Research Report

IN SEARCH OF REMEMBRANCE: Evidence for Memory in Visual Search

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Abstract—*Observers searched for a target among distractors while the display items traded places every 110 ms. Search was slower when the target was always relocated to a position previously occupied by a distractor than when the items remained in place, showing the importance of memory for locations in a visual search task. Experiment 2 repeated a previous study in which items could move to any location within the display, but used a larger range of set sizes than tested in the earlier study. A cost in search times to relocating items was found at the larger set sizes, most likely reflecting that the probability that the target would replace a distractor increased with the set size. The findings provide strong evidence for the role of memory for locations within trials in a visual search task.*

Most theories of visual search assume that when observers search a difficult display for a target, the display items are checked systematically and the same locations are not usually rechecked. Search terminates either when the target is found or when all items have been inspected (Duncan & Humphreys, 1989; Grossberg, Mingolla, & Ross, 1994; Treisman & Gelade, 1980; Wolfe, 1994). This assumption accords well with the finding that for many difficult search displays, response times are twice as long when the target is absent as when it is present, because all items need to be examined to decide that the target is absent, whereas only half the items need to be checked, on average, to decide that the target is present (cf. Wolfe, 1998).

How does visual attention keep track of items that have been searched? Posner and Cohen (1984) reported that when visual attention has visited a particular location, the latency of a revisit to that location is increased. Klein (1988) proposed that this *inhibition of return* allows observers to tag items in search arrays as already checked, thus facilitating search. Although this finding proved hard to replicate (Wolfe & Pokorny, 1990), more recent evidence reinforces the original conclusion (Klein & MacInnes, 1999; Takeda & Yagi, in press). Such inhibitory tagging could serve as a memory for locations during search.

Recently, evidence for memory across trials in visual search paradigms has also accumulated. Maljkovic and Nakayama (1994, 1996) reported priming for target features and the location of the target, and Kristjánsson, Mackeben, and Nakayama (1999) found evidence for rapid learning of spatial relations between a cue and target. Chun and Jiang (1998) also found evidence for implicit memory for context in visual scenes.

In contrast, Horowitz and Wolfe (1998) recently challenged the assumption that search proceeds through inhibitory tagging of the items to be searched. They argued that observers do not keep track of the spatial locations they have just searched. The observers in their study searched for a *T* among *L* distractors in a dynamic array in which the target and distractors were randomly relocated every 110 ms. Horowitz and Wolfe found no differences in search slopes (reaction times as a function of set size) between this random condition and a baseline condition in which the items remained in place. This surprising result implied that observers do not use memory for locations when searching, because the cost in response time for each added item was the same when the items were relocated and when they remained in place. Horowitz and Wolfe proposed that the visual system retains little information about the locations of objects over time, but instead acts on fleeting neural representations that are overwritten by a change in the visual scene. This conclusion seemed in line with research showing that visual memory is often surprisingly poor (Rensink, O'Regan, & Clark, 1997; Simons & Levin, 1997; Wolfe, 1999).

The purpose of the research presented here was to investigate the role of memory within trials in a visual search task, using a dynamic search display like the one used by Horowitz and Wolfe (1998). The critical manipulation was that moving the target to locations previously occupied by a distractor interfered with a strategy of tagging locations as checked for the presence of the target. Thus, there was a penalty for keeping track of checked locations.

EXPERIMENT 1: RELOCATING THE TARGET WITHIN A TRIAL AFFECTS SEARCH RATES

If a memory strategy that involves tagging locations as already checked for the presence of a target is used in visual search, the most straightforward way of disrupting such a strategy is to move the target to a location that has already been checked off as not containing a target. Given perfect memory for locations, that location would not be rechecked; in contrast, if memory were not used, that location would remain as likely as other locations to be checked. Relocating the target to a previously visited location provides a direct test of whether memory for spatial locations is used in visual search, because the target moves to a location that may already have been tagged as not containing the target. If observers keep track of locations they have checked, a target that moves to a position that has previously been checked will be missed. Thus, this procedure imposes a cost to keeping track of locations. If observers use spatial memory, the relocation condition should result in slower search rates as observers try to maintain reasonable accuracy levels. If, however, visual search does not rely on spatial memory, this relocation condition should not produce any slowdown.

