

Research Article

HOW MUCH MEMORY DOES OCULOMOTOR SEARCH HAVE?

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Abstract—Research has demonstrated that oculomotor visual search is guided by memory for which items or locations within a display have already been inspected. In the study reported here, we used a gaze-contingent search paradigm to examine properties of this memory. Data revealed a memory buffer for search history of three to four items. This buffer was effected in part by a space-based trace attached to a location independently of whether the object that had been seen at that position remained visible, and was subject to interference from other stimuli seen in the course of a trial.

Both sensory and cognitive constraints limit the amount of information that can be acquired with a single gaze, such that inspection of a scene typically entails a series of saccadic eye movements. The ability to quickly localize the informative areas within a scene—the capacity for efficient visual search—is therefore crucial to adaptive behavior. Appropriately, visual search has been studied extensively, and from this study elaborate models have emerged (e.g., Itti & Koch, 2000; Wolfe, 1994).

An assumption common to many models of visual search, though sometimes implicit, is that mechanisms prevent attention from revisiting locations or objects that have already been inspected. Eye-tracking data have confirmed that this is true of oculomotor search¹; having foveated a given location, observers are less likely to reinspect that site than to shift their gaze to a new location (Gilchrist & Harvey, 2000; Klein & MacInnes, 1999; Peterson, Kramer, Wang, Irwin, & McCarley, 2001). Various reports, however, have given conflicting evidence as to the capacity of observers' memory for search history. Gilchrist and Harvey (2000) asked participants to search static displays for a target letter among a large number of distractors. Data indicated that refixations were infrequent within the first two to three saccades following inspection of an item, but were common thereafter. The authors suggested that some form of memory for search history exists, but that this store is short-lived or small in capacity. In contrast, Peterson et al. (2001), asking observers to search for a T-shaped target among L-shaped distractors, found that refixations were rare even after very long intervals. These data implied a memory store of as many as 11 items (the maximum number of unique items, given the display size of 12, that could have been fixated before the target).

Unfortunately, neither the data of Gilchrist and Harvey (2000) nor those of Peterson et al. (2001) provide an unambiguous estimate of the capacity of the memory driving oculomotor search. The stimuli employed by Gilchrist and Harvey were large enough that multiple items

could be identified at least coarsely with each gaze, so that guidance of attention based on analysis of target or distractor features (e.g., Itti & Koch, 2000; Wolfe, 1994) was possible. The effects of memory may thus have been attenuated by competition from mechanisms guiding saccades toward items similar to the target. Alternatively, the relatively large stimuli used by Gilchrist and Harvey may have allowed observers to survey displays with a small number of fixations, so that refixations after two to three intervening saccades reflected efforts to double-check search rather than failures of memory. In either case, results would have underestimated the true capacity of memory for search history. In the experiment of Peterson et al., conversely, stimuli were too small to be identified without foveation. Saccade guidance based on analysis of target or distractor features was therefore unlikely to have compromised the role of memory in guiding search. The difficulty of the search task, however, might have encouraged participants to buttress their true memory for search history with mnemonic scanning strategies. Individual observers, for example, may have followed stereotyped scan paths (e.g., scan right to left, scan top to bottom) to avoid refixations, or may have geographically chunked items in memory so that they could preclude redundant fixations by simply avoiding a particular region within the display. The large-capacity memory observed by Peterson et al. thus may not have been the product of an unaided memory store.

In the experiment reported here, we employed a new gaze-contingent search paradigm to measure the capacity of memory for oculomotor search history independent of mnemonic strategies. Unlike in a more typical search paradigm, stimuli were not all visible simultaneously within a static display. Rather, spatially distributed items were revealed a few at a time in a temporal stream. After each fixation, observers were presented a pair of potential saccade targets. One was an item that had not yet been revealed, the other a decoy chosen from among the items that had been presented earlier in the trial. Preferential selection of the new item as the saccade target was taken as evidence of memory for having inspected the old item. The frequency with which an old item was refixated, when examined as a function of lag since the item was last inspected, provided a measure of the capacity of memory for oculomotor search history. To prevent interference from feature-based attentional guidance, we used stimuli that were achromatic and too small to be identified without foveation.

