Research Article

VISUAL SEARCH HAS MEMORY

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Abstract—*By monitoring subjects' eye movements during a visual search task, we examined the possibility that the mechanism responsible for guiding attention during visual search has no memory for which locations have already been examined. Subjects did reexamine some items during their search, but the pattern of revisitations did not fit the predictions of the memoryless search model. In addition, a large proportion of the refixations were directed at the target, suggesting that the revisitations were due to subjects' remembering which items had not been adequately identified. We also examined the patterns of fixations and compared them with the predictions of a memoryless search model. Subjects' fixation patterns showed an increasing hazard function, whereas the memoryless model predicts a flat function. Lastly, we found no evidence suggesting that fixations were guided by amnesic covert scans that scouted the environment for new items during fixations. Results do not support the claims of the memoryless search model, and instead suggest that visual search does have memory.*

From the time we wake in the morning until we go to bed at night, we spend a good deal of each day searching the environment. For example, as we drive from home to work, we scan the roadway for other automobiles, pedestrians, and bicyclists. In the office, we may look for a coffee cup, the manuscript we were working on several days ago, or a phone number of a colleague that we wrote down on a scrap of paper. In short, much of our life is spent searching for information relevant to the task at hand.

The scientific study of visual search has a long history in psychology. One of the first and simplest models of visual search was the serial self-terminating (SST) model, in which items are examined one at a time, and search is terminated after a target has been found or all of the items have been examined (Falmagne & Theios, 1969). Later, models such as the unlimited-capacity parallel models (SST can be considered a parallel model with a limited capacity of one) became popular. These models assume that all visible items are processed concurrently (Eriksen & Lappin, 1965) and that search is terminated after the target is found or all items have been examined. As time has gone on, more complex models have been developed as researchers have tried to capture the complexities of visual search. The reallocatable attention models (Atkinson, Holmgren, & Juola, 1969; Townsend, 1974) view attention as a resource that can be allocated in parallel to process various items. If one item finishes processing before the other items do, the resulting excess capacity can be reallocated to facilitate processing of the remaining items.

All of these models contain the implicit assumption that once an item has been examined, it is never reprocessed. Recently, however, Horowitz and Wolfe (1998) have questioned this assumption. In their experiments, subjects searched random or static displays for the presence of a target. In both types of displays, four frames of stimuli were presented, with a new frame occurring every 111 ms. In the random displays, stimulus locations were changed in each frame, whereas in the static condition, stimulus locations remained constant. If visual search is able to keep track of which locations have already been examined, then the static displays should presumably have shown a distinct advantage over the random displays. Surprisingly, search efficiency was equivalent for the two types of displays, with both yielding identical search slopes (i.e., response times increased at the same rate as the number of items in the display increased). From these search slopes, Horowitz and Wolfe inferred that visual search has no memory. More precisely, they proposed that visual search relies on a momentary representation of the environment and that the mechanism guiding attention from one item to another during visual search does not keep track of which items have already been examined.

A closer look at Horowitz and Wolfe's (1998) data, however, raises some questions. First, although the slopes were identical in the two conditions, the intercepts were not. Search was quicker for the static displays, suggesting that subjects might not have employed the same strategies when searching the two types of displays. Furthermore, the error rates were not equivalent across conditions (and appeared to interact with set size), with more errors occurring in the random than in the static condition. This suggests that search indeed might have been more efficient in the static condition.

Furthermore, other research has indicated that memory can guide attention during visual search. Klein and MacInnes (1999) have recently demonstrated that during visual search, saccades are more likely to go away from a previously fixated item than toward the item. This effect reaches as far back as items examined three fixations ago (the analysis reported stopped at three items), suggesting to Klein and MacInnes that the bias was not due to a momentary suppression of responses to the most recently visited item, but rather was due to a memory for items that did not need to be reexamined.

