $p > .05$. The same pattern of results was found in error rates. Only a main effect of distractor presence was significant, $F(1, 10) = 10.912$, $p < .05$.

To reveal the effect of WM load on distractor processing, the data in distractor-present blocks with correct DMS responses were separately submitted to a 2 x 2 repeated-measures ANOVA, with WM load (low vs. high) as one factor and congruency between names and background faces (congruent vs. incongruent) as the other factor. Mean RTs and mean error rates are shown in Table 2. Mean RTs showed

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a significant main effect of congruency, $F(1, 10) = 27.586$, $p < .05$. However, there were no significant main effect of WM load and interaction between WM load and congruency, $p > .05$. Mean error rates did not show any significant effects, $p < .05$.

Neuroimaging data Results from FFA ROI analysis were similar to those in Experiment 1 as shown in Fig. 4a. Percent signal changes showed a significant main effect of distractor presence, $F(1, 10) = 13.758$, $p < .05$ and, more importantly, a significant interaction between distractor presence and WM load, $F(1, 10) = 5.012$, $p < .05$, indicating that the difference between distractor present and absent conditions was smaller in the high WM load condition than in the low WM load condition. A main effect of WM load, however, was not significant, $F(1, 10) = 3.898$, $p > .05$. The t-test revealed a significant difference between the distractor-present versus distractor-absent conditions in the low WM load condition, $t(10) = 3.362$, $p < .05$, and in the high WM load condition, $t(10) = 2.630$, $p < .05$. Finally, unlike Experiment 1, voxel-based whole-brain analyses did not show any significant activation.

Discussion

The FFA ROI results in Experiment 2 matched those in Experiment 1. Higher WM load decreased distractor processing when the contents of WM overlapped with task-irrelevant information. However, the RTs of both experiments failed to show a significant interaction between WM load and distractor interference, which might be due to weak statistical power. Thus, we conducted an additional ANOVA with a mixed design; WM

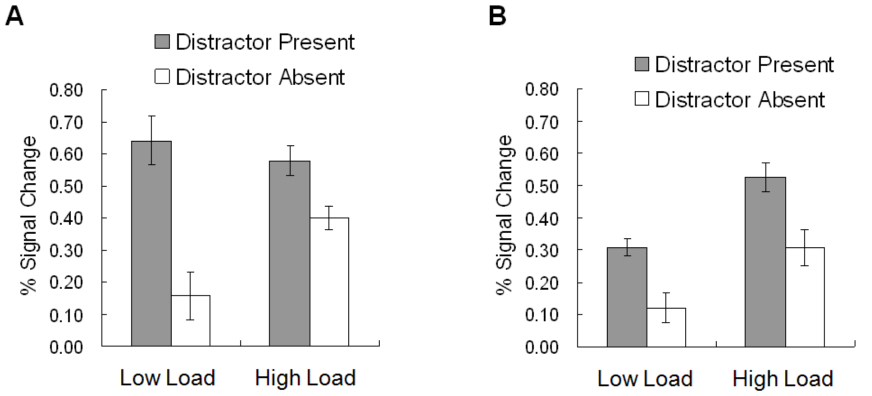

Fig. 4. Results of FFA ROI analysis in Experiment 2 (A) and Experiment 3 (B). Error bars indicate within-subject standard error.

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load and distractor presence were used as two within-participant factors, and WM task type as a between-participant factor (Experiment 1: manipulating the familiarity of a sample face vs. Experiment 2: manipulating the number of different sample faces). As expected, we found a significant two-way interaction between WM load and distractor presence, $F(1, 20) = 13.758$, $p < .05$, indicating that distractor interference with low WM load was greater than with high WM load across the two experiments. The other interactions were not significant, $p > .05$. The main effects of WM load, congruency, and WM task type were significant, $F(1, 20) = 7.267$, $p < .05$; $F(1, 20) = 67.585$, $p < .05$; $F(1, 20) = 1067.325$, $p < .05$, respectively. This cross-experimental analysis of RTs further supports the interpretation of the ROI results.

