Refixation frequency and memory mechanisms in visual search

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Visual search – looking for a target object in the presence of a number of distractor items – is an everyday activity for humans (for example, finding the car in a busy car park) and animals (for example, foraging for food). Our understanding of visual search has been enriched by an interdisciplinary effort using a wide range of research techniques including behavioural studies in humans [1], single-cell electrophysiology [2], transcranial magnetic stimulation [3], event-related potentials [4] and studies of patients with focal brain injury [5]. A central question is what kind of information controls the search process. Visual search is typically accompanied by a series of eye movements, and investigating the nature and location of fixations helps to identify the kind of information that might control the search process. It has already been demonstrated that objects are fixated if they are visually similar to the target [6]. Also, if an item has been fixated, it is less likely to be returned to on the subsequent saccade. This automatic process is referred to as inhibition of return (IOR [7,8]). Here, we investigated the role of memory for which items had been fixated previously. We found that, during search, subjects often refixated items that had been previously fixated. Although there were fewer return saccades than would be expected by chance, the number of refixations indicated limited functional memory, indeed the memory effects that were present may primarily be a result of IOR.

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Received: **21 June 2000**
Revised: **25 July 2000**
Accepted: **8 August 2000**

Published: **22 September 2000**

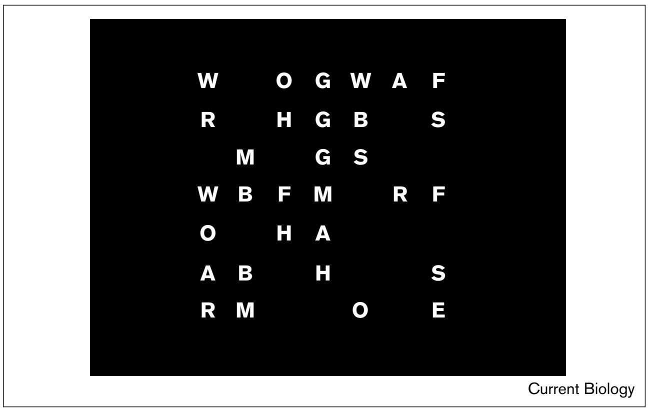
Current Biology 2000, 10:1209–1212

0960-9822/00/$ – see front matter

Results and discussion

Horowitz and Wolfe [9] have argued that memory for the location of items in a display plays little role in determining search performance. They changed the visual search display regularly during a single search trial and found that subjects were no more efficient (in reaction time) at finding a target than if the display was left unchanged. This result suggested that visual attention moved randomly around the display with no memory for which locations had been previously inspected. A more direct method to assess the allocation of attention in visual search is to measure saccadic eye-movements. In tasks that require fine discrimination for target detection, given the concentration of high-resolution vision in the fovea, location of the eyes gives a good indication of where attention is allocated. Such an approach has provided important converging evidence about the processes that support successful search performance [10–12].

Figure 1



Example display from the experiment. The subject's task is to search for an E target among the distractor letters.

Figure 1 shows an example of a display for a search task that we carried out to investigate memory effects in visual search. There were three observers, who are referred to here by their initials AH, MH and SC. Participants searched for a target letter E among 31 other capital letters. Error rates were low overall (Table 1) and subjects made a number of saccades in each trial before making a manual response to indicate the presence or absence of the target. Figure 2 shows the frequency distributions of the number of fixations in a trial for the three participants.

To assess the extent to which subjects avoided previously visited locations, we considered two models that represented the two extremes of memory performance: perfect-memory and no-memory. In the first model, the location of each item that had already been fixated would be remembered, and previously fixated items would never by refixated. Such a model can be formalised within probability theory as it is analogous to sampling without replacement. In contrast, in the second model, it is assumed that no memory is formed for which items have been previously fixated; this is equivalent to sampling with replacement. For the first model, in which memory is perfect, the simple prediction is that there would be no refixation. For

