*Research Article*

# Visual Search Does Not Remain Efficient When Executive Working Memory Is Working

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ABSTRACT—***Working memory (WM) has been thought to include not only short-term memory stores but also executive processes that operate on the contents of memory. The present study examined the involvement of WM in search using a dual-task paradigm in which participants performed visual search while manipulating or simply maintaining information held in WM. Experiments 1a and 2a involved executive WM tasks that required counting backward from a target digit and sorting a string of letters alphabetically, respectively. In both experiments, the search slopes in the dual-task condition were significantly steeper than those in a search-alone condition, indicating that performing the WM manipulation tasks influenced the efficiency of visual search. In contrast, when information was simply maintained in WM (Experiments 1b and 2b), search slopes did not differ between the single- and dual-task conditions. These results suggest that WM resources related to executive functions may be required in visual search.***

The working memory (WM) system is thought to consist of short-term stores and executive processes that operate on the contents of these stores; in addition, executive WM processes are assumed to be required for allocating attention and coordinating maintained information (Baddeley, 1992). Recent studies indicate that executive WM processes such as multiple-task coordination, set shifting, interference resolution, and memory updating play essential roles in high-level cognitive processes (e.g., D'Esposito et al., 1995). Consequently, it is necessary to elucidate the full range of executive WM processing, including whether WM is required for attentional scanning in visual search.

Several studies have focused on the possibility of a relationship between WM storage and attention, especially in the context of visual search. Bundesen (1990) suggested that visual targets and distractors must first be stored in visual short-term memory, so that later they can be identified as search task-related stimuli. Some other studies suggested that only by maintaining search templates in WM is it possible to efficiently activate the representation of targets and to effectively inhibit distractors (Desimone, 1996; Duncan & Humphreys, 1989). In addition, several studies have indicated that WM contents and load have important roles in controlling selective attention (Downing, 2000; Fockert, Rees, Frith, & Lavie, 2001). These studies imply that there might be a close link between WM and attention.

In contrast, there have also been several studies that appear to be inconsistent with WM involvement in visual search. Horowitz and Wolfe (1998) found that observers did not even remember the locations of the items they had searched, so attention sometimes revisited a nontarget item several times. On the basis of this finding, they impugned those theories that proposed a relationship between WM and attention, suggesting that visual search has no memory. Recently, Woodman, Vogel, and Luck (2001) also suggested that visual search requires minimal or no visual WM resources. Woodman et al. measured visual search efficiency while participants were maintaining four nonspatial visual objects in memory, which they regarded as filling visual WM to its capacity (Luck & Vogel, 1997). They hypothesized that if visual search requires the continual transfer of information about the searched item into WM, performance on either or both of the individual tasks would be impaired when they were performed together. That is, filling visual WM to its capacity would interfere with the transfer of search-related information into memory. The results, however, showed that search slopes, or the efficiency of search, were nearly identical for the single-task (search-alone) and dual-task (memory and search) conditions, implying that the efficiency of the search process was not impaired even when visual WM was filled to its capacity. On the basis of this result, Woodman et al. claimed that visual search, especially attentional processes in a visual search task, requires minimal or no visual WM resources.

In that study, maintenance of nonspatial visual WM did not affect the operation of visual search, but Woodman et al. (2001) did not explore whether other aspects of WM might be more closely tied to search. That is, the WM system consists of short-term stores and executive processes (Baddeley, 1992), and executive WM processes are required for allocating attention and coordinating maintained information in the short-term stores (Baddeley, 1992; Tuholski, Engle, & Baylis, 2001). We hypothesized that while memory stimuli are

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manipulated, WM's executive functions are actively working. In addition, we postulated that the performance of a visual search task would be affected by the manipulation required by a WM task if WM and attention are related to each other.

In the present study, we revised the dual-task paradigm of Woodman et al. (2001). Our participants performed visual search while manipulating information held in WM. Experiment 1a required counting backward from a target digit, and Experiment 2a required sorting a string of letters alphabetically.

