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ORIGINAL ARTICLE

Memory processes in multiple-target visual search

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Abstract Gibson, Li, Skow, Brown, and Cooke (*Psychological Science, 11*, 324–327, 2000) had participants carry out a search task in which they were required to detect the presence of one or two targets. In order to successfully perform such a multiple-target visual search task, participants had to remember the location of the first target while searching for the second target. In two experiments we investigated the cost of remembering this target location. In Experiment 1, we compared performance on the Gibson et al. task with performance on a more conventional present–absent search task. The comparison suggests a substantial performance cost as measured by reaction time, number of fixations and slope of the search functions. In Experiment 2, we looked in detail at refixations of distractors, which are a direct measure of attentional deployment. We demonstrated that the cost in this multiple-target visual search task was due to an increased number of refixations on previously visited distractors. Such refixations were present right from the start of the search. This change in search behaviour may be caused by the necessity of having to remember a target-allocating memory for the upcoming target may consume memory capacity that may otherwise be available for the tagging of distractors. These results support the notion of limited capacity memory processes in search.

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Introduction

The visual environment contains multiple objects most of which are irrelevant to the current behavioural goal. The task for any organism, including humans, is to locate and identify the item that is relevant (the target) from amongst the other objects (the distractors). In a complex environment this task involves visual search: a topic that has attracted a great deal of research effort over the last 30 years. One question in this research area is the extent and nature of the memory processes that support search (see Shore & Klein, 2000; Wolfe, 2003). If in search, which of the distractors has already been checked is remembered the target may be found more efficiently because distractors are less often rechecked by mistake.

A number of research groups have argued that there is no memory for previously visited distractors (e.g., Horowitz & Wolfe, 1998, 2001). In a highly influential paper Horowitz and Wolfe (1998) had subjects perform a standard visual search task (search of a T amongst L's) in a regular (static) display and in a so called dynamic display. In the dynamic display, the items were reshuffled every 100 ms so that memorising distractor positions during search was impossible. A comparison of the slopes of the search functions (a measure of search efficiency) between the static and the dynamic condition indicated no differences. Horowitz and Wolfe concluded that subjects performed search in both displays in the same way and did not use memory to support search.

The denial of memory for distractors in a search has since become a controversial topic (see Shore & Klein, 2000). Some research groups have produced empirical evidence for memory mechanisms that prevent item revisits (e.g., Kristjansson, 2000; Peterson, Kramer, Wang, Irwin, & McCarley, 2001); while other groups have emphasised the limited capacity of these memory processes (Gilchrist & Harvey, 2000; Körner & Gilchrist, 2006) and the strategic task-dependent deployment of memory (Gibson, Li, Skow, Brown, & Cooke, 2000; Gilchrist, North, & Hood, 2001; Gilchrist & Harvey, 2006).

Ward and McClelland (1989) introduced a paradigm using two identical targets to investigate differences between search models. More recently, a few studies have used such a paradigm to investigate the role of memory in search (Gibson et al., 2000; Horowitz & Wolfe, 2001; Husain et al., 2001). In these experiments participants have to search for more than one target amongst distractors and report either the exact number (Gibson et al., 2000; Husain et al., 2001) or make an upper bound judgment for the number of targets (Horowitz & Wolfe, 2001). Gibson et al. carried out the first of these multiple-target search experiments to study memory. Participants had to search for the presence of either one or two identical targets and make a manual response to indicate the number of targets. Performance on this multiple-target search task shared many features with traditional visual search in which the participants indicate the presence or absence of a target. First, search times increased linearly with display size, suggesting that attention was being allocated to items, or groups of items, in a serial manner. Second, the search slopes for the one-target condition were approximately double that of the two-target condition, paralleling the ratio typically found between target-present and target-absent search trials. Indeed, the task for the participants in this new task appears to be very close to traditional search.