I compare two conditions: In the *relocation* condition, the target was moved to a position previously occupied by a distractor every 110 ms. In the *static* condition, the display items remained in the same location from one frame to the next. Under both conditions, the items changed orientation randomly from frame to frame. Comparing these two conditions directly addresses whether memory for locations is at work during visual search, because the only difference between the

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two conditions was that the target's location changed from frame to frame in the relocation condition.

The increase in reaction time as a function of set size is a measure of the difficulty of a particular search task, because this slope indicates how much slower the search becomes with each item added to the display. If the relocation condition disrupted a memory component to visual search, it would be expected to produce steeper slopes than the static condition. In the following analysis, I concentrate on the trials on which the target was present (50% of the trials). How searches are terminated when no target is present is a complex topic (Chun & Wolfe, 1996), not made any simpler by moving display items around (Horowitz & Wolfe, 1998).

Method

Six naive observers responded by indicating whether a white (51.5 cd/m^2) *L* target was present or absent in a field of white *T* distractors, shown against a dark (0.50 cd/m^2) background. The set sizes were 4, 8, 12, and 16, and the target was present on 50% of the trials. Two conditions were compared: In the static condition, items remained in the same locations throughout the trial; in the relocation condition, the items traded places every 110 ms (see Fig. 1). When the items were relocated, they always fell on positions previously occupied by other items. The items were thus confined to the same number of locations as the set size on each trial. The display items were presented within an imaginary square grid of 64 cells (height and width = 19.2°) at a viewing distance of 57 cm. Each item subtended 1.2°. The target and distractors could be oriented 0°, 90°, 180°, or 270° from their upright positions. Although the items did not change locations within each trial in the static condition, they still changed orientation randomly from frame to frame, as did the items in the relocation condition. In both conditions, each frame was followed by a 27-ms mask that appeared only in locations that contained display items. The mask consisted of a "+" surrounded by a square (see Fig. 1), and thus contained all the individual features of the *T*s and *L*s at any of the four possible orientations.