We also used simple storage tasks as WM tasks in Experiments 1b and 2b. Because our memory stimuli were verbalizable, unlike those Woodman et al. (2001) used, any change in the efficiency of visual search in the dual-task conditions of Experiments 1a and 2a might have been due to verbal WM storage, rather than executive WM processes (i.e., manipulation). To rule out this alternative explanation of the results, we compared the effects of simple memory storage and memory manipulation on visual search.

## GENERAL METHOD

### Participants

Forty undergraduate students (10 in each experiment) at Yonsei University, Korea, participated for course credit, after giving informed consent. All had normal or corrected-to-normal vision. None knew the purpose of the experiment or the expected result.

### Stimuli and Apparatus

The experiment was conducted using a Pentium-III computer, which was controlled by programs written in Matlab with Psychophysics Toolbox extensions (Brainard, 1997). Stimuli were presented on a 17-in. LG Flatron monitor with a 75-Hz refresh rate (13.3 ms/frame). Participants looked at the screen from a distance of 57 cm using a chin rest and responded by pressing one of the prespecified keys on a computer keyboard.

The visual search stimuli were identical to those used by Woodman et al. (2001). The stimuli were presented on a video monitor with a white background; all stimuli, including instructions and warning messages, were black. The memory array for backward counting in Experiment 1a consisted of three black digits (each $2.5° \times 2.5°$) presented at the center of the display. In Experiment 1b, the memory array for stimulus storage consisted of seven black digits. The memory stimuli used in Experiments 2a and 2b were four black alphabet letters (each $2.5° \times 2.5°$).

### Procedure

Figure 1 illustrates the procedures in all four experiments. At the beginning of the dual-task condition (memory and search) in Experiment 1a, a random three-digit number was presented at the center of the display. In memory, participants were required to count backward from that number by 3s. For the first 4 s, they performed this memory manipulation task alone, and then a visual search array was pre-