In addition, Chun and Jiang (1998, 1999) have demonstrated a phenomenon they named contextual cuing, in which implicit memory can guide attention to the likely location of a target when a display shares a global pattern similar to ones previously encountered. If memory representations for the locations of items can last over multiple encounters, then a memory for locations within an encounter is certainly feasible. However, what is not certain is whether the guidance mechanism involved in contextual cuing, which is sensitive to global pattern information from separate encounters, is involved in storing the locations of items already examined while searching a new display.

It certainly is the case that visual short-term memory exists, however (e.g., Baddeley, 1986; Logie, 1995; Luck & Vogel, 1997; Phillips, 1974), and one might reasonably expect visual search to take advantage of it. Furthermore, there is direct evidence that people can remember the locations of at least some items during visual scanning when they are required to do so (e.g., Hayhoe, Lachter, & Feldman, 1991; Irwin, 1992; Irwin & Andrews, 1996; Irwin & Gordon, 1998).

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For example, subjects are able to remember the location and identity of approximately four items from one eye fixation to the next, and items that are the targets of saccades are more likely to be remembered than items that are not targets of saccades (Irwin & Gordon, 1998). However, it is not clear whether this transsaccadic memory is also involved in keeping track of which items have already been examined during visual search.

Given these uncertainties, we decided to take a closer look at visual search by monitoring subjects' eye movements during a more conventional visual search task than that used by Horowitz and Wolfe (1998). Monitoring eye movements in a conventional visual search task not only allowed us to test whether eye movement-based search has memory, it also allowed us to track visual attention during the search. Previous studies have found an obligatory coupling between covert attention and voluntary saccades (Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Kowler, Anderson, Dosher, & Blaser, 1995; Rayner, McConkie, & Ehrlich, 1978; see also Henderson & Hollingworth, 1999, for a demonstration of increased sensitivity to deletions during a change-detection paradigm), suggesting that covert attention always precedes the saccade to the location of the saccade target. Although saccade execution and covert attention are obligatorily coupled, the execution of a saccade is not necessary to shift covert attention: In the absence of eye movements, covert attention can be allocated to a new location within 200 to 400 ms of a signal to shift attention (Cheal & Lyon, 1991; Müller & Rabbit, 1989; Sperling & Weichselgartner, 1995; Weichselgartner & Sperling, 1987).

To prevent parallel search from occurring, we used a set of stimuli with high target-distractor and distractor-distractor similarity, rotated *T*s and *L*s. These stimuli have been shown to produce inefficient (slow) search (Wolfe, Cave, & Franzel, 1988). In addition, to discourage participants from scanning the environment using only their covert attention, we made the items sufficiently small and spaced far enough apart that only one item could be examined in a single glance. Under these circumstances, the items being examined are the items being fixated, so we were able to track the search path by recording eye movements.

A memoryless search model makes several predictions. First, if visual search has no memory, subjects should frequently reinspect locations that have already been examined. However, this does not mean that a memory-based model must predict that locations will never be reexamined. For example, a model with perfect memory might predict that subjects will reexamine an item if attention has prematurely left the item before it has been adequately identified. In such a case, subjects might willfully make regressive saccades to reinspect the item. This would lead to a pattern of revisitations that is distinctly different from the pattern predicted from the memoryless model.

Second, because memoryless search is equivalent to sampling with replacement, memoryless search predicts a flat hazard function. Hazard functions give the instantaneous probability that an event will occur given that the event has not yet occurred. In our case, the hazard function represents the probability that the target will be found on fixation n given that the target has not already been found. In the case of amnesic search, because there is no memory for which items have been examined, the potential search set does not decrease as more and more items are examined. The probability that the target will be found (given that it has not already been found) will remain constant during the course of a trial, leading to a flat hazard function. In contrast, SST predicts that the likelihood that the target will be found increases as the number of items examined increases (an increasing hazard function). That is, as more and more items are examined, the set of possible items to choose from

shrinks, increasing the likelihood that the next item chosen will be the target and producing an increasing hazard function (the longer you search, the more likely you are to find the target). If subjects produce a hazard function with a slope that is significantly greater than zero, then we can conclude that visual search has memory.

