Research Article

VISUAL SEARCH REMAINS EFFICIENT WHEN VISUAL WORKING MEMORY IS FULL

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Abstract—*Many theories of attention have proposed that visual working memory plays an important role in visual search tasks. The present study examined the involvement of visual working memory in search using a dual-task paradigm in which participants performed a visual search task while maintaining no, two, or four objects in visual working memory. The presence of a working memory load added a constant delay to the visual search reaction times, irrespective of the number of items in the visual search array. That is, there was no change in the slope of the function relating reaction time to the number of items in the search array, indicating that the search process itself was not slowed by the memory load. Moreover, the search task did not substantially impair the maintenance of information in visual working memory. These results suggest that visual search requires minimal visual working memory resources, a conclusion that is inconsistent with theories that propose a close link between attention and working memory.*

This article examines interactions between visual attention and visual working memory in the context of visual search. In visual search tasks, observers typically search for a predefined target item (e.g., the letter *T*) among distractor items (e.g., other letters). In most experiments, the observers press one button if the target is present in a given stimulus array and another if it is absent (for a review, see Wolfe, 1998). Under many conditions, the reaction times (RTs) in these tasks increase linearly as the number of items in the arrays is increased, a finding that is typically interpreted as evidence for the involvement of attention in the search process.

Many of the major theories of attention implicitly or explicitly propose that visual working memory also plays a significant role in visual search. There are three likely ways in which visual working memory might be involved in visual search. First, a template of the search target may be stored in visual working memory (Desimone & Duncan, 1995). Second, several theorists have proposed that once a target is detected, it must be transferred into working memory so that it can be used to control overt behavior (Duncan, 1980). Third, several investigators have proposed that when attention is focused on an item, this item is automatically transferred into visual working memory. In fact, many investigators have assumed that holding a set of objects in working memory is achieved by attending to the objects, so that the limited capacity of working memory is a consequence of the limited number of objects that can be simultaneously attended (e.g., Cowan, 1997). Some theories also propose that an object must be transferred into visual working memory in order to be classified as a target or nontarget (Bundesen, 1990).[1] Thus, in some serial models of visual search, the shift of attention from one object to another would be accompanied by the transfer of a representation of the currently attended object to working memory.[2] Similarly, several parallel models of visual search propose that groups of items are transferred into working memory by attention (e.g., Duncan & Humphreys, 1989). The goal of the present study was to determine whether visual search does indeed involve the transfer of information into visual working memory, so that observers cannot simultaneously perform visual search and maintain a set of objects in working memory without interference.

Although many investigators have proposed that the searched items are stored in working memory, there is at least one good reason to believe that searched items are not stored in visual working memory. Specifically, considerable evidence suggests that visual object identification can occur more rapidly than the encoding of information into visual working memory (Jolicoeur & Dell' Acqua, 1998; Potter, 1976; Thorpe, Fize, & Marlot, 1996; Vogel, Luck, & Shapiro, 1998). Consequently, it would seem very inefficient to transfer each searched item (or group of items) into working memory, especially for nontargets. After all, there is no need to remember the nontargets, so why should they be transferred into working memory? Indeed, Horowitz and Wolfe (1998) have recently provided evidence that observers do not even remember the locations of the items they have searched, so attention may revisit a given nontarget item multiple times.

To assess the role of visual working memory in visual search, we used a dual-task approach in which one task was used to fill visual working memory with a set of objects and a second task was used to assess the efficiency of visual search.[3] The tasks are illustrated in Figure 1a. In the dual-task condition, the participants were first shown a *memory array* that they stored in memory until the end of the trial. While they held these objects in memory, the participants were presented with a *search array* that required a speeded response. Finally, a *memory-test array* was presented, and the participants were required to indicate whether this array was identical to the original memory array. We also tested the memory and search tasks individually to assess baseline levels of performance.

The dual-task condition required the participants to perform a visual search task while holding several objects in visual working memory. If visual search involves the continual transfer of information about the searched items into working memory, then performance on either or both of the individual tasks would be impaired when they

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1. Several investigators use the term *visual short-term memory* rather than visual working memory, but the concepts appear to be identical. That is, both terms refer to a limited-capacity system for temporarily storing visual information.

2. This is a plausible interpretation of the creation of *object files* for attended objects, as proposed by feature integration theory (Treisman, 1988, 1992).