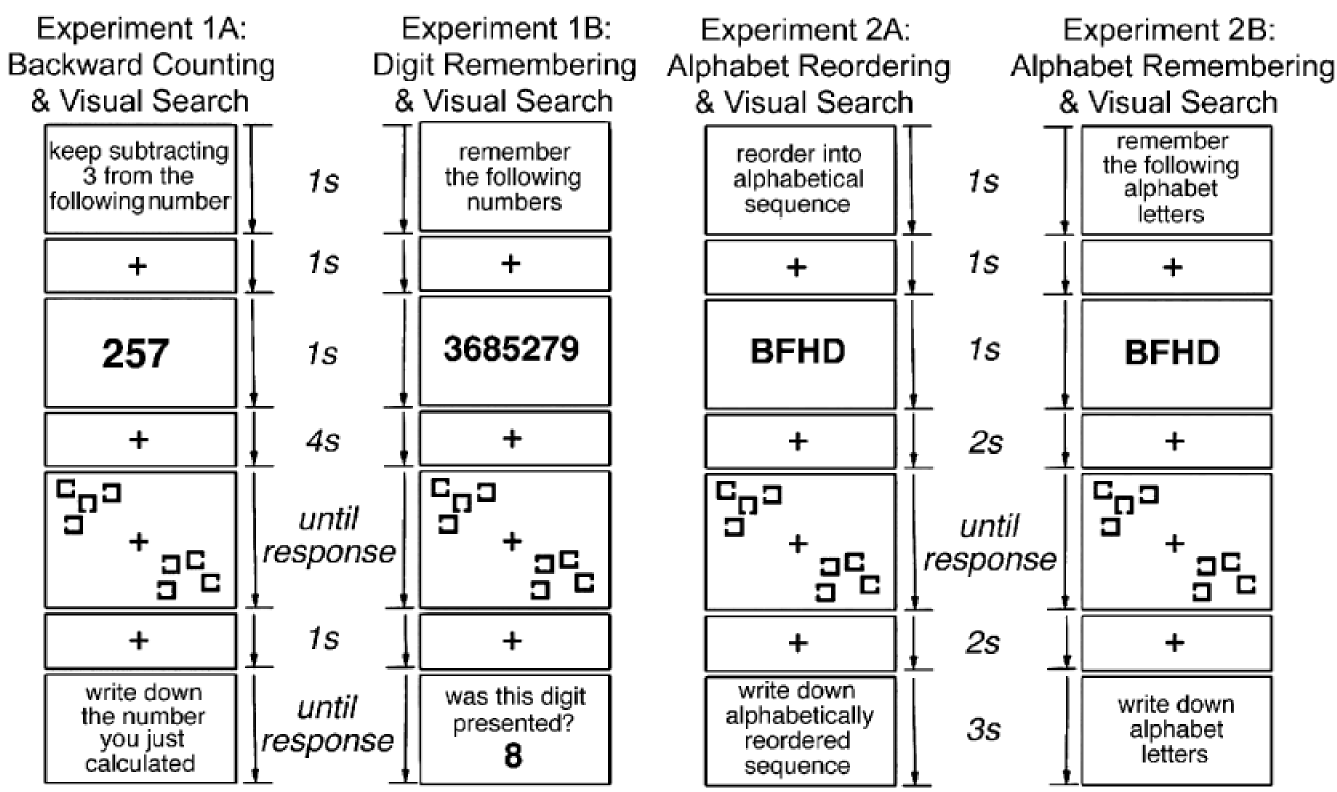


**Fig. 1.** Illustration of the trial sequences in Experiments 1a, 1b, 2a, and 2b. Experiment 1a required counting backward from a target digit, and Experiment 2a required alphabetizing a string of letters. While performing these manipulation tasks, participants needed to search for a predefined target (a square with a gap at the top or bottom) among distractors (squares with gaps on the side). Experiments 1b and 2b presented the same stimuli used in the manipulation tasks, but participants simply maintained these items in memory for later testing at the end of the trial.

sented. Participants were required to use their left hand to make a speeded response to this array while they continued to count backwards. The index or middle finger was used to press the "S" or "X" key on the computer keyboard to indicate the presence of a top-gap or bottom-gap target, respectively. The search array was presented until participants responded. A 1-s blank period followed. Then the instruction message for the memory test ("Write down the number you just calculated") was presented until participants finished writing down the number that they just had in memory. The next trial started when participants pressed the space bar.

In Experiment 1b, participants were required to remember a random seven-digit number presented on the screen, without performing any manipulation process in WM. We assumed participants rehearsed the memory stimuli to maintain them in WM while they were presented with a visual search array, as in Experiment 1a. The offset of the search array was followed by a 1-s blank period and then the instruction message for the memory test ("Was this digit presented?"). A digit that either had or had not been included among the seven digits in the memory array was then presented until participants made their memory response, by using the right hand to press a key labeled "Y" ("yes") or "N" ("no").

In the dual-task condition of Experiment 2a, four random alphabet letters were presented at the center of the screen. While participants alphabetized the letters in memory, they were presented with a visual search array that required a speeded response to a target. The duration of the memory array was the same as in Experiment 1a, but participants had only 2 s to reorder the letters before the visual search array appeared. We assumed that diminishing the duration of the memory stage preceding search (from 4 s to 2 s) would force participants to perform visual search while simultaneously manipulating information held in WM. A 2-s blank period followed the offset of the search array, and then the instruction message for the memory test ("Write down alphabetically reordered sequence") was presented for 3 s, followed by a beep, which indicated the end of a trial. The procedure of Experiment 2b was nearly identical to that of Experiment 2a except that participants simply retained the presented letters in memory without performing the reordering task.