Notably, this search paradigm allowed us to investigate three characteristics of memory in oculomotor search that have not been, or cannot be, studied with a conventional search task. First, because the items revealed at any given time were arbitrarily distributed across the display, observers could not rely on stereotyped scanning or geographic chunking of items to guide selection of the saccade target. The task thus enabled us to estimate memory capacity independent of such mnemonic strategies. Second, because subjects were required to choose between a new item and a decoy item several times consecutively each trial, the task allowed us to determine whether memory for search history changes through the course of search. These data will constrain models of search-guiding memory. For example, a finding

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1. The role of memory in covert visual search remains contentious (cf. Horowitz & Wolfe, 1998, 2001, with Müller & von Mühlhausen, 2000; Peterson, Kramer, Wang, Irwin, & McCarley, 2001; and Takeda & Yagi, 2000).

that memory did not change throughout a trial might suggest that failures of memory result when items are displaced from a simple limited-capacity buffer. In contrast, a decline in performance through the course of a trial would suggest memory lapses produced by accumulating interference from earlier-seen stimuli. Finally, because individual stimuli appeared and were removed unpredictably through the course of a trial, the task allowed us to determine whether memory for having inspected an item is contingent on the item remaining visible within the display. If evidence of memory-guided search emerges only when previously fixated items remain visible on screen, then the memory is object dependent (e.g., Klein & MacInnes, 1999; Müller & von Mühlenen, 2000; Takeda & Yagi, 2000). If subjects can avoid a decoy item even after it has been temporarily removed from display, then the memory for having inspected the item is not tied to the presence of the object itself, but has a space-based component. Examining these properties of search-guiding memory can provide insight into how this memory might relate to better-studied phenomena such as visual short-term memory (VSTM; Phillips, 1974), transsaccadic memory (Irwin, 1996), and inhibition of return (IOR; Posner & Cohen, 1984).

METHOD

Observers

Eight adults, with a mean age of 27 years, were observers. Six observers were naive to the purpose of the experiment. The other 2 were the authors J.S.M. and M.S.P. All observers had normal or corrected visual acuity.

Apparatus

Stimuli were presented on a 21-in. monitor with resolution of 1280×1024 pixels and a refresh rate of 85 Hz. Eye movements were recorded with an Eyelink eyetracker (SR Research Ltd., Mississauga, Ontario, Canada) with temporal resolution of 250 Hz and spatial resolution of 0.2° . An eye movement was classified as a saccade when its distance exceeded 0.2° and its velocity reached $30^\circ/\text{s}$, or when its distance exceeded 0.2° and its acceleration reached $9500^\circ/\text{s}^2$. Observers viewed displays from a distance of 71 cm.

Procedure

Stimuli were left- or right-pointing T-shaped characters and L-shaped characters randomly rotated 0° , 90° , 180° , or 270° from upright. Characters were all $0.17^\circ \times 0.17^\circ$, too small to be identified without foveation. The observers' task was to find a T-shaped target among L-shaped distractors, and to press either the "F" or the "J" key on the experimental computer's keyboard to indicate the direction in which the target pointed. Stimuli were presented in sets of one, two, or three items at a time in a series of gaze-contingent events.