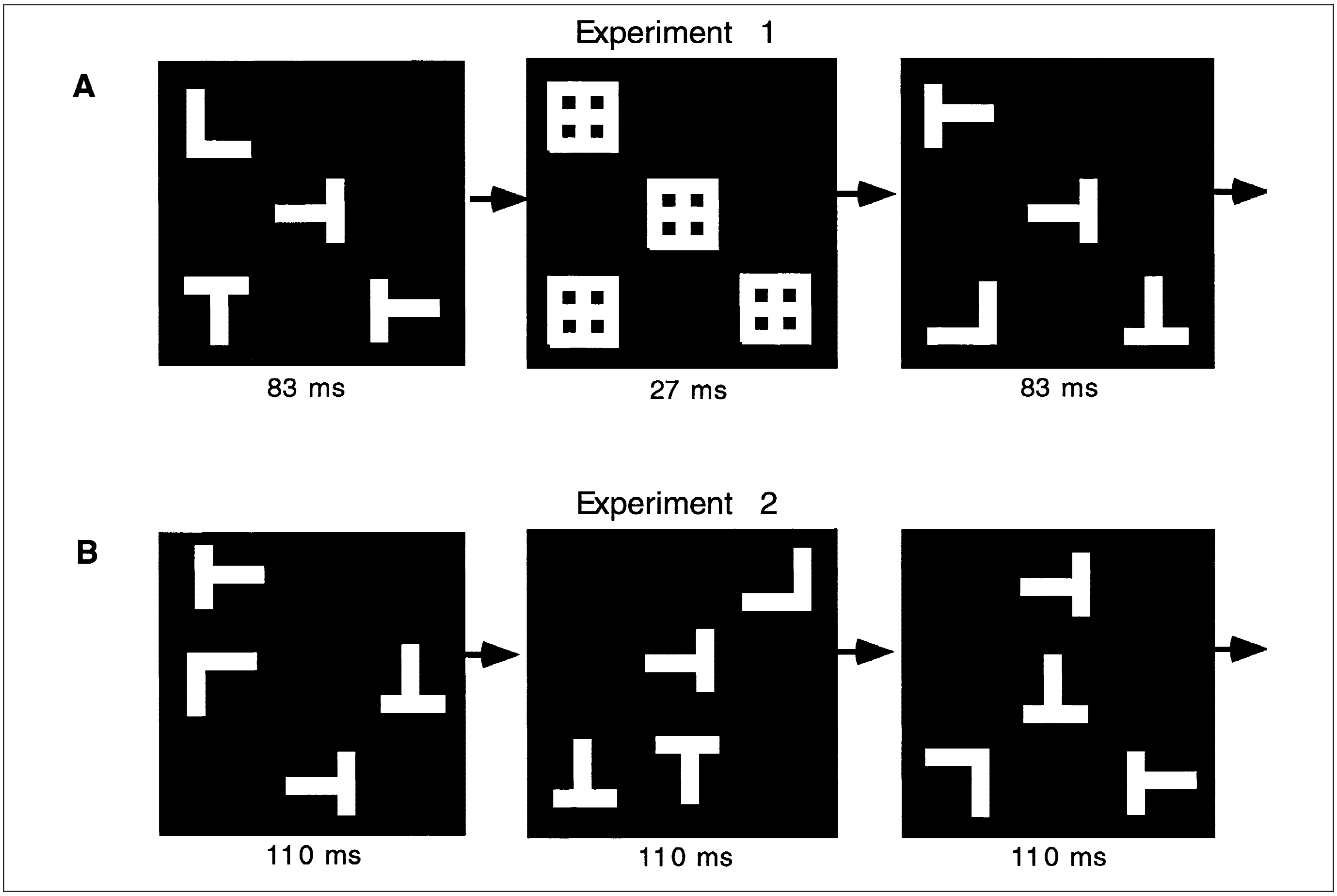

Fig. 1. Three display frames from the relocation condition of Experiment 1 (a) and Experiment 2 (b). In Experiment 1, each stimulus frame was presented for 83 ms. The mask followed for 27 ms, followed by another stimulus frame. From one frame to the next in the relocation condition, all the display items randomly traded places within an 8 × 8 stimulus array and also randomly changed orientation. This sequence was repeated until observers made their response. The items in the static condition remained in their places from one stimulus frame to the next, but their orientation changed randomly. In the relocation condition of Experiment 2, the display items were randomly relocated to any position within an 8 × 8 stimulus array from one frame to the next. No mask was presented between stimulus frames. In the static condition, the items were unchanged until observers responded. Note that the illustrations show arrays with 9 (3 × 3) possible locations, whereas in the experiment, there were 64 (8 × 8) possible locations.

Stimuli were presented on a screen (with a frame rate of 75 Hz) driven by an Apple Macintosh 7500 computer. Observers participated in six randomly ordered blocks of 100 trials each (three blocks in the static condition and three blocks in the relocation condition). Thus, there were 600 trials altogether, 300 under each condition; the six test blocks were preceded by 60 practice trials. Observers were instructed to maintain fixation on a central crosshair for the duration of each trial.

Results and Discussion

Figure 2 shows the results. When the target was relocated, search rates were slowed dramatically. The search slopes were 37 ms/item (target present) and 48 ms/item (target absent) in the relocation condition and 11 ms/item (target present) and 28 ms/item (target absent) in the static condition. The difference in search rates between the two conditions on target-present trials was significant, $t(4) = 4.75$, $p < .005$. Error rates are presented in Table 1.

The results provide strong evidence for the role of memory for locations in a visual search task. A memory-free search process would not keep track of checked locations, and thus should not be affected by the relocation of the target.

Horowitz and Wolfe (1998) did not observe any differences in slopes when the display items were relocated to random positions in the search array and when they remained in place, a result indicating that the difficulty of the two tasks was comparable. I suggest two reasons for the discrepancy between the present results and those of Horowitz and Wolfe. First, locations were always reused in my experiment, whereas they were rarely reused in Horowitz and Wolfe's experiment. That is, in my experiment, each item moved to a location that had contained an item in the previous frame, but in Horowitz and Wolfe's experiment, relocated items could appear anywhere within the array, and so often moved to previously blank locations. Second, in my experiment, there were no sudden appearances of display items in previously blank locations, whereas in Horowitz and Wolfe's experiment, there were many such sudden appearances; abrupt onsets are known to capture attention under a variety of conditions (Yantis & Jonides, 1990).