In the search-only tasks of all experiments, a 500-ms blank screen was substituted for the memory array, and there was no memory test. In all other respects, the procedures of the dual-task conditions were followed. The dual-task and single-task conditions were tested in separate blocks, each of which contained 48 trials at each of three visual search set sizes (total of 144 trials in each block). The order of blocks was randomized across participants. Each participant completed approximately 15 practice trials before each block.

## EXPERIMENT 1A

Experiment 1a investigated the influence of executive WM processes on visual search using a dual-task paradigm. In the memory task, three digits that were randomly renewed each trial were presented on the screen, and participants counted backward from that number in memory by continuously subtracting 3. The participants also searched for a predefined target. Any significant decrease in search performance with an increase in stimulus set size indicates that attention is necessary to identify the target (Cave & Wolfe, 1990; Treisman & Gelade, 1980). In the current study, any decrease in search efficiency in the dual-task condition might also indicate that attention is affected by the executive operation of WM. Thus, nearly identical search slopes for the single-task (search-alone) and dual-task (memory and search) conditions would indicate that there is no close link between executive WM and visual search. In contrast, a difference in search slopes would indicate involvement of executive WM processes in visual search.

### Results

As shown in Figure 2, search reaction time (RT) in the search-alone condition increased linearly as set size increased, with a slope of 49 ms/item. Compared with the search-alone condition, the dual-task condition had a substantially larger slope (119 ms/item). RTs were submitted to an analysis of variance (ANOVA) with factors of set size and task condition. This analysis yielded highly significant main effects of set size, $F(2, 18) = 52.830$, $p < .001$, $\eta_p^2 = .854$, and task condition, $F(1, 9) = 33.369$, $p < .001$, $\eta_p^2 = .788$. In addition, set size and condition had a significant interaction, $F(2, 18) = 9.537$, $p < .01$, $\eta_p^2 = .514$. Trials with an error on the search task were excluded from the RT analysis. Search accuracy was above 99% correct for both the search-alone and the dual-task conditions. We focused on whether or not search efficiency was changed by the WM task. The impairment in search efficiency indicated that participants in fact engaged in the WM manipulation task. We did not analyze accuracy in the WM task because various factors from the experiment could have impaired memory. For example, the search test was self-paced, so there was no fixed duration for the memory task. This means that memory impairment could have been affected by search set size, as well as by the duration of the task. Longer durations could have increased errors, complicating the analysis of factors affecting memory. Therefore, only search efficiency was analyzed.

### Discussion

In this experiment, the participants were required to actively manipulate a memory stimulus in the dual-task condition. Search slopes were significantly steeper in this condition than in the search-alone condition, indicating that performing a WM task influenced the efficiency of visual search. Our results contrast with those of Woodman et al. (2001), suggesting that WM plays an important role in visual search and that there is a close link between WM and attention. That is, WM resources, especially resources involving executive functions, seem to be required in visual search.

In the present study, cognitive resources allocated to the backward-counting task slowed down participants' performance of the visual search task. This implies that attention and manipulation of information in WM might share common processes that consume a unitary mental resource. Our results are consistent with findings from a previous study about the relationship between WM and controlled processing (attentional operation). Focusing on individual differences in WM capacity, Tuholski et al. (2001) demonstrated that participants with different WM capacity show a concomitant difference in performance on attentional tasks such as counting. This finding indicates that WM capacity is closely related to attentionally controlled performance.

Although our results can be explained by the involvement of executive WM processing in visual search, because our memory-task