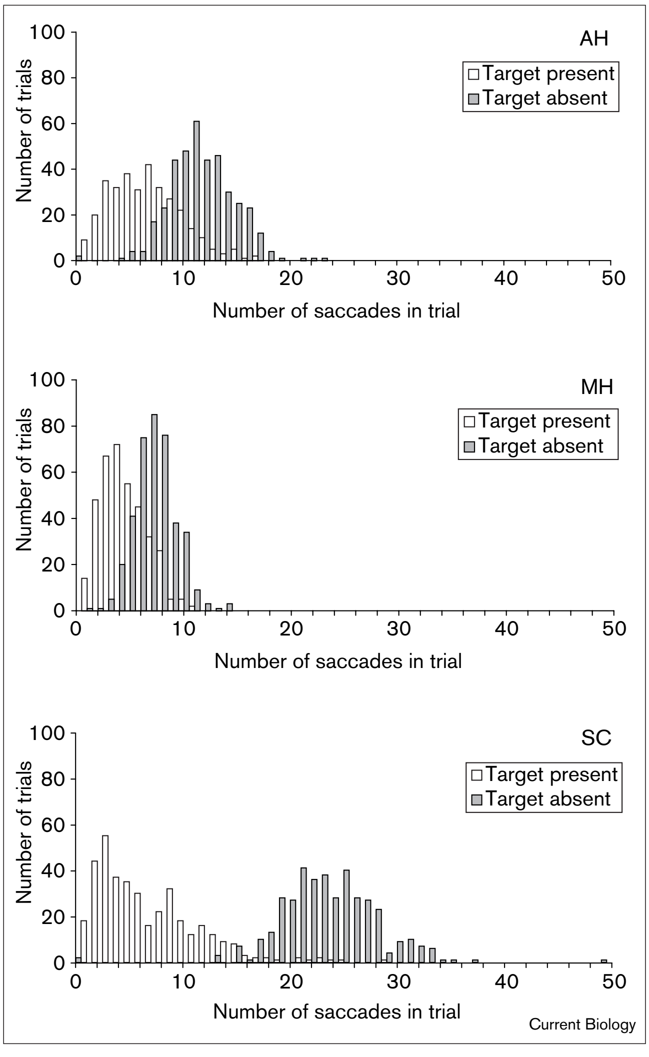
Table 1

Summary statistics for the three participants.

Measure	Condition	Participant AH	Participant MH	Participant SC
Mean reaction time in msec (SD)	Present	1892 (824)	1385 (598)	2282 (1340)
	Absent	3136 (694)	2249 (395)	7325 (1191)
Error rate (%)	Present	16.1	4.85	1.53
	Absent	0.26	0	0.26
Mean fixation duration in msec (SD)	Present	189 (85)	195 (89)	241 (129)
	Absent	176 (63)	189 (77)	211 (78)
Memory metric (%)	Present	45.0	57.0	52.3
	Absent	48.7	60.2	12.2

Where appropriate the standard deviation (SD) for the descriptive statistics is shown in brackets. Details of the calculation of the Memory Metric can be found in the main text.

Figure 2

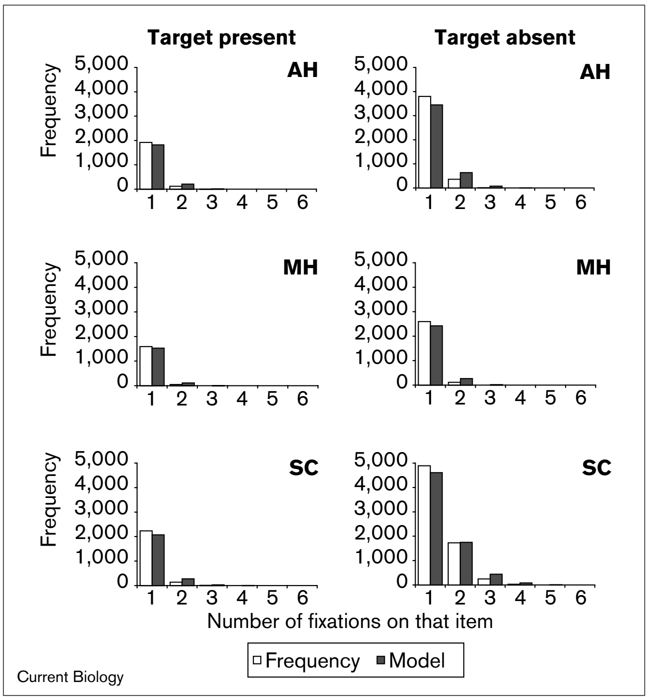


The graphs show the number of trials (vertical axis) which contained a given number of saccades (horizontal axis). Data from the three observers (AH, MH and SC) are plotted separately. Target present trials are plotted in white and target absent trials are plotted in gray.

the second model, in which there is no memory, we used elementary probability theory to calculate for each trial the proportion of returns we would expect, given the number of saccades in each trial. This included a calculation for the number of single returns — fixating an item and then returning to it once during the search — and the number of higher-order or multiple returns expected. These frequencies were combined across trials to give an expected frequency of returns for target present and target absent trials for each subject. These expected frequencies are plotted along with the observed return frequencies in Figure 3. For all subjects, for both target present and target absent, there were a large number of refixations. This suggests that the perfect-memory model is inadequate, as returning to a previously fixated item constitutes a failure of memory. However, Figure 3 also shows that the no-memory model overestimated the number of return saccades that had occurred. Participants were less likely to refixate an item that had been previously fixated than would be predicted by chance. The memory performance seemed to fall somewhere between these two extremes.