A direct comparison between these two types of search (traditional search versus multiple-target search) provides one measure of the consequence of remembering the target. In order to make this comparison, in Experiment 1 we replicated the Gibson et al. (2000) task, but also included a traditional target present–absent search task. We also recorded participants' eye movements as this provides an alternative measure of performance (Williams, Reingold, Moscovitch, & Behrmann, 1997). Replicating the more novel Gibson et al. paradigm alongside the more traditional visual search paradigm within the same participants allowed a more direct comparison of these paradigms while avoiding display manipulations that disrupt the normal search process (cf. Horowitz & Wolfe, 1998).

Experiment 1

Method

Participants

There were 16 students (nine males, seven females) all from the University of Bristol who participated for course credit; the average age was 24.8 years (ranging 20–38 years) and all had normal or corrected-to-normal vision. The experiments had ethical approval from the University of Bristol.

Stimuli and procedure

As far as possible the displays were identical to those in Gibson et al. (2000). We used the same abstract symbols, but in our experiment, these items subtended an area of $1° \times 2°$ at the viewing distance of 63 cm. The items appeared randomly at the intersections of an imaginary 7×7 grid with an additional random deviation of $\pm 0.24°$ both in horizontal and vertical direction (see Fig. 1).

Participants carried out two tasks in separate blocks. In one block the task was a standard target present–absent search; the second task was a one or two targets present task. At the beginning of each block subjects were familiarised with the search items on a piece of paper and we explained what was the

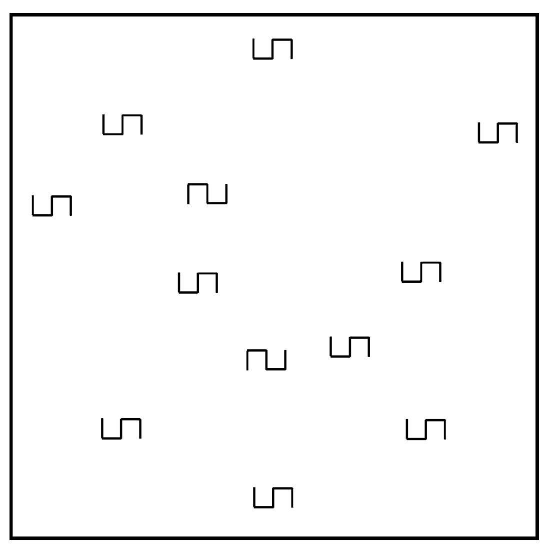

Fig. 1 Example search display with ten distractors and two targets

target and what was the distractor symbol. We also explained that there could be either a single target or no in the displays (present–absent task), or that there could be one versus two targets in the display (two-target task). Each block contained 120 trials. In both tasks, trials could contain 8, 12, or 16 items and there was an equal number of trials for the two response types. Trial order was randomised and task order was counterbalanced across participants. The two conditions (one- versus two-target condition) for the two-target task and the two conditions (target-absent versus target-present) for the present–absent task produced four search functions.

At the beginning of each trial, a fixation point was presented in the centre of the screen until fixation was registered. The display was then presented until the participant pressed one of two buttons on a response box. Subjects were told to use the dominant hand for a target-present response and the other hand for an absent response in the present–absent task, and the dominant hand for a two-target response in the two-target task, respectively. Participants were instructed to respond as quickly and accurately as possible.

Apparatus

We recorded two-dimensional eye movements using an Eye-Link II eye tracker (SR Research, Osgoode, Canada). We recorded from both eyes at a sampling rate of 250 Hz and analysed the data from the eye that produced the best spatial resolution, which was typically better than 0.35°. Displays were presented on a 21 in. monitor with a resolution of 1,152 × 864 pixels. A chin rest was used to minimise head movement.

Results and discussion

The overall error rate was low in the target-absent condition, 1.6% (range 0–6.7%), and in the target-present condition, 4.2% (range 0–10%). Similarly, error rates were low in the one-target condition, 2.1% (range 0–8.3%) and the two-target condition, 7.8% (range 1.7–16.7%). These error rates are consistent with, though lower than the error rates reported by Gibson et al. (2000). For all the following analyses only data from correct trials were considered.