3. Logan (1978, 1979) has previously demonstrated that the maintenance of information in verbal working memory does not interfere with visual search. However, this finding does not rule out a role of visual working memory in visual search, because there are separate visual and verbal stores in working memory (Baddeley, Grant, Wight, & Thomson, 1975; Hanley, Young, & Person, 1991; Logie, 1995), and many theories of attention propose that it is the visual component of working memory that is involved in visual search.

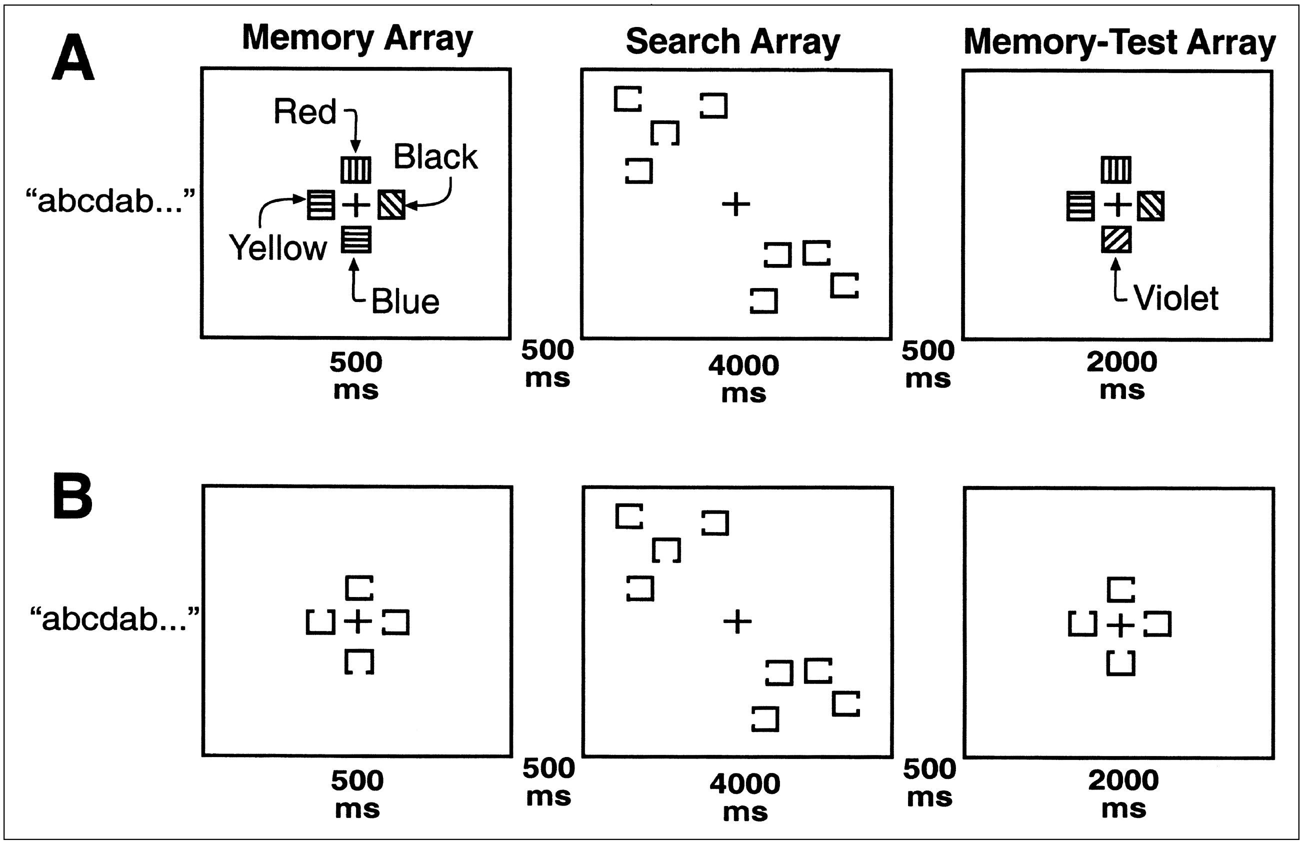

Fig. 1. Examples of a dual-task trial in Experiment 1 (a) and a dual-task trial in Experiment 2 (b). In the single-task conditions, either the memory stimuli or the search stimuli were replaced by blank screens. The letters that appear in quotation marks indicate that subjects maintained an articulatory suppression load of four different letters or numbers during every trial block.

were performed together. That is, just as filling verbal working memory to capacity leads to impairments in tasks such as sentence verification (Baddeley & Hitch, 1974), filling visual working memory to capacity may interfere with visual search.