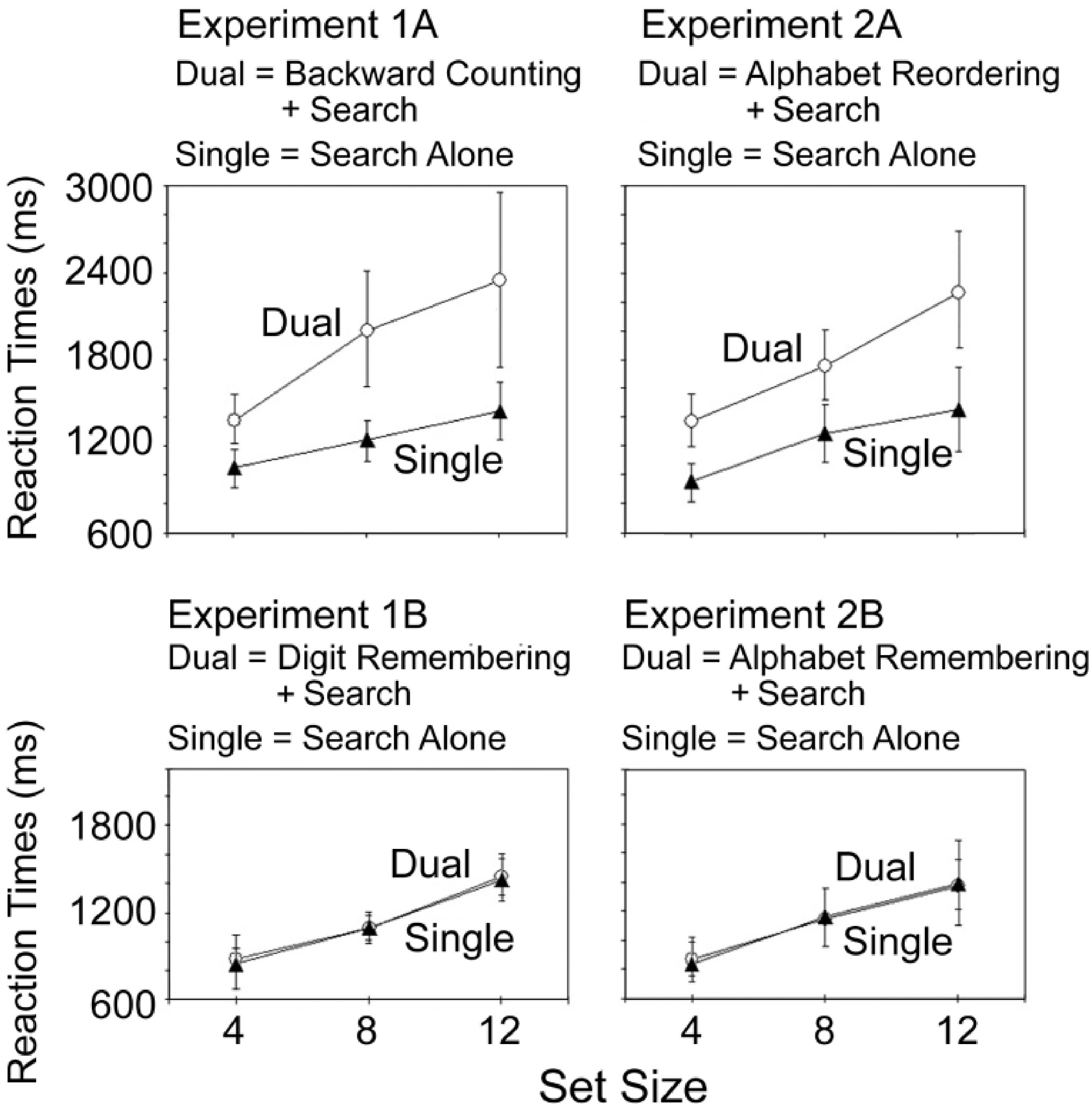


**Fig. 2.** Mean reaction times in Experiments 1a, 1b, 2a, and 2b. The dual-task conditions required memory and search; the single-task conditions required search alone. Error bars indicate the within-subjects 95% confidence intervals.

conditions differed from the one Woodman et al. (2001) used, alternative explanations can be suggested. One is that our use of verbal instead of visual memory stimuli might have influenced whether the inclusion of the memory task affected the efficiency of visual search. To clarify the relation between executive WM processes and search performance, it was necessary to rule out this possible objection.