One concern about our main results was that the neural activity measured in the FFA might not only represent task-irrelevant processing of face distractors but also represent face items held in WM. It is well known that face WM load can increase the FFA activity during a sample-probe delay period (Druzgal & D'Esposito, 2003). Inspection of the FFA ROI results in Fig. 2b and 4a indicates that, when there was no face distractor in a display, FFA activity was greater with high WM load than with low WM load in both experiments. Thus, the two-way interaction between WM load and distractor presence was largely driven by a difference in activity during face absence trials. Our design in Experiments 1 and 2 was not optimal enough to distinguish transient activities due to distractor faces from sustained activities due to faces held in WM. Therefore, we conducted an additional experiment to ensure that the observed two-way interaction was not dominantly driven by WM-related activities in the FFA.

Experiment 3

In the current experiment, we presented a word or a nonword on a background face during each of intervening trials within a DMS task. Participants performed word-nonword categorization, which was orthogonal to the category of background faces. Thus any interference effects between a target and distractors should be negligible. If the pattern of the FFA results in Experiments 1 and 2 was dominantly driven by WM-related activities, then replacing a name categorization task with a semantic judgment task would not affect the observed two-way interaction effect.

Methods

Participants Eleven college students were newly recruited for monetary compensation (7

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females, mean 24.67 years old).

Stimuli and procedure The current methods were identical to those used in Experiment 2, except that a word-nonword categorization task was used as a selective attention task instead of a name categorization task.

As a word-nonword categorization task, two to four word (or nonword) displays were presented, each of which showed a string of letters for 500 ms either with or without a distractor face in the background. Participants were required to judge if a given string of letters was a word or a nonword and to respond by pressing a button as quickly as possible. Words were all nouns. Distractor faces were equally likely to be athletes, politicians, or non-famous persons. In contrast to Experiment 1 and Experiment 2, word-nonword responses were always neutral with the distractor faces.

Imaging data acquisition and analysis Data acquisition and statistical analyses were identical to those in Experiments1 and 2. The mean Talairach coordinates of the FFA ROI ($x = 46$, $y = -42$, $z = -23$) were also similar to those of Experiments 1 and 2.

Results

Behavioral results For both the word-nonword categorization task and the DMS task, the data were submitted to a 2 X 2 repeated-measures analysis of variance (ANOVA), with WM load (low vs. high) as one factor and distractor presence (present vs. absent) as the other factor. RTs and error rates for all conditions are shown in Table 1. In the DMS task, participants showed better WM maintenance for low load than for high load. When a distractor face was present, mean error rates was 11% with low WM load and 19% with high WM load. When there was no distractor face, Mean error rates was 6% with low WM load and 15% with high WM load. Main effects of WM load and of distractor presence were significant, $F(1, 10) = 25.521$, $p < .05$, $F(1, 10) = 7.780$, $p < .05$, respectively. However, a two-way interaction between WM load and distractor presence was not significant. Thus, WM load was properly manipulated in this DMS task.

In the word-nonword categorization task, RTs showed a significant main effect of distractor presence, $F(1, 10) = 34.367$, $p < .05$. However, neither a main effect of WM load nor a two-way interaction was significant, $p > .05$. The same pattern of results was found in error rates. Only a main effect of distractor presence

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was significant, $F(1, 10) = 12.757$, $p < .05$.

Neuroimaging data The results from the FFA ROI were quite different from those in Experiments 1 and 2 as shown in Fig. 4b. Both main effects of WM load and distractor presence were significant, $F(1, 10) = 15.825$, $p < .05$, $F(1, 10) = 11.636$, $p < .05$, respectively. More importantly, however, an interaction was far from significance, $p > .05$, indicating that neural activity due to task-irrelevant face processing was not modulated by differential WM load. The *t*-test revealed a significant difference between the distractor-present versus -absent conditions in the low WM load condition, $t(10) = 3.421$, $p < .05$, and in the high WM load condition, $t(10) = 2.524$, $p < .05$. Finally, similar to Experiment 2, voxel-based whole-brain analyses did not show any significant activation.