There are several possible ways in which search performance might be impaired by the visual working memory load. First, it might be impossible to search accurately while visual working memory is full, leading to a large error rate in the search task. Second, the efficiency of the search process itself might be reduced by the memory load, leading to a steeper slope in the function relating RT to the number of items in the search array (the set size). Third, there might be some other type of dual-task interference that would impair processes that precede or follow the search process (e.g., response selection); this would lead to an increase in the intercept of the search function, but no change in the slope.

EXPERIMENT 1

Experiment 1 examined performance on a demanding visual search task when visual working memory was filled to capacity with a set of four objects (for evidence that four objects are sufficient to completely fill working memory, see Luck & Vogel, 1997; Vogel, Woodman, & Luck, 2001). In all conditions, participants also performed a concurrent articulatory suppression task that inhibits the use of verbal coding in the memory task (Baddeley, 1986; Besner, Davies, & Daniels, 1981; Murray, 1968).

Two aspects of the visual search task used in this experiment deserve mention. First, to encourage uniformly high accuracy, we included one of two possible targets in every search array, and the participants reported which target was present. Second, the search task emphasized perceptual-level attentional demands by using a high degree of similarity among the target and nontarget items (see Duncan & Humphreys, 1989). We have previously shown that attention shifts serially from object to object in this task at a rate of approximately 100 ms/item (Woodman & Luck, 1999), so this task should be optimal for revealing any interactions between attention and working memory that occur under typical laboratory conditions.

Method

Participants

A group of 10 undergraduate students with normal or corrected-to-normal vision participated to receive credit toward a course requirement, after informed consent was obtained.

Stimuli

The stimuli were presented on a video monitor with a gray background (9.9 cd/m^2) and a continuously visible central fixation cross (43 cd/m^2) at a viewing distance of 70 cm. The memory array consisted of four colored squares (each 0.45° $\times$ 0.45°) centered 0.68° from fixation, one above, one below, one to the left, and one to the right (see Fig. 1a).

The colors of the squares were selected at random (without replacement) from a set of seven highly discriminable colors (red, blue, violet, green, yellow, black, and white, as described fully in Vogel et al., 2001).

The search arrays consisted of 4, 8, or 12 black items (similar to Landolt Cs), one of which was a target. The nontargets were 0.45° × 0.45° outlined squares (0.08° line thickness) with a 0.12° gap on the left or right side. The target was an identical square except that the gap was either on the top or on the bottom. The items were presented at randomized locations within a 6.1° × 6.1° display region, with a minimum center-to-center distance of 0.6° and a minimum distance of 1° from the fixation point. So that the same display density would be maintained across set sizes, the squares were presented in clusters of four, and set size was manipulated by varying the number of quadrants containing a cluster of four squares.

Procedure

In the dual-task condition, each trial began with a 500-ms presentation of the memory array, followed by a 500-ms blank period and then a 4,000-ms presentation of the visual search array. The participants were required to make a speeded response to the search array, indicating whether the top-gap or bottom-gap target was present. The offset of the search array was followed by another 500-ms blank period and then a 2,000-ms presentation of a memory-test array. The memory-test array was identical to the original memory array, except that on 50% of trials the color of one of the squares was changed to a new randomly selected color (one that was not present in the original memory array). Participants made an unspeeded response to indicate whether the memory-test array was identical to the original memory array. The index and middle fingers of the preferred hand were used to indicate top-gap or bottom-gap target for the search task, respectively, and the index and middle fingers of the other hand were used to indicate change or no change for the memory task, respectively.

In the memory-only condition, the search array was replaced by a 4,000-ms blank period; in the search-only condition, the memory array was replaced by a 500-ms blank period and the memory-test array was replaced by a 2,000-ms blank period. The dual-task, memory-only, and search-only conditions were tested in separate blocks, each of which contained 48 trials at each visual search set size. The order of blocks was randomized across participants. Each subject received approximately 10 practice trials before each block.

In all three conditions, the participants were required to perform an articulatory suppression task, repeating a sequence of four letters or digits aloud throughout each trial. This task was used to minimize verbal encoding of the memory array (Besner et al., 1981).