## EXPERIMENT 1B

In this control experiment, the memory manipulation task was replaced with a simple maintenance task using the same verbal stimuli. The participants simply maintained the verbal stimuli in memory without performing any manipulation. With this change, we were able to compare the effects of memory manipulation (Experiment 1a) and memory storage (Experiment 1b) on visual search. If the simple memory maintenance task in Experiment 1b did not affect the efficiency of visual search, this would suggest that continuous manipulation of stimuli in WM was the crucial factor responsible for the change in search efficiency observed in Experiment 1a.

### Results

Figure 2 shows RTs for the search-only and dual-task conditions in Experiment 1b as a function of the number of items in the search array. The slopes of the search functions were nearly identical (about 71 ms/item). The main effect of set size was significant, *F*(2,

18) = 108.976, $p < .001$, $\eta_p^2 = .924$, but the main effect of task condition was not significant ($p > .75$). In addition, the interaction of set size and condition did not reach significance ($p > .75$).

### Discussion

The result that the search slopes were nearly identical for the single-task (search-alone) and dual-task (memory and search) conditions implies that the efficiency of visual search is not impaired while participants simply maintain verbal information in WM. Although Woodman et al. (2001) found an increase in the intercept of the search function in their dual-task condition, we did not find any increase in the intercept in Experiment 1b. This result might be attributed to the fact that we used verbal stimuli that could be kept in memory with the help of verbal WM as well as the help of visual WM. However, the significance of this experiment is that it shows that the factor responsible for the change in search efficiency in the dual-task condition of Experiment 1a was the executive WM processing required by the memory manipulation task. The comparison of the single-task conditions in Experiments 1a and 1b did not reveal a significant difference in search slope ($p > .15$). This indicates that the baseline response tendencies of the two participant groups, such as adopted search strategies, were not different. Because our focus in Experiments 1a and 1b was on the comparison between manipulating and maintaining verbal stimuli in WM, we did not use an articulatory suppression task.

## EXPERIMENT 2A

In Experiment 2a, we used another controlled WM task to generalize our findings in Experiment 1a: Participants were given four randomly ordered letters of the alphabet and had to reorder the letters alphabetically. In contrast to the backward-counting task, which lacked a clear termination point (simply keep counting until the end of a trial), the reordering task in Experiment 2a had a common, definite end—when participants finished the reordering (see Fig. 1). This alphabet-reordering task was previously used for investigating which brain regions are associated with WM manipulation processes (D'Esposito, Postle, Ballard, & Lease, 1999).

The results of Experiment 2a were nearly identical to the results of Experiment 1a (see Fig. 2). An ANOVA with factors of set size and task condition yielded highly significant main effects of set size, $F(2, 18) = 32.410$, $p < .001$, $\eta_p^2 = .783$, and task condition, $F(1, 9) = 17.067$, $p < .005$, $\eta_p^2 = .655$. There was also a significant interaction between set size and condition, $F(2, 18) = 5.460$, $p < .05$, $\eta_p^2 = .378$. The mean search slopes were different in the search-alone and the dual-task conditions (62 ms/item vs. 111 ms/item, respectively). Search accuracy in Experiment 2a was above 99% correct for both the search-alone and the dual-task conditions. Thus, the results are consistent with those of Experiment 1a in indicating that there seems to be a close link between WM and attention. Executive WM seems to be required in visual search.

## EXPERIMENT 2B

Much like Experiment 1b, Experiment 2b served as a control experiment for Experiment 2a. We used a simple memory maintenance task that did not require manipulating WM information. Participants were presented with four letters of alphabet and were required to simply retain those letters in memory.