The observer initiated each trial by gazing at a fixation mark and pressing the space bar. Thereupon, the fixation mark was removed and a single character appeared within the display (Fig. 1, Event 1). Because the character was not large enough to be identified without foveation, the observer was required to saccade toward it. During this saccade, a second item appeared within the display (Fig. 1, Event 2). If the first item was the target, the observer responded to it and the trial was ended. If the first item was not the target, the observer was required to execute a saccade toward the second item. Another new item appeared during this saccade (Fig. 1, Event 3). If the second item was not the target, the observer was required to saccade toward another item. Note that at this point, however, two potential saccade targets were available: the new item and the first item that had been presented. The observer was therefore forced to choose between a saccade toward an item that had not yet been identified and a saccade toward an item that had already been inspected and identified as a nontarget. We refer to the latter item as a *decoy*. Upon execution of a saccade toward either of these items, the alternative item and the item from which the saccade was launched were removed, and were replaced with another new item, and another decoy item drawn randomly from the set of all items that had already appeared that trial (including the item that had been the decoy in the immediately preceding event; i.e., the same decoy could be presented for multiple consecutive events; Fig. 1, Event 4). A decoy always reappeared in the same location and at the same orientation as it was originally presented. This pattern of events was repeated (Fig. 1, Event 5) until the observer discovered and responded to the target, or until the observer executed a saccade toward the 11th new item of the trial, whereupon the trial ended.

Observers were thus required, over a series of events within each trial, to choose whether to shift gaze toward a decoy item that had already been inspected and identified as a nontarget character or toward

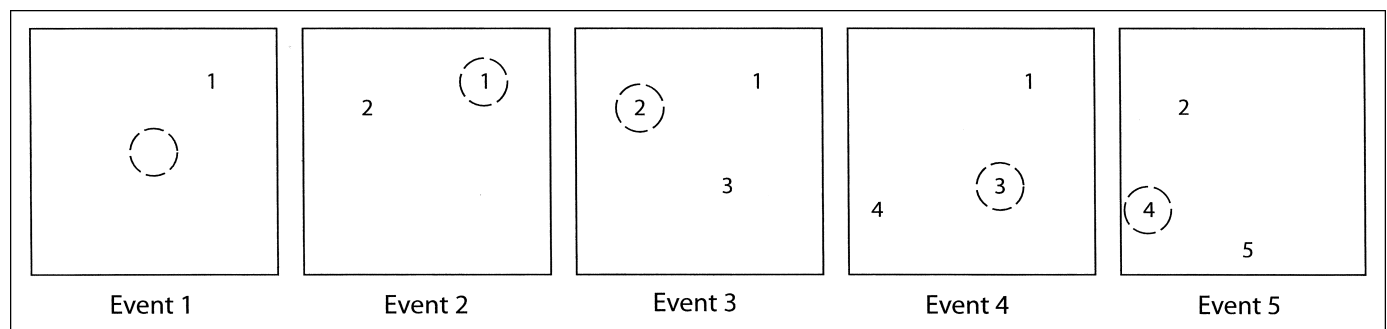


Fig. 1. The sequence of events within a typical trial. The dashed circle indicates the observer's point of regard. Numbers are used to indicate different stimulus items. Stimuli in the actual displays were T- and L-shaped characters too small to be discriminated without foveation. Note that from Event 3 onward, the observer was forced to choose between executing a saccade from the currently fixated item toward a new item and executing a saccade toward a decoy item that had already been seen. See the text for additional details.

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an item that had not been inspected and might therefore have been the target. To the extent that saccades were guided by memory for search history, observers should have preferred to fixate the new item rather than the decoy. Note that because decoys were drawn randomly from the pool of old items, the lag between the time a character was presented once and the time it reappeared as a decoy, measured in number of events, varied randomly. So that the two potential saccade targets available at a given event were always equidistant from the current point of regard, the new item was always placed the same distance from the currently fixated item as the decoy, with the constraint that the minimum separation between new items and decoys was 5.43° (a trial was terminated early if the software was unable to meet these constraints). A saccade toward an item was detected when gaze entered an imaginary 2.18° -radius circle centered on the item.

Each observer completed three sessions of 150 trials each. The first session was considered practice, and the first 25 trials of each of the last two sessions were considered warm-up. A target was present on 25% of all trials. An error message appeared if the observer completed a target-present trial without responding, or if the observer executed an incorrect manual response on a target-present trial.