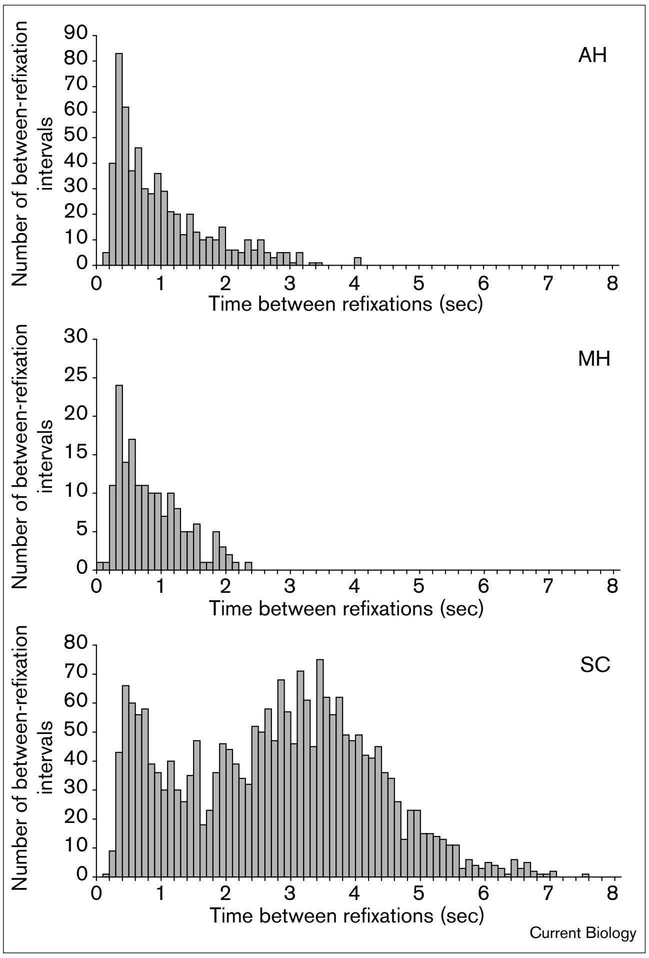
We can extend this analysis and use these estimates to calculate a single memory metric. This is the percentage of returns observed compared with the number of returns expected from the no-memory model; 0% corresponds to no-memory and 100% corresponds to perfect memory. These proportions are reproduced in Table 1. In general, these estimates were somewhere around 50%. In fact, there are a number of reasons why the analysis presented may overestimate the extent of the memory component. The model assumes that in the search task only the fixated item is processed. There is good evidence that this is probably not the case in search [6,13], and that during each fixation there is the capacity to process, at least partially, adjacent items to the current fixation. In addition, saccades can be guided to display items that are similar to the target [6] (although see [10]). Such guidance suggests that peripheral processing of items also occurs in a fixation. In the model, if a subject fixates a location that has

Figure 3



The graphs show the number of times an item was visited (vertical axis) plotted against the number of fixations on that item (horizontal axis) combined across all trials. These data from each participant (AH, MH and SC) for target present and target absent are plotted separately in white. The dark bars show the distribution of number of visits expected if items were fixated on the basis of random selection of the next item to be fixated.

Figure 4



The graphs show the number of between-refixation intervals (vertical axis) plotted against the time between refixations. These data, combined across present and absent trials, are plotted for the three participants separately (AH, MH and SC).

not been previously fixated, this is never counted as a refixation. If the new location is adjacent to a previously fixated location, however, then it may have already been previously processed and could have been identified as a distractor. This then should count as a failure of memory but does not in the model.

In contrast, there are reasons why the model may also underestimate the extent of the memory component. Henderson [14] suggested that the fixation duration is controlled by a deadline after which the next saccade is generated. As a result, the next saccade can be generated before the processing of the fixated item is complete. When this occurs, refixations constitute a return to complete processing of an item rather than a failure of memory.