Figure 2 (solid lines) shows the mean correct response times as a function of condition and display size. Search was slower and less efficient in the target-absent condition (258 ms per item) compared with the target-present condition (108 ms per item). In the two-target task the search slope was 171 ms per item in the two-target condition and 308 ms per item in the one-target condition. Despite the fact that our participants were more accurate and so somewhat slower on average, this difference in search rate is comparable with the findings of Gibson et al. (107 ms per item in the two-target condition and 180 ms per item in the one-target condition). Comparing across tasks, performance in the target-absent condition was more efficient (258 ms per item) than in the one-target condition (307 ms per item), a difference of 49 ms per item ($F(1, 15) = 10.40, p < 0.01$).

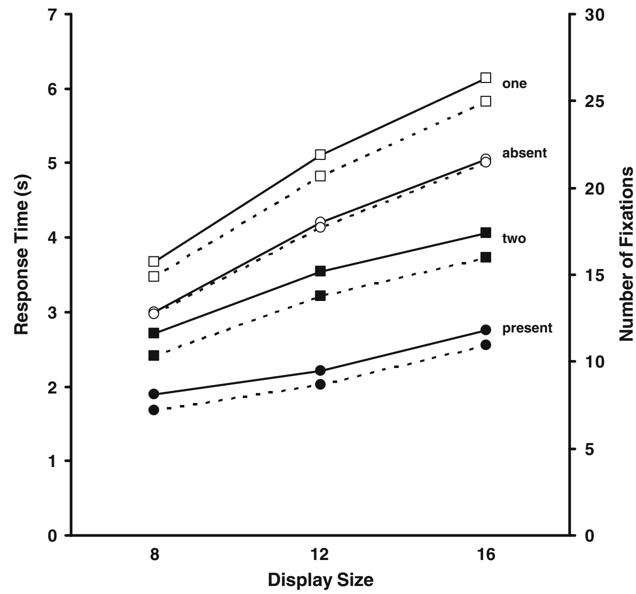

Fig. 2 Experiment 1: mean response times (*solid lines*) and mean number of fixations (*dashed lines*) per condition and display size

Figure 2 (dashed lines) shows the mean number of fixations as a function of condition and display size per trial. The number of fixations closely mirrored the manual reaction times. For example, for the display size of 12, subjects needed a mean of 17.68 fixations (corresponding to 4,200 ms) before responding in the target-absent condition as opposed to 8.65 fixations (2,205 ms) in the target-present condition; likewise, search took 20.68 fixations (5,111 ms) in the one-target condition compared with 13.76 fixations (3,542 ms) in the two-target condition. Search proceeded at a rate of 1.1 fixations/item in the target-absent condition compared with 0.47 fixations/item in the target-present condition. Likewise, search proceeded at a rate of approximately 0.72 fixations/item in the two-target condition and 1.26 fixations per item in the one-target condition.

Within classic models of visual search (e.g., Treisman, 1988) the assumption would be that, in a target-absent trial, the participants attend to each item in turn until all the items have been checked (the so-called *exhaustive* *serial search*) and then respond. Assuming sampling without replacement, in the display of size 12 it can be expected that subjects have to check all 12 items before they respond. The expected value of finding the target and responding in a target-present trial is after the subject has attended to on average 6.5 items (the so-called *self-terminating serial search*). Similarly, in the one-target condition of the two-target task the participants should pay attention to each item, and can be expected to find the target after having attended to on average 6.5 items (in a display of size 12), then continue with an exhaustive search of the remaining items and respond after having attended to 12 items. By the same rationale, in the two-target condition, they are expected to find the first target after having attended to on average 4.33 items and respond after finding the second target when they have attended to on average 8.66 items.