RESULTS

Data for naive and nonnaive observers were similar, and are combined for presentation here. Figure 2 presents the mean proportion of events on which observers chose to saccade toward an earlier-fixated decoy item in lieu of a new item. Data are plotted as a function of lag, measured in number of intervening items fixated since the last fixation on the decoy item. A lag 1 refixation indicates a saccade from the currently foveated item back to the item that was inspected with the immediately preceding fixation, a lag 2 refixation indicates a saccade toward the item that had been inspected with the penultimate preceding fixation, and so on. Because two possible saccade targets were present on each event, the new item and the decoy, a value of .50 indicates chance performance.

Evidence of memory-driven saccade targeting persisted for at least three to four events following fixation on a given item; one-sample t tests confirmed that refixation rates remained below chance level until lag 4 ($p < .001$ for lags 1 and 2, $p = .001$ for lag 3, $p = .044$ for lag 4; rates for lags 1–3 remained significant after Bonferroni correction; uncorrected $p > .1$ for lag 5). The data thus indicate that memory guides saccadic eye movements away from previously fixated items during search, but suggest that the capacity of this memory is limited. Mean fixation rate for decoys that were not fixated when originally presented as new items was .40, and did not vary as a function of the interval since first presentation, $F < 1$. The memory guiding search therefore appeared to be largely contingent on the observer having fixated the item at a given location.

In further analysis, we examined the form of this saccade-guiding memory more carefully. An item could become a decoy in either of two ways. The item could be removed from the display after it was fixated, then reappear later as the decoy. We call such an item a *nonpersistent* decoy. Alternatively, the item could be randomly chosen as the decoy for one or more consecutive events immediately after it was fixated. In such case, it would have been visible continuously from the time it was originally fixated. We label an item such as this a *persistent* decoy. Note that an observer could avoid refixating a nonpersistent decoy only if a memory trace independent of the item itself marked the location at which the item had appeared, because a trace attached to the

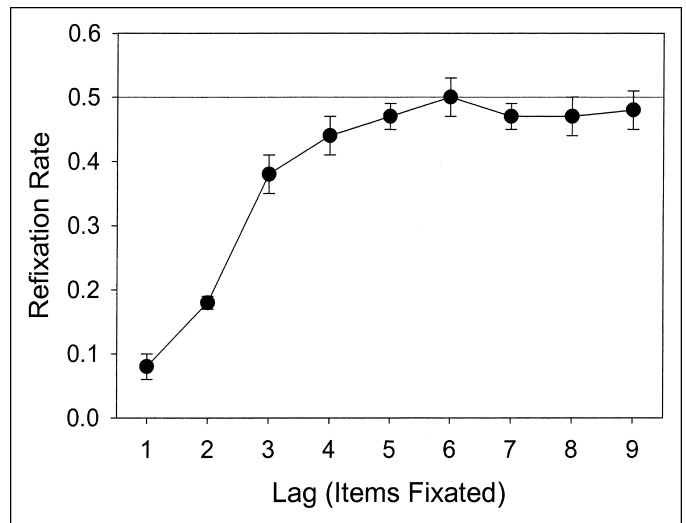


Fig. 2. Rates of refixation on decoy items, as a function of lag since the item was last fixated (number of intervening items fixated). Chance level was .50. Error bars indicate $\pm 1 SE$.

item would have disappeared when the item was removed from the screen. Below-chance refixation rates for nonpersistent items, therefore, would provide evidence for space-based memory traces.

Figure 3 presents refixation rates for persistent and nonpersistent lag 2 decoys.² We present the data as a function of within-trial temporal position³ (fifth event, sixth event, . . .) to allow for analysis of changes in performance across the course of a trial. For analysis, data were submitted to a within-subjects analysis of variance with decoy type (persistent vs. nonpersistent) and temporal position as factors. Two aspects of the data are noteworthy. First, although a main effect of decoy type confirmed that revisits were less frequent to persistent than to nonpersistent decoys, $F(1, 7) = 24.962$, $p = .002$, refixation rates, collapsed across temporal positions, were below chance for both persistent decoys, $M = .17$, $SE = .02$, $t(7) = 21.698$, $p < .001$, and nonpersistent decoys, $M = .34$, $SE = .03$, $t(7) = 5.546$, $p = .001$. The data thus indicate that observers had some memory for having inspected a given location even after the object occupying that location had been temporarily removed from the display. Second, performance reliably deteriorated across the course of a trial, $F(6, 42) = 5.960$, $p < .001$, for the main effect of temporal position, and $F(1, 7) = 9.465$, $p = .018$, for linear trend. The data thus suggest that one cause of imperfect memory was interference between items. The effects of decoy type and temporal position did not interact, $F < 1$.