Results

As illustrated in Figure 2a, search RT increased linearly as set size increased, with a slope of 61 ms/item. The slopes of the search functions were nearly identical for the search-alone and dual-task conditions. However, the intercept of the search function was greater for the dual-task condition than for the search-alone condition, with a difference in mean intercept of 390 ms. An analysis of variance (ANOVA) was conducted with factors of set size and condition, and this analysis yielded highly significant main effects of set size and condition (Fs $>$ 15, ps $< .005$). However, the interaction did not approach significance ($p > .95$). Search accuracy was above 98% correct for both the search-alone and the dual-task conditions.

Accuracy in the memory task was well below ceiling (see Fig. 2a), indicating that memory capacity was indeed exceeded by this task. In addition, memory performance was approximately 9% worse in the dual-task condition than in the memory-alone condition. A t test of accuracy in the dual-task and memory-alone conditions (averaged across search-set sizes) was significant, $t(9) = 5.69$, $p < .001$. However, a one-way ANOVA comparing accuracy in the dual-task condition across the three search-set sizes failed to reach significance, $F(2, 18) = 2.90$, $p = .08$. Moreover, this nonsignificant trend reflected greater accuracy in the memory task for a search-set size of 8 than for search-set sizes of 4 or 12, and the nonmonotonicity of the set-size effect suggests that the marginally significant effect was spurious. Thus, accuracy in the memory task was impaired when the search task was added, but this effect was largely independent of the search-set size.

To assess the degree to which the search task disrupted the memory task, we used an equation developed by Pashler (1988) to estimate the number of items that were accurately retained in visual working memory (see Cowan, in press, for a discussion of the assumptions of this equation). According to this equation, the participants held a mean of 3.2 items in working memory in the memory-only condition, whereas they held a mean of 2.7 items in working memory in the dual-task condition. Thus, the search task caused an average impairment of approximately half an item's worth of information in the memory task.

Discussion

The simultaneous performance of a visual search task and a visual working memory task did not lead to a severe disruption of either task. There were, however, two significant differences between the single- and dual-task conditions. First, a constant value was added to the search RTs when the memory task was added to the search task. In the absence of a change in the slope of the search function, this change in intercept implies that the memory task led to a slowing of a process that either preceded or followed the actual search. For example, the memory load may have delayed the onset of the search process, or it may have slowed the response-selection process. However, there was no evidence that the search process itself was impaired by the addition of a memory load.

The second significant effect was an impairment in memory accuracy when the search task was interposed between the memory array and the memory-test array. This impairment was equivalent to the loss of half an item's worth of information from memory, and the degree of impairment did not increase significantly as the size of the search set increased. This small impairment in memory performance may reflect a nonspecific disruption of the working memory representation by the mere appearance of the search array; we address this possibility in the section on Experiment 3.

Although Experiment 1 appears to indicate that observers can perform a difficult visual search task just as well when working memory is full as when it is empty, there are three alternative explanations that must be ruled out. The first alternative is that the experiment did not have sufficient statistical power to detect a change in the search slope. To rule out this possibility, we computed the 95% confidence interval on the difference in slope between the search-alone and dual-task conditions. The resulting confidence interval was –1.7 ± 18.4 ms/item, meaning that we are 95% confident that the true slope in the dual-task condition was no more than 16.7 ms/item greater than the true slope in the search-alone condition. As an additional check on sensitivity, we conducted an experiment in which we manipulated the perceptual discrimination difficulty of the objects in the arrays to directly influence the search slope, and we found that a slope difference of 16 ms/item was highly significant,

