Research Report

Rapid Resumption of Interrupted Visual Search

New Insights on the Interaction Between Vision and Memory

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ABSTRACT—*A modified visual search task demonstrates that humans are very good at resuming a search after it has been momentarily interrupted. This is shown by exceptionally rapid response time to a display that reappears after a brief interruption, even when an entirely different visual display is seen during the interruption and two different visual searches are performed simultaneously. This* rapid resumption *depends on the stability of the visual scene and is not due to display or response anticipations. These results are consistent with the existence of an iterative hypothesis-testing mechanism that compares information stored in short-term memory (the perceptual hypothesis) with information about the display (the sensory pattern). In this view, rapid resumption occurs because a hypothesis based on a previous glance of the scene can be tested very rapidly in a subsequent glance, given that the initial hypothesis-generation step has already been performed.*

Although visual search has been studied extensively (e.g., Wolfe, 1998), many questions regarding the role of memory remain. Some theorists have claimed memory plays no role; when participants search for a target among a set of distractor items, they shift their attention from one item to the next without any guidance from the items already encountered (Horowitz & Wolfe, 1998, 2001, 2003). Others have argued for implicit memory of item location, because search can be facilitated by repeated display configurations (Chun & Jiang, 1998, 2003; Chun & Nakayama, 2000) and by information regarding the three previously scanned locations (McCarley, Wang, Kramer, Irwin, & Peterson, 2003; Peterson, Kramer, Wang, Irwin, & McCarley, 2001). Yet when explicit memory tasks are performed concurrently with search, performance is unaffected, as if memory played no role (Woodman, Vogel, & Luck, 2001; but see Oh & Kim, 2004). Consequently, the role of memory in visual search is still uncertain.

Our approach to this question begins with the observation that people rarely perform only one task at a time. For example, while driving, people often perform visual searches, such as looking for a friend they have planned to meet. If memory plays a role, one should see benefits in returning to a search that has been momentarily interrupted. We show here that such benefits are substantial.

Our results point to a hypothesis-testing mechanism in visual perception, one that forms an initial perceptual hypothesis based on a first glance at a scene and then tests this hypothesis in subsequent glances when the scene reappears. Note that this account of perception is not new: Such iteration has been proposed for visual masking (e.g., Di Lollo, Enns, & Rensink, 2000; Enns & Di Lollo, 2000; Lleras & Moore, 2003). Here we show that the initial hypothesis-generation stage can improve performance. If the initial hypothesis is stored in memory for later use, when the display reappears, participants can test it directly against the current sensory information, skipping the initial hypothesis-generation stage, and thereby substantially reducing target-identification time. We present six experiments that provide strong evidence for this proposal.

GENERAL METHOD

Subjects

A total of 110 undergraduate students at the University of British Columbia, Canada, participated for extra course credit. All had normal or corrected-to-normal vision and were naive to the purpose of the experiments.

Task, Equipment, and Stimuli

Participants were required to report the color of a target *T* shape (either red or blue), presented among *L* shapes, by pressing the "z" key for a blue target and the "/" key for a red target.

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Experiments were run on e-Mac computers, controlled by VScope software (Enns & Rensink, 1992). There were 16 or 32 items in each display. Each item appeared in one of four randomly selected orientations, and each line segment in the items subtended 0.5° of visual angle. Items were arrayed inside an invisible 6 × 6 grid (cell size = 1.5°), with a random amount of jitter (± 0.2°) to avoid the collinear alignment of items. Letters could be either blue or red, and there was always an equal number of red and blue items in the display.

Procedure

The procedure is illustrated in Figure 1a. The search display was presented for 100 ms at a time (100 ms or 500 ms in Experiment 3) and interrupted by blank displays of longer duration (900 ms in Experiments 1, 5, and 6; 950 ms in Experiment 2; 1,600 or 2,000 ms in Experiment 3; and 1,400, 2,400, or 3,400 ms in Experiment 4). We use the term *epoch* to refer to the time between the onset of a display and its reappearance (Rensink, 2000). Each session was about 45 min long and was divided into 10 blocks of 60 trials each. Formal test trials were preceded by 30 trials of practice. The intertrial interval was 1 s. During the first 500 ms of a trial, participants viewed a fixation cross (0.5°) in the center of the display before the search cycle began. The cycling of displays (search display on followed by search display off) continued until the participant responded or 16 s had elapsed, whichever occurred first.