METHOD

Participants

Five students (3 males and 2 females) from the University of Illinois were paid to participate in the study. The average age of the participants was 19.6 years. All had normal or corrected-to-normal visual acuity.

Apparatus

A Gateway Pentium 133-MHz computer with a 19-in. SVGA color monitor running custom software was used to present the stimuli, control the timing of the experimental events, and record participants' response times. Eye movements were recorded with an Eyelink tracker (SR Research Ltd.) with 250-Hz temporal resolution and a 0.2° spatial resolution. The system uses an infrared video-based tracking technology to compute the center and size of the pupils in both eyes. An infrared system tracked head motion. Even though head motion was measured, the head was stabilized by means of a chin rest. The chin rest was located 53.3 cm from the monitor.

Stimuli

The stimuli consisted of white *T*s and *L*s approximately 0.19° tall and 0.19° wide (3 × 3 pixels) drawn on a gray background. Targets were *T*s rotated 90° left or right of vertical. Distractors were normal or mirror-imaged *L*s rotated 0°, 90°, 180°, or 270°, and premasks consisted of squares with dimensions identical to those of the targets and distractors. Premasks were used to prevent the appearance of the stimulus displays from acting as an onset. The minimum distance between stimuli was 4.9°, and the display was approximately 35.6° wide and 25.4° tall. One target and 11 distractors were present within each display.

Procedure

Participants initially fixated a central cross in the premask display and pressed the space bar to start a trial. The trial proceeded only if the participant was fixating within 2° of the cross. The fixation display was then replaced by the stimulus display, and the subject was free to search the display. The participant's task was to determine which target, a left or right 90°-rotated *T*, was present in the display. The participant responded by pressing the "z" or "/" key on the computer keyboard, and the mapping of the keys to the target identity was counterbalanced across subjects. A tone sounded if an incorrect response was made.

Subjects participated in a single 1-hr session consisting of 15 practice trials and 384 experimental trials.

RESULTS

Eye Movement Data

Eye movements were classified as saccades if they met one of two criteria: (a) speed greater than 30°/s and acceleration exceeding 8000°/s²

or (b) acceleration exceeding 8000°/s² and a distance greater than 0.2°. The first saccade was the first eye movement that landed outside of a 2° imaginary circle around fixation.

The data were analyzed to determine how often and how long ago an item was revisited. A fixation was counted as landing on an item if it occurred within 2.16° (roughly half the closest distance between any two items). If several fixations in a row landed on the same item, they were treated as a single fixation and their durations summed. In addition, revisitations at greater than 13 lags were included in the 13th-lag bin. As can be seen in the top panel of Figure 1, almost all of the revisits were made to the item visited two lags previously (one intervening item).