Discussion

When face distractors did not interfere target processing, the two-way interaction between WM load and distractor presence failed to reach significance. As shown in Fig. 4b, the high load condition produced greater FFA responses than the low load condition. Interestingly, such a load effect showed up even when there was no face distractor. Thus, WM load did shift the baseline FFA activity measured in each trial. However, the effect WM load and that of distractor presence were additive in the current experiment. Increased FFA responses due to distractor were comparable between two WM load conditions. The current results suggest that neural response to task-irrelevant distracters was dissociable with neural responses to WM load, and argue strongly against a possibility that the two-way interaction effects in Experiments 1 and 2 were mainly driven by WM-related activities in the FFA.

The current experiment was identical to Experiment 3 except the type of selective attention task. To test statistically the difference between two experiments, we conducted an additional ANOVA with a mixed design; WM load and distractor presence were used as two within-participant factors, and attention task type as a between-participant factor (Experiment 2, name categorization vs. Experiment 3, word-nonword categorization). We found a significant three-way interaction between WM load, distractor presence, and attention task type, $F(1, 20) = 4.435$, $p < .05$. Increasing the demands on face WM decreased face?related activity in the FFA only when participants actively ignored distractor faces in a concurrent selective attention task (Experiment 2), but not when participants did not have to ignore distractor faces (Experiment 3). These results

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further support our claim that the two-way interaction effects in Experiments 1 and 2 were not confounded with load-dependent baseline shifts in the FFA activity.

General discussion

The current study tested the hypothesis that distractor processing in an attentional selection task would decrease when WM demands the same processing resources as distractor processing depends on. The critical assumption was that the information processing system has multiple mechanisms, each with limited processing capacity (Desimone & Duncan, 1995; Posner & Petersen, 1990; Treisman, 1969). The extent to which a target or a distractor is processed depends on the competition between stimuli for process-specific attentional resources. Thus, distractor suppression would be enhanced when the type of concurrent WM load overlaps with distractor processing, but not with target processing. This hypothesis was tested in a name-face Stroop task with a concurrent WM task.

In the first two experiments, we demonstrated that face processing in terms of the face-selective neural activity became insensitive to the presence or absence of distractor faces when the WM system was demanded by concurrent WM load of faces. Such load-dependent decrease of the FFA activity was consistent in the current study regardless of how WM load was manipulated. Specifically, Experiment 1 demanded participants ’ WM with either a famous face or a nonfamous face. Previous WM studies have reported that familiar items, such as faces or names of celebrities, are easier to remember than unfamiliar items (Eng, Chen, & Jiang, 2006; Jackson & Raymond, 2008). Relative to faces of unknown people, faces of athletes and politicians used in Experiment 1 were associated with rich pictorial and contextual information (Bar, Aminoff, & Isahi, 2008), which might help encoding, maintenance, and matching processes in a DMS task. Moreover, famous faces had access to both verbal and visual codes while only visual codes were available for nonfamous faces. Such additional information associated with famous face relative to nonfamous faces, however, should not be considered as a confounding factor in Experiment 1. On the one hand, WM load is operationally defined by task difficulty, which can be quantitively measured from behavioral data. Participants produced faster RTs and less errors with famous faces than with nonfamous faces during a DMS task. Thus, famous faces did demand WM less than nonfamous faces. On the other hand, de Fockert et al. (2001; also Lavie et al., 2004) have never specified the type of WM load in their claim. Accordingly, it is expected that any manipulations that incur cognitive demand should enhance task-irrelevant distractor

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processing. In Experiment 1, the nonfamous face condition incurred such cognitive demand, but its effect was opposite; task-irrelevant distractor processing was decreased. Moreover, both behavioral and fMRI results in Experiment were strikingly similar to those in Experiment 2, which demanded participants' WM with either three identical faces or three different faces. We also verified that the observed neural activity in the FFA represents task-irrelevant processing of face distractors under WM load in Experiment 3. WM load did not interact with task-irrelevant distractor processing in a word-nonword categorization task. These results speak against a possibility that WM load alone could cause the observed effects in the first two experiments.