EXPERIMENT 1: INTERRUPTING SEARCH WITH BLANK DISPLAYS

We were initially interested in evaluating participants' general ability to perform this modified version of a normal visual search task. Twelve participants were tested (mean accuracy = 95%). To evaluate the impact of the interruption on search performance, we looked at the distribution of response times (RTs) for trials with correct responses. Figure 1b shows the RT distribution for this first experiment (display-on time = 100 ms; display-off time = 900 ms; set size = 16 items). Several features of this histogram are notable. First, with only a single glance, participants were able to identify the target correctly on 28% of the trials. Second, it took participants 500 ms to begin responding in the first epoch (only 4% of responses were faster than 500 ms); this can be interpreted as the time needed to initiate visual search. Third, the most remarkable finding is that this initial lag was absent in subsequent epochs. During the second epoch, 53% of responses occurred within the first 500 ms; during the third epoch 52% of responses did so. We refer to this phenomenon as *rapid resumption* (RR), because it indexes the benefit of having begun the search prior to its interruption.

To better illustrate RR, we normalized the RT distribution separately for Epoch 1 (Fig. 1d) and Epochs 2 through 6 (Fig. 1e). As is readily seen, participants responded in a fundamentally different way to the first display than to all subsequent displays,

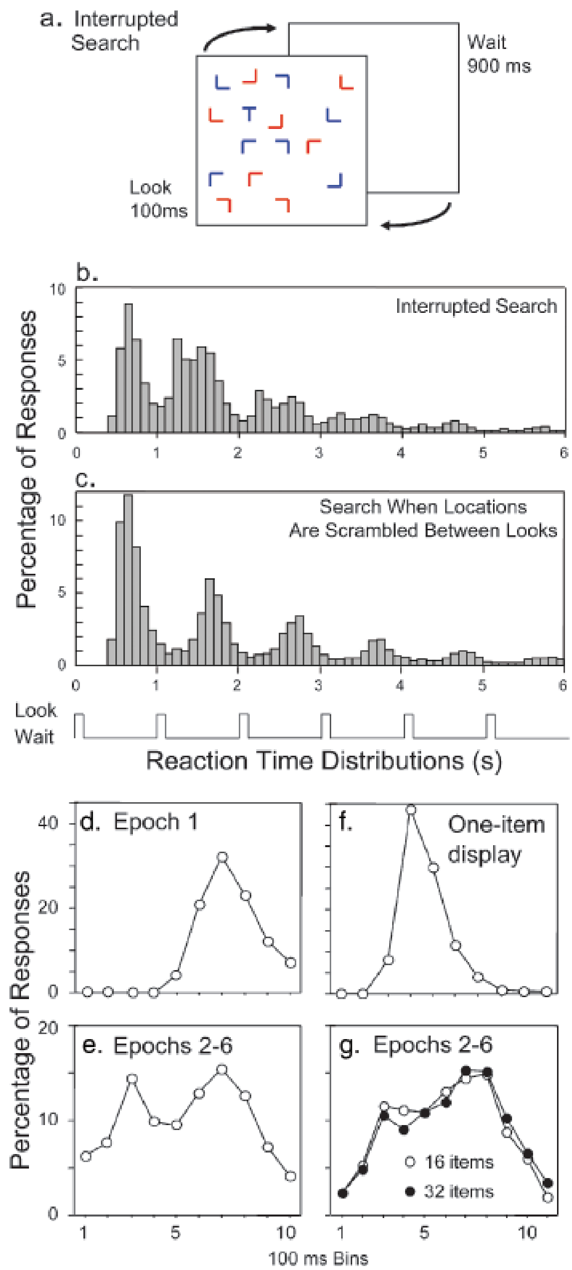

Fig. 1. Schematic depiction of the interrupted visual search task (a) and experimental results (b–g). Participants were required to report the color of a red or blue *T* presented along with distractors in alternating search and blank displays. The frequency distribution of reaction times (RTs) for correct responses in Experiment 1 (b) illustrates *rapid resumption*, the increased frequency of correct RTs within 500 ms of display onset in all but the first epoch. The graph in (c) presents the RT frequency distribution from Experiment 6, in which items randomly switched locations between display presentations. The time line below (c) indicates when the displays were presented during the trials: Vertical rectangles indicate when the search display was shown, and their width represents the duration of the display (in this case, 100 ms), whereas flat lines indicate when blank displays were present. The line graphs present normalized RT distributions for correct responses in Epoch 1 (d) and Epochs 2 through 6 (e) in Experiment 1; for a control experiment in which all the *L*s were erased from the display and only the color of a single *T* was identified (f); and for Epochs 2 through 6 from an experiment similar to Experiment 1 except that set size was manipulated and epoch duration was slightly longer (1,050 ms, with a 950-ms blank display) (g).

$\chi^2(9, N = 7{,}957) = 1{,}588.69, p < .001$, Cramer's $V = .45$ (comparison across ten 100-ms bins). Specifically, they were able to resume a search much faster than they were able to start one.

For comparison, Figure 1f shows the RT distribution from a control experiment ($n = 12$, accuracy = 97%) that was identical in every way to Experiment 1 except for set size: Only one *T* was present in the display (zero distractors). In this control experiment, the peak of the RT distribution occurred 400 ms after the onset of the display, comparable to the latency of the first peak in the RT distribution when RR occurred (Fig. 1e), which was also within 500 ms after display (re)presentation. The peak in the control experiment was also much earlier than the second peak in Epochs 2 through 6 of Experiment 1 (Fig. 1e), which was at a latency of about 800 ms (close to the latency of the peak in the RT distribution for Epoch 1; Fig. 1d).