Monte Carlo Simulation

To more accurately compare our results with the expected results from memoryless search, we performed a Monte Carlo simulation of
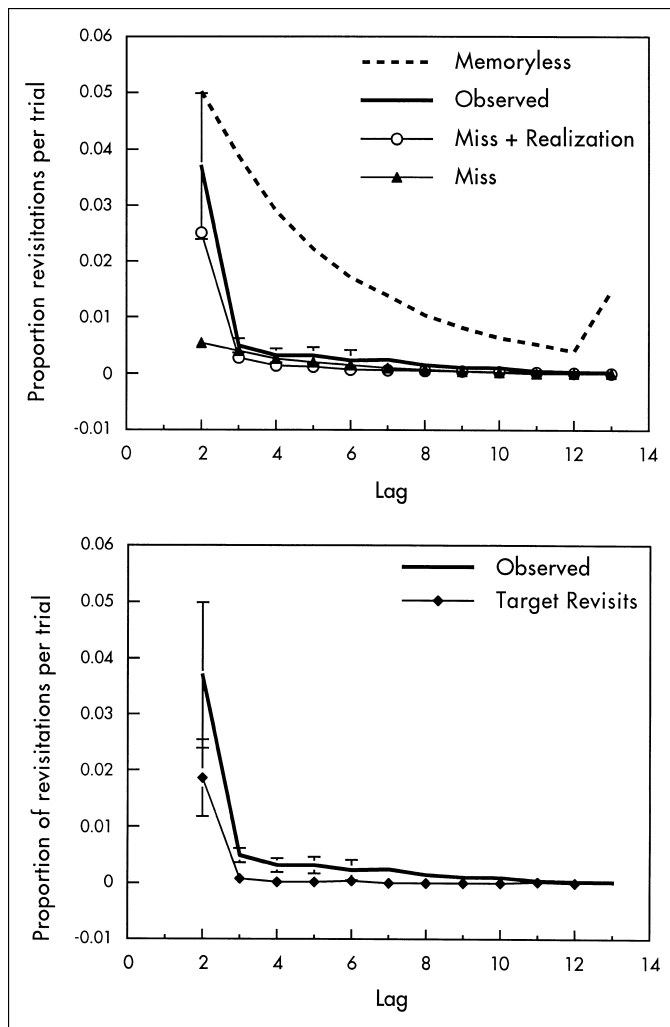

Fig. 1. Proportions of revisitations as a function of intervening items (lag). The top panel shows the observed data (error bars represent the 95% confidence interval) and the predictions for memoryless search and for the miss and miss + realization models. The bottom panel shows the proportion of revisitations that were destined for the target, along with the observed data for all revisitations.

the memoryless search model. The expected results for the model were calculated by randomly selecting items to "examine" on each trial until the target was found, with the constraint that the item currently being examined could never be picked as the next item to be examined. If an item had already been examined on that trial, the lag since its last examination was recorded. The probability of revisiting an item was then calculated for each lag for each trial by dividing the number of revisitations at that lag by the total number of visitations in that trial. As in the analysis of the behavioral data, revisitations greater than 13 lags were grouped in the 13th bin. The simulation was run using 5 "subjects," with each subject receiving 384 trials with a set size of 12.

The observed and predicted data were compared using multiple t tests with a Bonferroni correction for the number of tests performed. The observed data were significantly different from the data predicted by the memoryless search model except at the second lag, with the highest p value occurring for the sixth lag, $t(4) = -11.9$, $p = .00008$. The revisitation rate at lag 2 was 3.7%, which is similar to the lag 2 revisitation rate of 3 to 4% Motter and Belky (1998a) observed in monkeys. In addition, the overall proportion of revisits was much smaller for the observed data than predicted by the memoryless model (5.7% vs. 26.1%), $t(4) = 377.5$, $p < .001$.

A closer examination of the revisitations suggests that a large portion of them were due to willful reexaminations of already-examined items. As can be seen in the bottom panel of Figure 1, a large proportion of the revisitations were to the target (5.7% of the gazes were revisitations, and 2% were revisitations to the target). This suggests that subjects not only had a memory for which items had been examined and which had not, but also had a memory for items that had been inadequately processed.

To test the hypothesis that the observed revisits were due to inadequate initial examinations, we tested two different models. In the first model, which we call the miss model, a certain proportion of items are not adequately processed, and these items are considered not-yet-fixated items and can be reexamined. Otherwise, adequately examined items are never revisited. The second model, which we call the miss + realization model, is an extension of the miss model in which there is a fixed probability that a subject consciously realizes that the last fixated item was not adequately processed and revisits that item on the next fixation. As in the miss model, inadequately processed items that the subject is not conscious of can be revisited. For both models, we estimated the probability that an item would be inadequately examined (i.e., "missed") by taking the observed average proportion of saccades that were revisits (5.7%). For the miss + realization model, we estimated the realization rate parameter by calculating the proportion of revisits that occurred at lag 2 (53.7%). The results of the miss and miss + realization models can be seen in the top panel of Figure 1 and compared with the observed data and results of the memoryless model. Both the miss model and the miss + realization model ($R^2 = .55$ and .86; $RMSE = 0.010$ and 0.005, respectively) fit the individual subject data better than the memoryless model ($R^2 = .53$, $RMSE = 0.017$), with the miss + realization model producing the best fit of all.