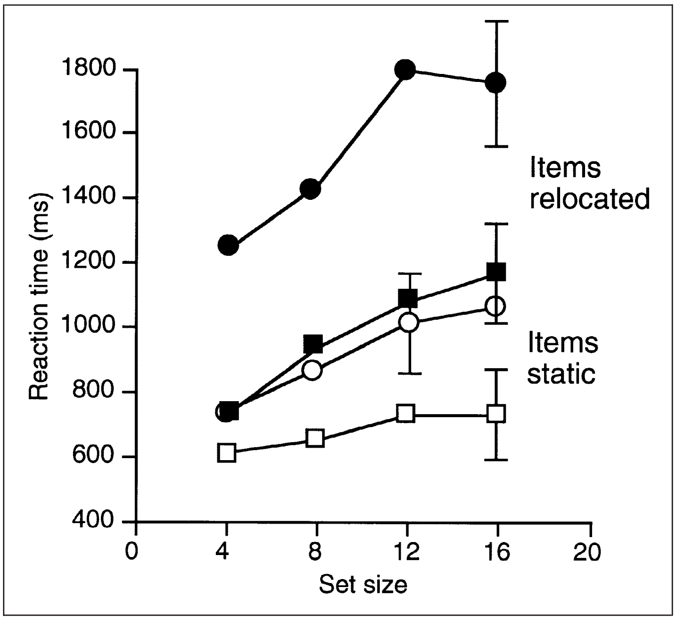

Fig. 2. Mean response times for 6 subjects locating an *L* target among *T* distractors in Experiment 1. The squares denote trials on which the target was present, and the circles denote trials on which the target was absent. The filled symbols denote the relocation condition, and the open symbols represent the static condition. The error bars show the largest *SEM* for each condition.

Table 1. *Error rates (in percentages) in Experiment 1 as a function of condition and set size*

	Condition			
	Relocation		Static	
Set size	Target present	Target absent	Target present	Target absent
4	8.5	8.2	9.6	8.1
8	10.6	9.6	7.9	9.7
12	9.5	11.5	12.2	11.1
16	9.9	10.9	12.5	13

EXPERIMENT 2: THE EFFECT OF SET SIZE

The results of Experiment 1 show that relocating the target had strong effects on search rates, and I proposed that these effects reflect the cost of placing the target in an already-checked location. When the items are randomly relocated to any position within the array (as in Horowitz & Wolfe, 1998, Experiment 2), the probability that the target replaces a distractor increases with set size, if the number of possible locations is fixed (which was the case in Horowitz & Wolfe, 1998). If my explanation for the results of Experiment 1 is correct, search is likely to be increasingly slow as set size increases under random relocation for two reasons: (a) The probability of a target replacing a distractor becomes greater. (b) Because the probability of replacement is higher, sudden onsets of stimuli are fewer. Relocating the items to random locations should then result in increasing costs in search rates as set size increases. In other words, when relocated items are not restricted to locations previously occupied by other items, if a memory strategy is used, it should be increasingly disrupted as set size increases, because the probability that the target will replace a distractor becomes greater. Thus, the response time functions for the relocation and static conditions should diverge at the higher set sizes. However, if the response time functions do not diverge with increased set size, an alternative explanation for the results of Experiment 1 should be sought.

In Experiment 2, I placed no restrictions on where relocated items could move to and greatly extended the range of set sizes. The probability that the target would move to a location previously occupied by a distractor is given by $1 - ((l - m)/l)^n$, where l is the number of possible locations (64, as in Horowitz & Wolfe, 1998), m is the set size, and n is the number of relocation frames. I tested nine different set sizes (ranging from 4 to 56). The probabilities that the target would replace a distractor from one frame to the next ranged from .062 for a set size of 4 to .875 for a set size of 56. As the set size increased, so did the demands on memory for locations, because the probability

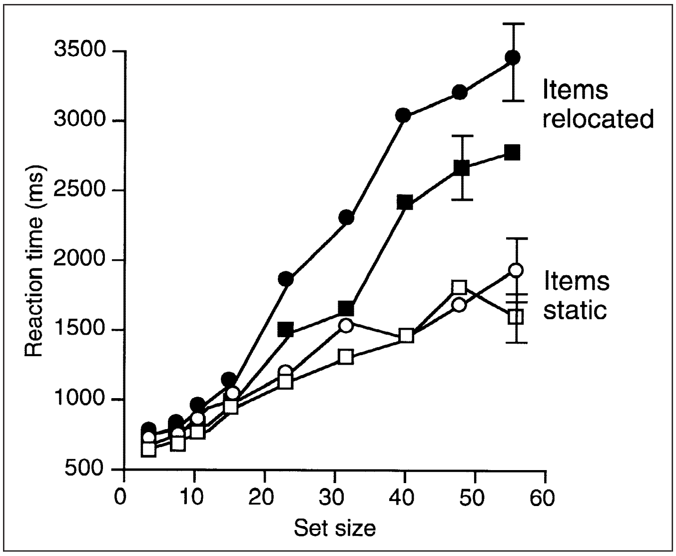

Fig. 3. Mean response times for 6 observers in Experiment 2. The squares denote trials on which the target was present, and the circles denote trials on which the target was absent. The filled symbols denote the relocation condition, and the open symbols represent the static condition. Error bars denote the largest *SEM* for each condition.

that the target replaced a distractor increased, and a penalty for keeping track of checked items was imposed.