The current findings allow for the reinterpretation of de Fockert et al.'s (2001) results, in which WM load increased neural responses to face distractors. It was suggested that concurrent load diverts WM away from maintaining the priorities of stimuli, and so, results in greater distractor processing. Alternatively, however, distractor processing might increase because the type of WM load (digits) in de Fockert et al.'s experiment overlapped with target processing (names), rather than distractor processing (faces). According to this view, a critical factor is not the load per se, but the extent to which WM load shares verbal resources with target and distractor processing. Such a 'specialized load' view has been supported by two recent behavioral studies. For example, Kim et al. (2005) has shown that Stroop interference increased with verbal WM load in a verbal target task and decreased with spatial WM load in a task using spatial distractors. Interestingly, Stroop interference did not change when there was no overlap between WM load and either target or distractor processing. Park et al. (2007) also reported equivalent findings using a non-Stroop task with face or scene stimuli. The current study, along with the reinterpretation of de Fockert et al.'s findings, corroborates the specialized load view with the neural correlates of distractor processing under WM load.

In conclusion, the current study demonstrated that maintaining faces in WM could reduce task-irrelevant face processing in the ventral visual cortex. If concurrent WM load exhausts resources relevant to the ongoing task, then target processing is impaired as shown in the de Fockert et al. (2001) study. In contrast, if concurrent WM load consumes resources shared by irrelevant information processing, then interference from distractors decreases as in the current experiments. Our findings further support the idea that WM and attentional selection operate on the same content-specific cognitive system.

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작업기억 부하에 의한 방추상얼굴영역의 방해자극 관련 정보처리의 감소

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작업기억은 시각적 선택에 어떠한 영향을 끼치는가? 기능성 자기 공명 영상 기법(fMRI)을 활용한 선행 연구에서는 작업 기억의 부하가 커질수록 동시에 수행 중인 주의 과제의 방해자극 정보처리가 증가한다는 결과가 보고된 바 있다. 이에 반해, 최근 연구에서는 행동 실험을 통해 작업기억 부하와 주의 선택 과제의 방해자극 정보처리가 동일한 심적 자원을 사용하는 경우에 오히려 시각적 선택이 강화될 수 있음을 보였다. 본 연구는 fMRI를 활용하여 이러한 행동 실험결과를 재현하고자 세 건의 실험을 실시하였다. 실험 1에서 참가자는 유명한 사람의 얼굴(낮은 부하) 혹은 낯선 사람의 얼굴(높은 부하)을 작업기억 속에 유지하는 동안 얼굴 방해자극 위에 제시된 이름이 정치인인지 운동선수인지를 구분하였다. 실험 2에서 참가자는 세 개의 동일한 얼굴(낮은 부하) 혹은 세 개의 다른 얼굴들(높은 부하)을 작업기억 속에 유지하는 동안 실험 1과 동일한 이름-얼굴 스트룹 과제를 수행하였다. 그 결과, 작업기억의 부하가 낮을 때에 비해 높을 때 얼굴 방해자극은 방추상 얼굴 선택 영역에서 덜 처리되었다. 실험 3에서는 이러한 결과가 작업 기억 속의 얼굴 정보에 의해 주도되었을 가능성을 배제함으로써 실험 1과 2의 결과를 보완하였다. 본 연구는 결과는 작업기억이 방해자극과 한정된 자원을 나누어 사용해야 하는 경우 작업기억 부하가 방해자극의 간섭을 감소시켜 목표자극의 선택을 강화할 수 있음을 증명한다.

주요어 : 주의, 작업기억 부하, 인지 통제, 스트룹 간섭, 기능적 자기공명영상

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