Fixation Distribution Results

A crucial prediction made by the memoryless search model is that there is a small, but real, possibility that search could continue indefinitely (or at least until some criterion maximum search duration is exceeded). That is, because memoryless search is equivalent to sampling with replacement with the only constraint being that no item is sampled

twice in a row, there is a possibility that the target might never be examined. Mathematically, memoryless search predicts a flat hazard function (the probability that the target is found on fixation n given that it had not been found by fixation $n - 1$) for the number of examinations per trial until the target is found. Figure 2 shows the predicted hazard functions from the Monte Carlo simulations of our memoryless, miss, and miss + realization models and the hazard function calculated from our subjects' data. The hazard function for the observed data has an increasing slope ($R = .75$), $F(1, 63) = 79.67$, $p < .001$, which clearly violates the prediction of the memoryless model. As with the refixation data, the two memory-driven models did a better job of predicting individual subjects' performance ($R^2 = .57$ and .64, $RMSE = 0.39$ and 0.49, for the miss and miss + realization models, respectively) than did the memoryless search model ($R^2 = .07$, $RMSE = 0.62$).

Covert Scanning

Although the pattern of eye movements suggests that visual search is guided by a representation in memory consisting of which items have and have not been examined, an alternative explanation is that covert attention scans the environment during each fixation until it finds an item that has not been visited. That is, the new item to be the target of the next saccade might not be automatically picked on the basis of a stored representation of locations and identities, but rather the effects of memory-guided search might be mimicked by attention randomly scouting the environment during a fixation until an unknown item is found.

Although this amnesic foraging could lead to a pattern of fixations that mimics memory-guided search, it predicts a different pattern of fixation durations. As more and more items are examined, the likelihood of randomly finding a new item decreases. This in turn predicts that as the number of items examined increases, the number of random attentional samplings needed to find a new item during a fixation will increase at an accelerating rate. If the number of attentional samples during a fixation increases, then it would be reasonable to assume that
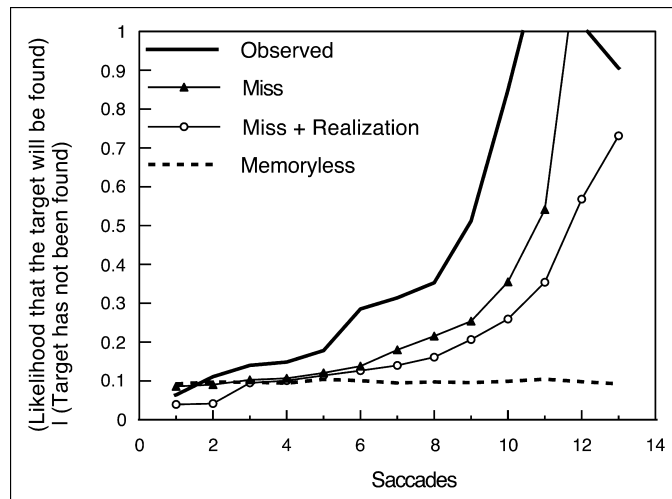

Fig. 2. Hazard functions for the observed data, memoryless model, miss model, and miss + realization model. Ideally, the hazard function for the observed data should reach 100% at 12 or more saccades, but because data for the denominator of the hazard function are frequently sparse, the right-hand tail tends to be noisy.

the duration does, too. More specifically, we used the probability of finding an old item, a, to calculate the maximum and then the mean number of samples needed to find a new item on fixation n given our subjects' average revisitation (failure) rate:

$$a = \frac{f - 1}{n - 1}$$

$$Max(f) = \log_a r$$

$$Mean(f) = \frac{1 - a^{Max(f)}}{1 - a}$$

where r is the revisitation rate, n is the number of items in the display, and f is the fixation number (or number of unique items fixated so far).