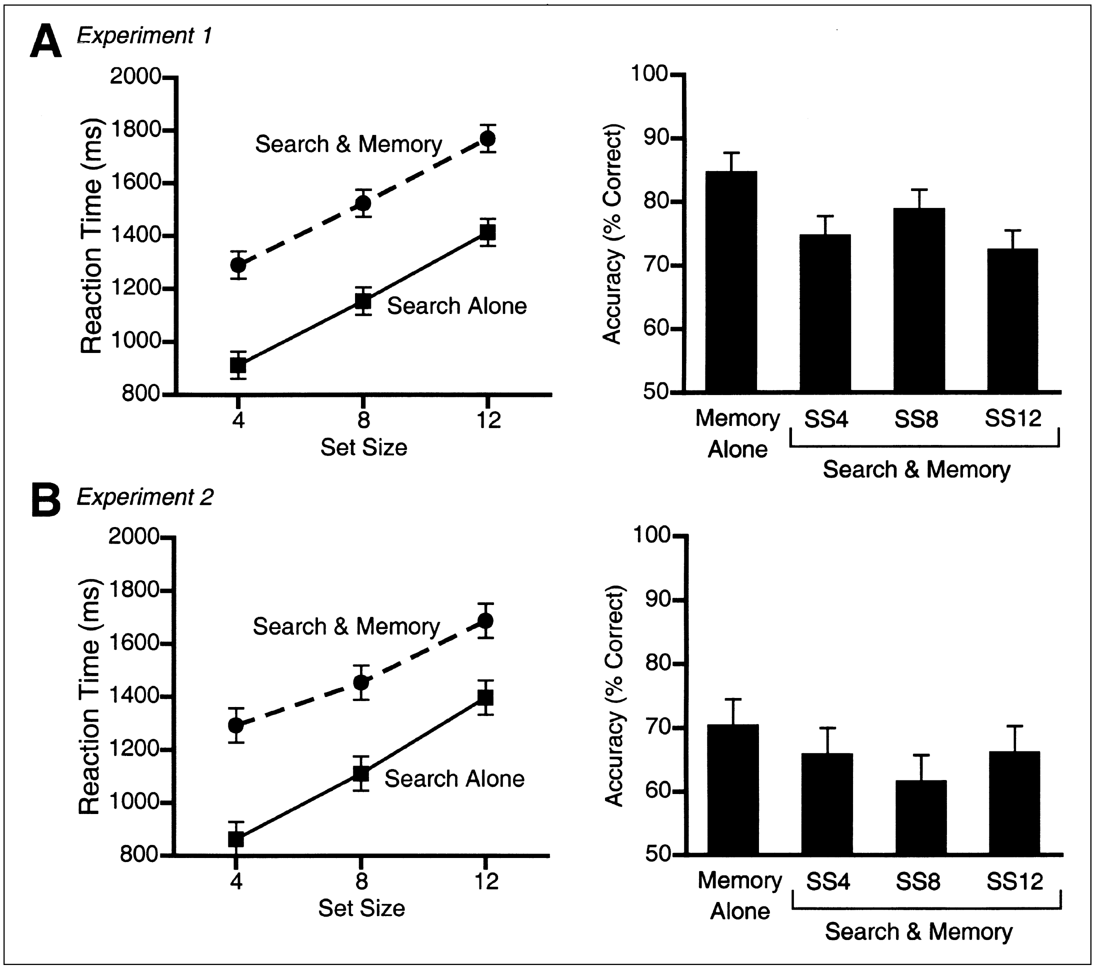

Fig. 2. Results from Experiments 1 (a) and 2 (b). The left panels show mean reaction time as a function of the search-set size. The right panels show mean accuracy in the memory-alone condition and for each search-set (SS) size in the dual-task condition. Error bars indicate the within-subjects 95% confidence interval, as described by Loftus and Loftus (1988).

$F(2, 18) = 4.96$, $p < .01$. Thus, although we cannot rule out the possibility of a small slope increase in the dual-task condition of Experiment 1, we can be confident that any effect of the working memory load on the efficiency of the search process was modest (i.e., less than 16 ms/item).

A second alternative explanation is that participants used different strategies in the memory-alone, search-alone, and dual-task conditions, invalidating any direct comparisons between these conditions. To test this alternative, we conducted a follow-up experiment in which memory-set size and search-set size were manipulated within blocks rather than between blocks. Specifically, whereas memory-set sizes of 0 and 4 were tested in separate blocks in Experiment 1 (i.e., the search-alone and dual-task conditions), memory-set sizes of 2 and 4 were randomly intermixed within blocks in the follow-up experiment. The methods were identical to those of Experiment 1 except that each block contained trials with memory-set sizes of 2 and 4 and search-set sizes of 4, 8, and 12. Because these types of trials were randomly mixed within a block, subjects could not anticipate the cognitive demands of the upcoming trial. As in Experiment 1, increases in the memory-set size caused a change in the intercept of the search function but no change in slope. An ANOVA on the search RTs yielded a significant main effect of search-set size, $F(2, 18) = 59.35$, $p < .001$, and a marginally significant effect of memory-set size, $F(1, 9) = 4.63$, $p = .06$, but no significant interaction, $F(2, 28) = 0.28$, $p = .76$. An ANOVA on accuracy in the memory task indicated a significant decline in performance as the memory-set size increased, $F(1, 9) = 36.31$, $p < .001$, but no main effect of search-set size ($p > .10$) or interaction between memory-set size and search-set size ($p > .45$). Thus, the pattern of results observed in Experiment 1 does not appear to reflect differences in strategy across different types of trial blocks.