DISCUSSION

Past research has demonstrated that oculomotor visual search can be driven by memory for which items or locations within a display

2. Lag 1 decoys were necessarily persistent, whereas persistent decoys of lags 3 and higher occurred only rarely. We therefore included only lag 2 decoys in the analysis.

3. Analysis began at temporal position 5 because this was the earliest position for which a nonpersistent lag 2 decoy was possible.

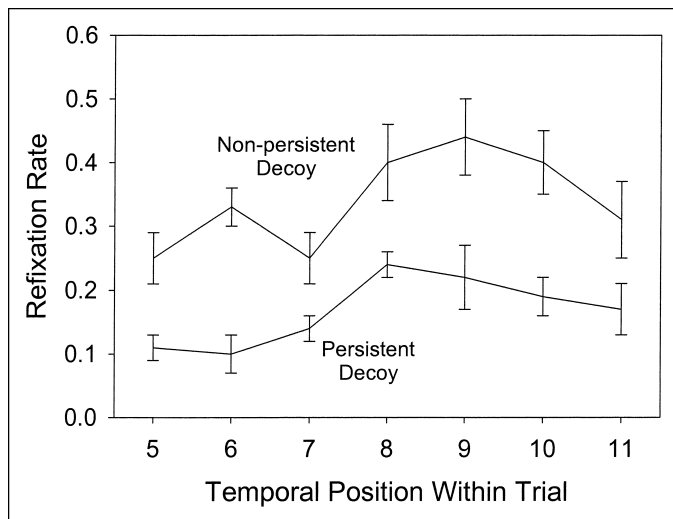


Fig. 3. Refixation rates for persistent and nonpersistent lag 2 stimuli. Error bars indicate $\pm 1 SE$.

have already been visited. In the present experiment, we employed a gaze-contingent visual search task to examine properties of this memory. Results indicated that for as many as three to four fixations following inspection of a given item, observers were less likely to reinspect that item than to fixate a new object at a different location. Memory was strongest for objects that remained on screen after having been fixated, but was evident even for stimuli that disappeared from the display before subsequently reappearing as decoys, indicating that traces for inspected locations existed even when no objects remained on screen to mark them. Finally, memory deteriorated as a trial progressed, suggesting that interference between stored items contributed to lapses in performance.

How do the present results accord with existing data bearing on the role of memory in guiding visual scanning? As noted, past studies have produced varying estimates of the capacity of memory for oculomotor search history. Gilchrist and Harvey (2000) found evidence that the memory buffer guiding oculomotor search may include no more than 2 to 3 items. Peterson et al. (2001), in contrast, found that observers could search displays of as many as 12 items serially while making very few fixations on previously inspected stimuli, a result that implied a large if not unlimited buffer. The current data indicate that true memory for search history is in fact limited in capacity, and suggest that the large-capacity functional memory observed by Peterson et al. may have been effected in part by mnemonic scanning strategies. Future research will be necessary to delineate the role and form of any such strategies more carefully.

Closer examination of the current results sheds light on the mechanisms underlying the unaided memory we observed. IOR (Posner & Cohen, 1984) has frequently been interpreted as a mechanism meant to encourage visual foraging by discouraging revisits of attention to previously inspected stimuli. In a study consistent with this speculation, Klein and MacInnes (1999) found evidence of IOR during oculomotor search of a naturalistic scene, and showed that the effects of IOR extended to at least the preceding two fixation locations. A study of covert attention by Snyder and Kingstone (2000), measuring IOR for sequentially cued objects, found that weak inhibition could exist

as far back as five to six items. It is thus plausible that IOR contributed to the memory buffer of three to four items observed in the current data. The only caveat is that very modest effects of IOR on covert attention, like those Snyder and Kingstone observed at lags of five to six items, might be too weak to reliably influence oculomotor behavior.