As illustrated in the middle panel of Figure 3, when there are only a few new items remaining to be discovered, memoryless scouting predicts that the expected number of samples needed to find these new items greatly increases. However, as can be seen in the top panel of Figure 3, the number of remaining items had little effect on the observed fixation durations. The bottom panel of Figure 3 shows the observed fixation durations as a function of the number of samples predicted by memoryless scouting. If we assume that each covert sample takes the same amount of time, memoryless scouting predicts that each additional sample will cause a corresponding increase in fixation duration. Although the observed fixation durations increased as the mean number of possible samples during a fixation increased, fixation durations increased at the rate of only 3.4 ms per covert sample. Given the abundant evidence suggesting that serial attentional shifts take on the order of 200 to 400 ms to complete (Cheal & Lyon, 1991; Moore, Egeth, Berglan, & Luck, 1996; Müller & Rabbit, 1989; Sperling & Weichselgartner, 1995; Weichselgartner & Sperling, 1987), it is highly unlikely that the lengthened fixation durations are due to amnesic covert scanning of the environment, a conclusion also drawn by Motter and Belky (1998b) with regard to visual search in monkeys. More mundane phenomena, such as intratrial fatigue, are more likely to be the source of the increased fixation durations.

DISCUSSION

The present results clearly do not support the memoryless search model of Horowitz and Wolfe (1998). The distribution of revisitations does not match the predictions for memoryless search, and a large portion (roughly 35%) of the revisitations were directed to the target, suggesting that the revisitations were not due to subjects forgetting which items had already been examined, but instead were due to subjects returning to items that had been inadequately processed on first examination. We fit two models based on the assumption that visual search has perfect memory and items are reexamined only when they are not adequately processed the first time they are examined. Both of these models fit the data better than the memoryless search model, with the miss + realization model providing the best fit. Furthermore, a truly memoryless search model leaves open the possibility that search could continue indefinitely, with the target never being found. This means that memoryless search predicts a flat hazard function, and our data do not fit this prediction. Both of our miss models predict an increasing hazard function and fit the observed data much better than the memoryless model. Finally, although the number of random covert samples needed to find an unexamined item would increase exponentially as
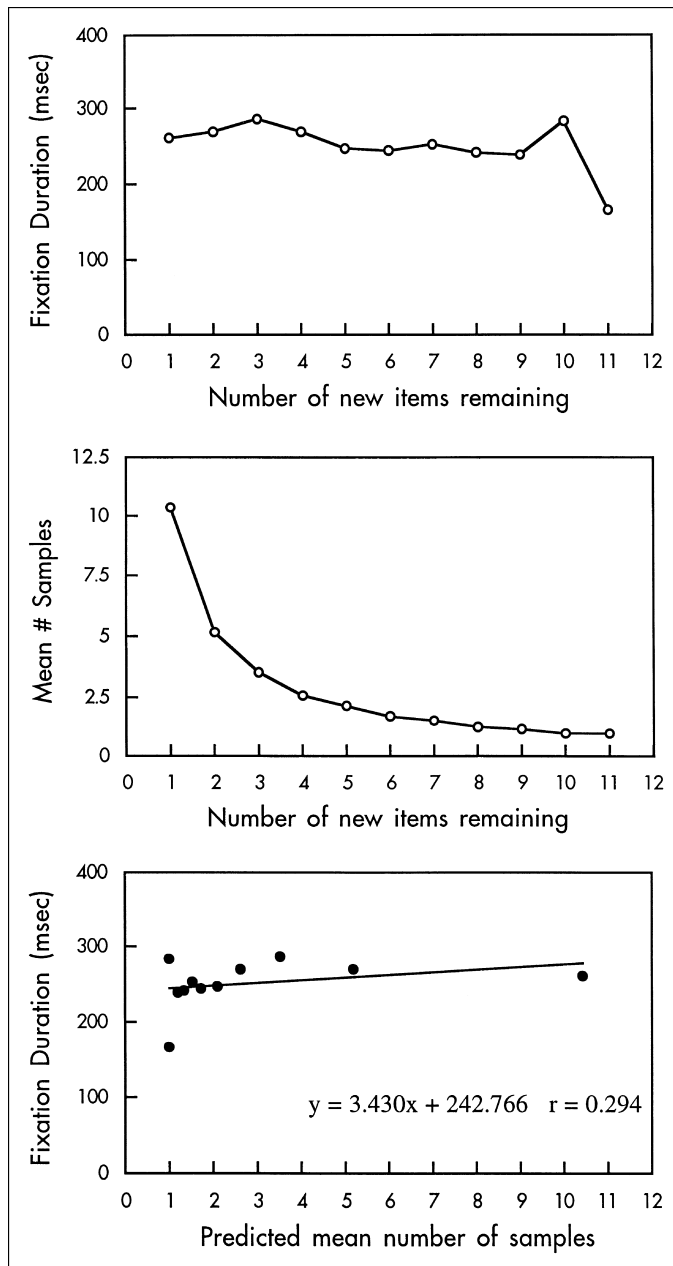
Fig. 3. Fixation durations compared with the number of items remaining and the predicted number of scans for memoryless serial covert search. The top panel shows mean fixation duration as a function of the number of unexamined items remaining in the display. The middle panel shows the predicted mean number of covert samples as a function of the number of new items remaining in the display. Fixation duration as a function of the predicted mean number of covert samples is graphed in the bottom panel. In all panels, fixation durations are for locations that were not subsequently revisited.