If we assume that each fixation represents the inspection of an item the observed fixation numbers are much greater than these expectations. However, the number of fixations reported in this experiment included fixations that were not close enough to an item for any visual analysis to be carried out. In addition, fixations were included that occurred after the target had been fixated but before the manual response occurred. The number of fixations observed in this experiment may also have been elevated because participants refixated items. Refixations are particularly interesting because they give us a direct index of the extent to which a location is remembered (e.g., Gilchrist & Harvey, 2000).

In Experiment 2, we repeated Experiment 1 but with a single display size which increased the power of the experiment. In addition, a more detailed and sophisticated analysis of the fixations was possible.

Experiment 2

Method

Participants

Sixteen students (three males, 13 females) at the University of Bristol participated for course credit; the average age was 20.6 years (range 18–32 years). They had not participated in Experiment 1 and all had normal or corrected-to-normal vision.

Stimuli and procedure

Stimuli and procedure were almost identical to Experiment 1. The only difference was that display size was held constant at 12. Again, there were two blocks of 120 trials (60 trials per condition).

Results and discussion

The error rate in the target-absent condition was as low as 1.8% (range 0–11.7%) and 5.6% (range 0–20%) in the target-present condition. In the one-target condition error rates were 1.5% (range 0–5%) and 9.9% (range 3.3–20%) in the two-target condition. For the following analyses only data from correct trials were considered.

Overall, subjects responded somewhat slower than in Experiment 1 but the pattern of response times replicated the findings from Experiment 1 (display size 12); target-absent search took longer than target-present search (4,403 ms versus 2,425 ms), and search in the one-target condition took longer than search in the two-target condition (5,601 ms versus 3,846 ms).

For the analysis of fixations in this experiment we were interested in looking at item directed fixations only. Fixations that are not close to any item do not allow useful information to be gathered about a particular item. Therefore, we defined fixations within a square area of size 2.4° × 2.4° around an item location as being on the item and excluded fixations from further analysis that did not satisfy this criterion (see Körner & Gilchrist, 2004). As a first analysis, we looked at the number of item fixations in the four conditions up until the manual response, these were: target present, 7.6; target absent, 14.5; one target, 18.2; two targets, 12.2[1]. From the analysis of a simple serial self-terminating search presented above it is clear that these numbers are in general close to but slightly above those predicted. Note that it is particularly the one and two target search conditions that exceed the prediction of this analysis. We will return to this result in the general discussion.

As in Experiment 1, search performance in terms of response time and number of fixations, is clearly worse in the one-target condition as compared with the target-absent condition. One explanation for this decrement in search performance between these two conditions is the different memory demands of the two tasks. In the one-target condition there is a requirement to remember the location of the first target while searching for the

[1] Note that some of these fixations occurred after the target has been identified while the manual response is being generated. For the target present trials there were on average 0.9 such fixations and we can use this as one estimate of the number of fixations that occurred after the target identification and before the manual response was generated.

second. If this is the case then there are two distinct ways in which the memory capacity could be allocated—a space in memory is allocated dynamically when the first target is encountered or space in memory is set aside in a more fixed manner from the beginning of the search. The comparison between target-absent and one-target search does not allow us to discriminate between these two possibilities.

However, in this context the comparison between the target-present condition and the one-target condition is useful. Note that the displays in these two conditions are identical and consequently, participants' performance up to the point of finding the target can be compared directly. According to the above presented analysis the expected value of finding the target is after 6.5 deployments of attention in both cases. Target fixations were recorded for 868 trials of the target-present condition and for 887 trials of the one-target condition. For these trials, we calculated the number of fixations from display onset up to that point when a participant fixated the target for the first time. Participants needed 6.7 fixations to detect the target in the target-present condition as opposed to 7.6 fixations in the one-target condition. The resulting difference was reliable ($t(1,15) = 2.84$, $p < 0.05$) showing that search performance was worse in the latter condition already during this short interval.