The memory calculation presented here includes both the marking of locations as visited [15] and low-level processes like IOR. We can get one measure of the extent of the IOR effect in these data by looking at the time spent fixating on other items in the display before refixation. Note that in the current experiment, this measure is equivalent to the number of fixations before refixation, as fixation duration was very stable across fixations as well as the type of item fixated. In the current experiment, IOR may prevent subjects from refixating a recently visited location by inhibiting that location. As this effect is only short-lived, we would expect a dip in the distribution for short inter-fixation durations. Inspection of Figure 4 shows that such a dip is present. The duration between refixations rises to a peak between 300 and 400 milliseconds for AH and MH which is equivalent to about two fixations before refixation. For SC this interval is between 400 and 600 milliseconds. This difference can be explained by the slightly longer fixation durations in this subject, but it also suggests that for this subject the inhibition had a slightly longer temporal influence. This pattern provides strong support for IOR in this task; subjects only occasionally fixated an item, generated a saccade away from it, and then immediately return to that item (this may not be the case for all types of search display [12]). Given the strong evidence for IOR in the current experiment, this suggests that memory for previously fixated items (excluding IOR) is even weaker than the previously calculated estimates suggest. Subject SC also had a second peak in the distribution of time between fixations after about 3 seconds. For target-absent trials in particular, SC generated more saccades than there were items in the display in a significant proportion of trials (see Figure 2). The second peak in Figure 4 then reflects the complete rechecking of locations. This is also reflected in SC's very low memory metric estimate for target-absent trials (Table 1) and may explain the differences in the shape of the distribution of number of saccades in a trial (see Figure 2).

Taken together, these results suggest that when the eyes move from one location to another in visual search, memory for the locations that have already been visited plays only a small part in shaping the scanpath. In contrast, we do find evidence that IOR plays a part in determining scanpaths in visual search [8]. More detailed analysis of scanpaths and more sophisticated models of sampling will be required to quantify the exact extent of the memory that is present. The current result suggests, however, that remembering the locations that have been visited in search, in order to avoid searching that location again, does not appear to be a dominant mechanism.

Materials and methods

Eye movement recording

Two-dimensional eye movements were recorded using an SMI Eye-Link eye tracker (SensoMotoric Instruments GmbH, Berlin, Germany), which is an infrared video system sampling at 250 Hz, and features a head movement compensation mechanism. We recorded from both eyes and analysed the data from the eye that produced the best spatial resolution, which in these experiments was typically less than 0.20°. Displays were presented on one personal computer (subject PC), while a second PC (operator PC) recorded the eye position data on-line. The display monitor was a 17 inch SVGA monitor with 800×600 pixel resolution. A chin rest was used to minimise head movements.

The eye-position data was analysed off-line by an automatic saccade detection procedure. A fixation was defined as having ended when the eye velocity exceeded 30°/sec. A fixation began after the velocity fell below this value for five successive samples (20 msec). The eye-tracker was calibrated and validated at the beginning of each experimental block.

Fixations were classified as being to a certain location if they landed within a 2° by 2° box around that item. Fixations classified as being a repeat fixation on the same location were combined together and for all the analyses reported counted as a single fixation. Fixations outside the display area, fixations to blank locations between item boxes and fixations on the target at the end of the search were all excluded from the analysis. These combined criteria resulted in the exclusion of 27, 33 and 28% of fixations for the three participants, respectively. The stringent exclusion criteria also slightly increased the extent to which the model overestimated the extent of memory. The analysis presented included the remaining 6118, 4084 and 10748 fixations for AH, MH and SC, respectively.

Design and procedure

Each participant completed nine blocks of trials. Three sessions were carried out on three separate days, with three blocks completed in each session. Each block contained 98 trials, resulting in 882 trials per participant. Figure 1 shows an example display. The stimulus display consisted of 31 capital letters arranged randomly at 31 of the 49 intersections of an imaginary 7 by 7 grid, with blank spaces appearing in the other 18 locations. There was a 2° centre-to-centre spacing between the intersections. The participants were instructed to make a present/absent judgement for the letter E, which was present in half the trials, appearing once in each location. The distractor items were the capital letters A, B, F, G, H, M, O, R, S and W, each appearing three times. In trials where the target was not present, the target letter was replaced with a letter chosen randomly from the distractor set. Present or absent manual responses were made by the participant using a button box with two buttons arranged side by side. Participants were given verbal instructions describing the task, requesting that responses be made quickly and accurately.

Acknowledgements

This work was supported by EPSRC, UK. We thank Emese Csete for collecting the data; and John Findlay and Jeremy Wolfe for insightful comments on an earlier draft of the manuscript.

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