However, the current findings also suggest that IOR may not be the sole form of memory for search history. Past results have indicated that IOR in visual search requires the continuous presence of the inspected object, being eliminated when the object disappears. That is, IOR in search appears to be strictly object based, showing no purely space-based component (Klein & MacInnes, 1999; Müller & von Mühlhagen, 2000; Takeda & Yagi, 2000). In contrast, the current data gave evidence of some memory for search history even after inspected objects themselves had been briefly removed from the display. One interpretation of this disparity is that IOR in oculomotor search can indeed be purely space based, but is more robust for locations marked by an object. Earlier studies might have simply lacked power necessary to detect a reliable effect of spatial IOR. Alternatively, the present results might indicate that some form of space-based memory for search history operates in addition to an object-based IOR to guide visual search (see Smith et al., 1995, for evidence of separate spatial and object working memory systems). There would be two manners, in this case, by which persistent decoys might facilitate memory-guided search. First, persistent decoys would allow object-based IOR to buttress space-based memory. Second, persistent decoys might serve as landmarks, preventing the decay of spatial information across saccades and reducing spatial uncertainty associated with location-based memory traces. Further research will be necessary to test these suggestions, and to further delineate the properties and functions of space-based memory for search history. One parsimonious possibility is that the well-studied phenomena of VSTM and transsaccadic memory (Irwin, 1996; Phillips, 1974), which themselves have a capacity of approximately four items (Irwin, 1992; Luck & Vogel, 1997), might contribute to guidance of oculomotor search, producing the space-based effects seen in the current data.

The present data also shed light on the dynamics of memory in search. Memory for previously fixated items deteriorated as visual search progressed, even when lag since previous fixation was held constant. This effect suggests that lapses of memory were produced in part by accumulating interference between stored items. Such interference might result from coarse spatial coding of previously inspected items. Assume, for example, that the trace labeling a location as having been inspected is not tightly localized, but shows some dispersion or spread about the position the inspected item actually occupied; this might arise because of a spatial-coding mechanism that is inherently coarse (e.g., Cohen & Ivry, 1989) or, as we speculated earlier, because of a decay of spatial information across saccades. In either case, an item appearing at a nearby location could be labeled as having been seen, even if it were actually new. As memory traces accumulated through the course of search, the portion of the display occupied by spillover of spatial traces would increase, and the frequency with which new items were misclassified as decoys would climb. Notably, the possibility of interference between traces provides a third mechanism by which persistent distractors might facilitate performance relative to that obtained with nonpersistent distractors. Presentation of the same decoy for two or more consecutive events would ensure that other items were *not* being presented as decoys, and would thereby minimize the amount of interference accumulating over those events.

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It is worthwhile, finally, to consider how the memory observed in the current experiment might contribute to normal visual search within a static display. The present results suggest that memory traces can exist at multiple recently attended locations, and thus that the memory observed here could operate within displays of many items. For at least two reasons, moreover, the current data seem likely to provide a minimal estimate of the influence of memory in a more typical search. First, the gaze-contingent method of presentation employed here would have greatly reduced the contribution of object-based memory mechanisms to the control of search. In contrast, a conventional procedure leaving all stimuli visible throughout the course of each trial would allow for a larger role of objects in maintaining memory for inspected locations, and would thus increase the general effectiveness of memory in guiding search. Second, as noted in the introduction, the procedure employed in the current experiment was designed to minimize the effects of mnemonic scanning strategies. When such strategies are practicable—as in a static display—and exploited, they might well expand the effective capacity of memory for search history. In contrast, the role of memory in visual search of items more discriminable than those used here may be attenuated by competition from mechanisms responsible for guiding attention on the basis of target and distractor features. Oculomotor search within a natural scene is thus likely to reflect the pull of feature-based saccade guidance as well as the push of memory for where the eyes have been.

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