The analysis of refixation rate up until the point of finding the target provides an even better test between the two possibilities outlined above. Refixations have been suggested as a hallmark of the limited capacity of the system (Gilchrist & Harvey, 2000; Gilchrist et al., 2001; Peterson et al., 2001; Smith et al., 2005). As short-term memory capacity becomes loaded there is less capacity to mark locations as visited, and consequently participants return to previously visited locations. Refixations then give a direct measure of this revisiting process and so a measure of the extent to which short-term memory capacity is available. In the current task, if memory is allocated dynamically to store the target information then the search process, before the target is found, should be comparable for these two conditions. However, if memory capacity is allocated to store the target before search begins then this should affect the search process before the target is found. Specifically, we would expect more refixations on distractors to occur.

We turn now to an analysis of refixations in order to clarify whether the increased number of fixations, up to the point when the target is identified, in the one-target condition is due to reallocation of attention to previously visited distractors. In total there were 47,778 item fixations. For each trial, we counted how often a distractor was fixated. Specifically, we counted how often a distractor was fixated twice (one refixation), and three or more times (two or more refixations). Figure 3 shows the average number of refixations in a trial. In the one-target search, distractors were significantly refixated more often once and two and more times ($t(1,15) = 3.1$, $p < 0.01$, $t(1,15) = 3.5$, $p < 0.01$). Thus, we found an increase in refixations in the one-target condition in comparison to the target-present condition.

As a result of these analyses, the additional fixations observed for the one-target search can be in large part explained by an increase in refixation. These differences are present in the period right from the start of the search even before the detection of the target. This suggests that the performance costs associated with the one-target condition is in part due to a reduced memory capacity for the tagging of distractors which is present even before the target has been encountered. This suggests that space in memory is set aside in a more fixed manner from the beginning of the search.

General discussion

In this article we investigated the cost of remembering targets in visual search. In Experiment 1, we replicated the findings of Gibson et al. (2000) and confirmed that participants could tag target locations in visual search. We contrasted one-target search with target-absent search and found that the former took more time and resulted in more fixations. It was also less efficient. This suggests a deterioration of performance that results from remembering the target.

In Experiment 2, we investigated if memory capacity is allocated dynamically when the first target is encoun-

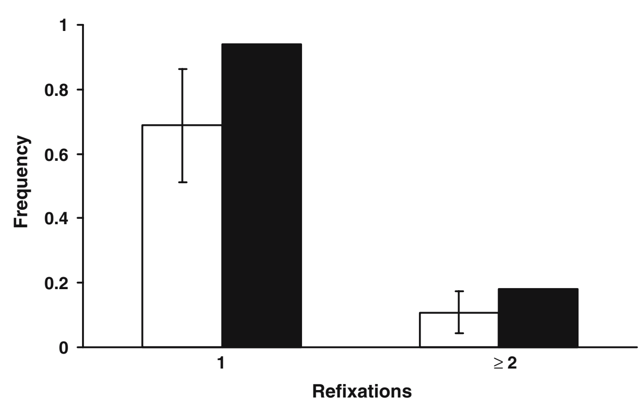

Fig. 3 Experiment 2: average number of refixations in a trial for target-present search (*white bars*) and one-target search (*black bars*). *Error bars* indicate within-participant 95% confidence intervals for comparisons between target-present search and one-target search conditions

tered or is set aside in a more fixed manner from the beginning of the search. To test this we analysed refixations in the interval before a target was encountered in the target-present search condition and the one-target search condition. Distractors were refixated more often during one-target search compared with target-present search. This result suggests that less memory capacity was available to keep track of previously attended distractors. We assume that this was due to memory capacity allocated to the tagging of targets.

The performance cost is present right from the start of the search and can be demonstrated within the interval from search onset to detection of the target, and thus before it becomes necessary to tag a target. This may reflect a general behaviour to reserve memory capacity for targets before that memory must be deployed. This is functional in a multiple-target search as participants know in advance that they will have to remember the locations of targets during the search. However, as a result, the memory set aside for the target is no longer available to support tagging of distractors and this in turn results in more refixations.