more and more items have been fixated, fixation duration increased only slightly, suggesting that covert scanning was not taking place during fixations. Taken as a whole, our results suggest that eye movement-based visual search does have memory, and it is not a result of memoryless attentional scanning between fixations.

Upon first glance, our results suggest that visual search has a memory of at least 12 items (because subjects rarely reexamined items). This estimate is considerably higher than previous estimates that the capacity of visual short-term memory (Luck & Vogel, 1997) and transsaccadic memory (Irwin, 1992) is approximately 3 to 4 items. However, it is certainly possible that the memory capacity of visual search is actually much less than 12 items, and that strategies such as chunking are able to expand the effective capacity (see also Pashler, 1997, for evidence that displays can be serially searched in clumps, with parallel processing occurring within the clumps). This is an issue for further research.

One question that remains is why Horowitz and Wolfe's (1998) results suggest memoryless search whereas our results suggest memory-based search. One possibility is that our displays, although somewhat artificial (i.e., on the one hand, people do not often search for letters randomly distributed in the environment, but, on the other hand, they do often search for targets, e.g., a friend in a crowd, that have features similar to those of distractors), were more ecologically valid than the flashing displays used by Horowitz and Wolfe. It is not often that people search through flashing environments, and the changes inherent in Horowitz and Wolfe's displays might have disrupted processes other than memory for searched items (see Kristjánsson, 2000, for evidence for memory during visual search when items in the random condition swap places rather than appearing at previous unoccupied locations). Another possibility is that a speed-accuracy trade-off occurred in Horowitz and Wolfe's study, making comparisons of the response times to the static and random displays difficult to interpret. A further possibility is that observers in Horowitz and Wolfe's experiments were able to accumulate evidence for the presence of a target in parallel over the entire display (Klein, Shore, MacInnes, Matheson, & Christie, 1998). In any event, our results clearly suggest that observers can keep track of where they have previously looked during visual search.

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