The results of this experiment were nearly identical to the results of Experiment 1b (see Fig. 2). The main effect of set size was significant, $F(2, 18) = 5.460$, $p < .05$, $\eta_p^2 = .916$. However, the main effect of condition was not significant ($p > .90$). There was no significant increase in the search slope of the dual-task condition ($p > .60$; 63 ms/item in the search-alone condition vs. 69 ms/item in the dual-task condition). These results suggest that simple maintenance of information in WM does not affect the efficiency of a secondary search task. The comparison of the single-task conditions in Experiments 2a and 2b did not reveal a significant difference in search slope ($p > .90$).

## GENERAL DISCUSSION

In four experiments, we investigated changes in visual search efficiency during dual-task performance. In Experiments 1a and 2a, participants needed to actively manipulate a memory stimulus in WM. Experiment 1a required counting backward from a target digit, and Experiment 2a required sorting a string of letters alphabetically. In both experiments, the search slopes were significantly steeper in the dual-task condition than in the search-alone condition, indicating that performing an executive WM task (manipulation) impaired visual search efficiency. These results suggest that WM resources, especially those relating to executive functions, are required in visual search.

In contrast, simple maintenance of verbal information in WM does not seem to affect visual search efficiency. Experiments 1b and 2b presented the same stimuli used in the manipulation tasks, but participants were required to simply maintain these items in memory for later testing at the end of a trial. In these experiments, the search slopes were nearly identical for the single-task (search-alone) and dual-task (memory and search) conditions. These results show that the efficiency of visual search is not impaired while information is simply maintained in verbal WM. This finding is consistent with what Logan (1978) observed using similar verbal maintenance tasks during visual search. However, he found that the intercepts of search functions differed in the single- and dual-task conditions. This result might have been due to his use of verbal search stimuli, whose recognition time may have been delayed by the verbal memory load.

Several studies have examined the relationship between WM storage and attention, especially in the context of visual search. Woodman et al. (2001) found that nonspatial visual WM load did not affect the operation of visual search. Our Experiments 1b and 2b extend this finding to verbal WM dual-task situations as well. In contrast, Oh and Kim (in press) assumed that spatial WM should affect spatial attention operations of visual search, on the basis of findings that visual search requires spatial attention (Kim & Cave, 1995, 1999; Kim & Robertson, 2001; Treisman & Gelade, 1980) and that spatial attention serves as a rehearsal mechanism for spatial WM (Awh, Jonides, & Reuter-Lorenz, 1998). Indeed, Oh and Kim found that spatial WM load does impair search performance, indicating that spatial WM plays an important role in a visual search. All of these findings are consistent with experimental results showing that maintaining spatial WM stimuli engages different brain processes than maintaining nonspatial WM stimuli (Courtney, Ungerleider, Keil, & Haxby, 1996; Smith, Jonides, & Koeppe, 1996; Ungerleider, Courtney, & Haxby, 1998).

Our novel finding is that executive processes, rather than the maintenance of information in WM, interfered with visual search operations. Our results are consistent with the findings of previous functional magnetic resonance imaging (fMRI) studies of brain activation related to WM and attentional control. D'Esposito et al. (1999) investigated which brain regions are activated during different types of WM processing. In their event-related fMRI study, participants performed a delayed-response task with two types of trials (*maintenance* and *manipulation* of memory stimuli). For both types of trials, all participants exhibited activity in both dorsolateral and ventrolateral prefrontal cortex during the delay period. However, activation of dorsolateral prefrontal cortex was greater on manipulation trials than on maintenance trials. This finding implies that executive WM processing needs to be considered separately from simple maintenance processes in WM. For instance, compared with simple maintenance in WM, executive WM processing might be more closely related with controlled processing, which has been assumed to be attentional (Tuholski et al., 2001). In addition, the brain area identified by D'Esposito et al. maintained a high level of activity throughout the delay period in the manipulation condition, whereas in the maintenance condition, activation was present only during the period of stimulus presentation and the probe periods. These patterns of activity signify that executive functions of WM may be inactive during the simple maintenance of information. These findings validate our use of WM manipulation tasks, such as backward counting and alphabetic reordering, to investigate the relationship between the executive function of WM and attention.

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