A third alternative explanation is that the memory task used in Experiment 1 did not actually fill working memory to capacity. That is, it is possible that participants did not or could not use all of their memory capacity to store the set of four colored squares and that sufficient capacity was available to store additional items from the subsequent search array. To test this hypothesis, we conducted a follow-up experiment in which participants were presented with a memory array of four colored squares, as in Experiment 1, and were then presented with a single square with a gap on one of the four sides (the same objects from the search task were used). In one condition, participants were required to remember both the colored squares and the square with the gap and to compare them with subsequently presented test stimuli. In another condition, they were required to remember only the colored squares. If storage of the colored squares does not completely fill working memory, then it should be possible for participants to remember the colored squares just as accurately when they must also remember the subsequently presented square with the gap. However, we found that participants were substantially worse when they were required to remember both sets of stimuli rather than just the four colored squares, $F(1, 9) = 11.77$, $p < .001$. In other words, when four colored squares are stored in working memory, there is not enough residual capacity to store an additional item. Thus, the minimal interference between the memory and search tasks in Experiment 1 cannot be explained by postulating that working memory had sufficient residual capacity to store items from the search array.

EXPERIMENT 2

Although we have previously provided evidence that different types of features are stored together in an integrated visual working memory system (Luck & Vogel, 1997; Vogel et al., 2001), it is possible that the lack of strong dual-task interactions in Experiment 1 can be explained by the different types of stimuli used for the search and memory tasks. Experiment 2 addressed this possibility by using memory stimuli that were identical to the search stimuli (see Fig. 1b). If the failure to find a strong dual-task interaction in Experiment 1 was caused by a difference in stimuli between the memory and search tasks, then strong interactions would be expected in the present experiment.

Method

The stimuli and procedure used in Experiment 2 were identical to those used in Experiment 1 except that the objects in the memory arrays were identical to the objects used in the visual search arrays (see Fig. 1b). In Experiment 1, each item in the memory array was a unique color; this uniqueness constraint was not possible for gap position in Experiment 2, so the gap position for each item was selected at random, with replacement, from the set of left, right, top, and bottom gaps. A new group of 10 students participated in this experiment.

Results and Discussion

As shown in Figure 2b, the results of this experiment were nearly identical to the results of Experiment 1, except that overall accuracy in the memory task was lower. Once again, the intercept of the search function was elevated in the dual-task condition relative to the search-alone condition (by approximately 494 ms), but there was no increase in the search slope in the dual-task condition (if anything, there was a trend in the opposite direction). An ANOVA on the search RTs yielded significant main effects of condition, $F(1, 9) = 7.82$, $p < .02$, and set size, $F(2, 18) = 89.28$, $p < .001$, but the interaction failed to approach significance, $F(2, 18) = 1.77$, $p = .20$. Search accuracy was above 97% correct for both the search-alone and the dual-task conditions.

Memory accuracy was lower in the dual-task condition ($M = 64.4\%$ correct) than in the memory-alone condition ($M = 70.2\%$ correct), although this difference did not reach significance, $t(9) = 1.64$, $p = .14$. In addition, there were no significant differences in memory accuracy as a function of search-set size in the dual-task condition, $F(2, 18) = 1.8$, $p = .19$. Pashler's (1988) equation yielded an estimate of 2.0 items accurately retained in the memory-alone condition and 1.9 items retained in the dual-task condition. In addition to supporting the main hypothesis of interest, these results suggest that storing and maintaining the more complex objects used in Experiment 2 reduces the total number of such objects that can be stored in visual working memory.

These results extend those of Experiment 1 by showing that interactions between the search and memory tasks are relatively minor even when the same stimuli are used for both tasks. That is, performing both tasks simultaneously did not influence the slope of the search function and created only a small, nonsignificant, and set-size-independent reduction in memory accuracy.