Method

In the relocation condition, items were moved every 110 ms to random positions in the array of 64 locations on each trial; in the static condition, the items remained in place. No mask was displayed between stimulus frames, so the display items in the relocation condition were visible for 110 ms in each frame, which was immediately followed by a frame on which they were randomly relocated. The set sizes tested were 4, 8, 12, 16, 24, 32, 40, 48, and 56. Six naive observers participated in 800 trials, 400 under each condition, run in blocks of 100 in a random order. Otherwise, methods were similar to what they were in Experiment 1.

Results and Discussion

The critical issue was whether there were differences in search rates for the larger set sizes, differences not observed for the smaller set sizes. As predicted by the expected frequency of location reuse, the search functions for the two conditions diverged strongly as the set size increased (Fig. 3). Interestingly, for the range of set sizes (8–16) tested by Horowitz and Wolfe (1998), there was no difference in search rates.

The search slopes for target-present trials were 45 ms/item for the relocation condition and 22 ms/item for the static condition. There was also a large difference in slopes for target-absent trials, 58 ms/item in the relocation condition and 23 ms/item in the static condition. On target-present trials, the difference in slope between conditions was not significant for the smaller set sizes (4–16), $t(4) = 1.59$, $p > .1$; in contrast, the difference between the conditions was significant for the larger set sizes (24–56), $t(4) = 4.71$, $p < .005$. Error rates are presented in Table 2.

The results show that with increased probability that the target will replace a distractor, responses are slower. Thus, the results indicate that the target must replace a distractor to interfere significantly with memory-based search. Locations were not reused in the experiments reported by Horowitz and Wolfe (1998), which may explain why they found no difference in search rates between their static and relocation conditions.

CONCLUSION

The results reported here are unambiguous: In visual search, moving items around within trials increases search time. This is strong evidence for the role of memory for locations in a visual search task. The results are consistent with the conclusions of Klein (1988; see also Klein & MacInnes, 1999, and Takeda & Yagi, in press), who proposed that inhibitory tagging is at work in visual search, because if search proceeds randomly, observers should be as likely to find the target when it is relocated as when it stays in place.

Although the present results support the existence of a role for memory in search, the question remains why Horowitz and Wolfe (1998) did not observe differences in search rates between their relocation and static conditions, because Monte Carlo simulations show that search rates should be doubled when the items are randomly relocated (Horowitz & Wolfe, 1998). One possible reason why Horowitz and Wolfe found no differences in search rates is that the putative 2:1 slope ratio is idiosyncratic to a serial, self-terminating search strategy. The results of Horowitz and Wolfe are actually consistent with other models of search, such as serial exhaustive search (Sternberg, 1975) and parallel search (Eckstein, 1998; Palmer, 1995), and may in fact indicate that a serial, self-terminating strategy of searching is not used in the present task. Further research may be necessary for a conclusive answer.

The evidence presented here indicates that when a visual search task is performed, locations are checked in a systematic manner. This is strong evidence that observers use spatial memory when searching for a target among distractors. This conclusion is in line with recent

Table 2. *Error rates (in percentages) in Experiment 2 as a function of condition and set size*

	Condition			
	Relocation		Static	
Set size	Target present	Target absent	Target present	Target absent
4	6.5	5.9	6.7	7.5
8	7.5	7.9	7.3	8.2
12	9.8	10.3	7.9	9.4
16	7.5	8.7	9.7	9.9
24	9.1	8.9	10.1	9.8
32	10.9	11.5	10.5	10.5
40	11.1	13.8	12.1	12.6
48	12.2	13.5	10.4	11.6
56	12.7	14.1	12.1	11.4

results showing the effects of implicit storage of various features of search stimuli (Chun & Jiang, 1998; Klein & MacInnes, 1999; Maljkovic & Nakayama, 1994, 1996; Takeda & Yagi, in press). The prevalence of results showing memory effects in different aspects of visual search tasks suggests a possible role for an interactive network of memory mechanisms that keep track of various aspects of such search tasks (see Shore & Klein, in press).

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