The displays in the target-present condition and the one-target condition are identical and this is one of the major strengths of this comparison. However, the task demands, and so task set, across these two conditions are different. In one task the participants are searching for the presence or absence of a single target and in the other they are searching for the presence of one or two targets. A key question then is how does this affect the task set of the participant. The first and primary difference that we have focused on in this paper is the different memory requirements across these two tasks: this is the primary consequence of the difference in task instructions. However, it is also possible that the difference in task set has a secondary influence on behaviour. For example, a participant may be more cautious and so engage in more rechecking or may even have a slower search rate. We believe that this is unlikely given the low and comparable error rates across conditions. Alternatively, it is possible that participants approach the two tasks in radically different ways; for example, participants could be carrying out two parallel searches concurrently for the two targets. In these data we see no evidence for such radical differences in approach in the two tasks: search behaviour, as measured by fixation behaviour, reaction time and error rates is consistent with serial scanning of the display and that serial scanning appears to proceed in a similar manner across the two tasks. Without further experimentation, the most plausible explanation is that the differences in behaviour in these two conditions are a result of the different memory demands.

The tagging of targets carries a cost that has an impact on the number of fixations and so on search performance suggesting that item tagging in visual search is possible but the necessity of having to tag even one target comes with a performance cost (see also Ballard, Hayhoe, & Pelz, 1995, for a similar argument). We have shown that the cost for remembering a target has an impact on the number of distractor (re-) fixations, which is an established measure of memory capacity (Gilchrist & Harvey, 2000; Gilchrist et al., 2001; Peterson et al., 2001; Smith et al., 2005). Thus, remembering a target item in the current experiments has an impact on memory capacity for distractor items. This suggests that the tagging of targets and distractors call on a common memory resource, a memory for items. It remains to be seen whether other memory processes that contribute to efficient search (see Shore & Klein, 2000) also share this same memory resource.

In our analyses, we have concentrated on the comparison between the target-present condition and the one-target condition because the displays in these conditions were identical. Our analysis of the number of fixations needed to complete search in Experiment 2 showed that these numbers were in general closer to those expected from a serial search process for the conditions of the present–absent task. The fixation numbers for the two-target task exceeded those predictions. This may be further evidence that the search process was impaired beyond the point of tagging the first target. Having reserved and deployed memory for remembering the first target may have left less memory capacity to tag distractors during the remainder of the search, thus leading to refixations and, in turn, to the observed increase in fixations for the two-target task. As fixation number is closely linked to reaction time this in turn may well have impacted on response time in these conditions.

Other mechanisms are conceivable that could lead to an increase in the number of fixations. Such mechanisms could involve different memory subsystems or even cognitive subsystems other than memory. For example, reserving memory for targets could lead to an impairment of the perceptual processing of distractors or to a reduction in eye movement programming. In a dual task paradigm, Woodman, Vogel, and Luck (2001) had their participants perform a visual search task during the retention interval of a visual working memory task. They did not find a deterioration of search performance as measured by the slope of the search functions for manual reaction times. However, the overall search performance (as measured by the intercept of those functions) was slowed down. More recently, Woodman and Luck (2004) showed that search rates were affected when subjects had to perform a spatial memory task and a search task concurrently (see also Oh & Kim, 2004). These examples indicate that there is a link between different memory subsystems. At present it is not known what role eye movements play in this context because these studies only measured manual reaction times. Future research could clarify the relationship between the different subsystems and the role of eye movements.

In the context of our simple search task which required memory for items (targets as well as distractors) we prefer the parsimonious interpretation that remembering a target and remembering distractors are supported by the same short-term memory store with a limited capacity. In that sense, our experiments add to the growing body of evidence that visual search is supported by memory processes (e.g., Gilchrist & Harvey, 2000; Kristjansson, 2000; Peterson et al., 2001). The current result also begins to investigate the type of memory system that is available and how, and under what circumstances, memory capacity is deployed (see also, Gibson et al., 2000; Gilchrist et al., 2001; Gilchrist & Harvey, 2006).

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