EXPERIMENT 3

Experiment 3 investigated the cause of the small impairment in memory performance that was observed in the dual-task conditions of Experiments 1 and 2. Specifically, this experiment tested the possibility that the search array acted as a nonspecific mask that partially disrupted the representation of the memory array, independently of any specific visual search processes (for related evidence, see Logie, 1986; Quinn & McConnell, 1996). A new group of participants was tested in the same memory task used in Experiment 1, either with or without the interposed search stimuli. When the search stimuli were present, they were completely irrelevant to the task (i.e., the participants were never required to perform visual search or any other task with these stimuli). If the dual-task impairment in memory performance observed in the previous experiments was caused by a nonspecific interruption of the working memory representation, then this effect would also be observed in the present experiment. However, if the impairment was a consequence of the search process, then the search arrays would cause no impairment in this experiment.

Method

A new group of 10 students participated in this experiment. Each participant completed only one trial block, which was identical to the dual-task condition from Experiment 1, with two exceptions. First, the search array was presented on only half of the trials. Second, the participants were told to ignore the search array.

Results and Discussion

Accuracy in the memory task was lower when the search array was presented during the retention interval ($M = 72.4\%$ correct) compared with when the retention interval was blank ($M = 82.4\%$ correct), a statistically significant difference, $t(9) = 5.13$, $p < .001$. When Pashler's (1988) equation was applied to these data, the estimated number of items retained in working memory was 3.3 when the retention interval was blank and 2.6 when the search array was presented during the retention interval. This effect was comparable to the difference in memory performance between the memory-only and dual-task conditions in Experiment 1. These results suggest that the deficit in memory performance observed in the dual-task conditions of the previous experiments was not due to visual search per se, but instead reflects some sort of nonspecific masking or interruption.

GENERAL DISCUSSION

Many theories of visual search have implicitly or explicitly proposed that visual working memory plays an important role in the search process (Bundesen, 1990; Duncan & Humphreys, 1989; Treisman, 1988). However, the present study indicates that visual search causes minimal displacement of information already in visual working memory and that the efficiency of the search process is not impaired when visual working memory is filled to capacity. The only substantial interaction between working memory and search in this study was an increase in the intercept of the search function, which may reflect a delay in the onset of the search process or a delay in postsearch processes such as response selection. Indeed, Jolicoeur and Dell' Acqua (1999) have recently demonstrated significant interactions between working memory and response processes. However, the present study provided no clear evidence of a specific interaction between working memory storage and the search process itself.

Although the working memory load in this study had no effect on search efficiency, it is possible that a different working memory task would interfere with the search process. The working memory task used in this study has been examined in considerable detail (Luck & Vogel, 1997; Vogel et al., 2001) and clearly measures one type of visual working memory. However, there may be multiple visual working memory systems (Potter, 1993; Smith et al., 1995), and search may rely on a visual working memory system that is not taxed by this task. Thus, additional experiments are necessary to establish the generality of the present findings.

These results have important implications for theories of visual search, because they indicate that visual search does not involve storing the searched items in working memory. These results also constrain theories of attention more generally, because they indicate that objects can be attended at a perceptual level without automatically being entered into working memory. This seems like a reasonable way for the brain to operate, because it may be more efficient to allow different cognitive subsystems to operate asynchronously, especially if they have different temporal dynamics. There is growing evidence that objects can be identified very quickly, whereas the process of encoding object representations in working memory is relatively slow (Jolicoeur & Dell' Acqua, 1998; Potter, 1976; Thorpe et al., 1996; Woodman & Luck, 1999). Thus, the brain may gain considerable efficiency by storing in working memory only a small subset of the objects that are perceived.

The present experiments do not imply that working memory has absolutely no role in visual search. In particular, our results are consistent with the possibility that a template of the search target is stored in visual working memory, as proposed by Desimone and Duncan (1995). The target template may require relatively little memory capacity when the target remains constant from trial to trial, as in the present study, although more memory capacity might be required if a new search target was specified at the beginning of each trial. Indeed, Downing (2000) has shown that storing an item in working memory increases the probability that attention will be drawn to that item when it is presented in an array of objects. Further research is necessary to determine whether visual search typically involves the maintenance of a target template in visual working memory.

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