Figure 1g shows the data from Epochs 2 through 6 of a separate experiment in which displays contained either 16 or 32 items ($n = 12$, accuracy = 93%). Epoch time was 1,050 ms (display-on time = 100 ms; display-off time = 950 ms). The similarity of the RT distributions for the two display sizes indicates that RR does not depend on the number of items in the display, $\chi^2(10, N = 2{,}964) = 14.21, p = .17$, Cramer's $V = .07$. A larger number of items simply resulted in a longer search, with the correct response occurring in a later epoch, but it did not affect the shape of the RT distribution within an epoch. Taken together, Figures 1f and 1g suggest that when RR occurs, it is as if the target were the only item on the display.

EXPERIMENT 2: INTERLEAVING TWO SEARCHES

As promising as the results from Experiment 1 are, it might be argued that search was never fully interrupted: The mental processes involved may have been continuously active, even during the blank display. To force participants to fully interrupt their search of a given display, we developed a modified version of the task in which two different displays were interleaved (see Fig. 2a): one containing red items, the second containing blue items in a different spatial layout. Participants again searched for the *T* and reported its color, but because they did not know in advance which display contained the target, they needed to search both displays. We included target-absent trials (20% of trials) to minimize guessing based on the failure to find a target in any given color. In each cycle, a display containing items of one color was shown for 100 ms, followed by a blank display of 950 ms, followed by a 100-ms display containing items of the other color, and finally another blank display of 950 ms (epoch duration = 2,100 ms).

Figures 2b and 2c show the RT distribution data from 12 participants (mean accuracy = 95%) for each of the interleaved search displays. Several new features of RR are evident. First, the initial setup time was found in search for targets of each color, indicating that searching for the target in displays of one color provided no benefit for searching for the target in displays of the other color. The initial search of each display resulted in

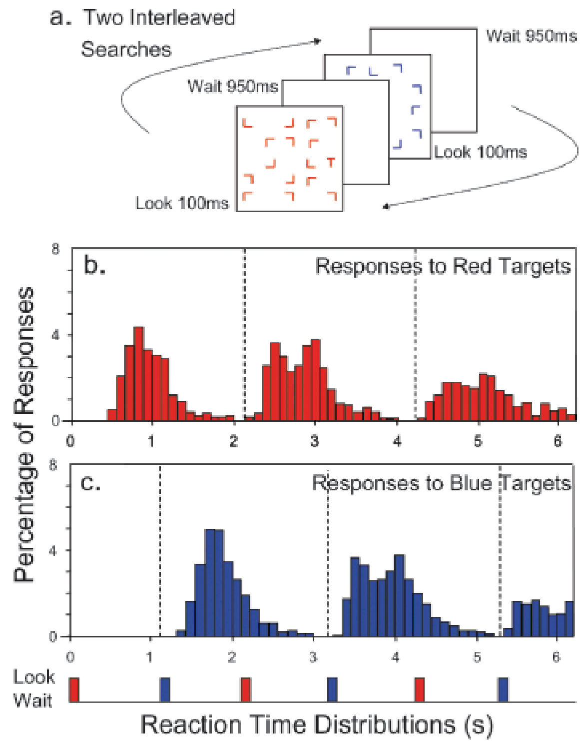

Fig. 2. Schematic depiction of the visual search task used in Experiment 2 (a) and experimental results (b, c). This task was similar to the one used in Experiment 1 (see Fig. 1a) except that two temporally interleaved search displays were presented and participants did not know which display contained the target. The distribution of correct reaction times (RTs) from this search is shown separately for red (b) and blue (c) displays (target-present trials only), on trials in which the first display contained red items (identical results were observed on trials in which the first display contained blue items). The time line below (c) indicates when the displays were presented during the trials, as well as the color of each display: Red and blue vertical rectangles indicate the presentation of red and blue displays, respectively, and their width represents the duration of the displays (in this case, 100 ms); flat lines indicate when blank displays were present.

the normal setup time, meaning that participants interrupted their search of the first display in order to begin searching the second display. Second, RR was observed on the second appearance of each display, indicating that participants could benefit from their previous search of that display, even though search through a different set of items had intervened. In summary, starting a search through the red items was different from starting a search through the blue items: Both searches incurred their own setup time. However, once each of the two searches had begun and had been interrupted, there was a large benefit to resuming the search as compared with starting it anew.

EXPERIMENT 3: EFFECT OF DISPLAY DURATION

Experiment 3 investigated the influence of display duration on RR. Figures 3a and 3b show normalized RT distributions from 12 participants (mean accuracy = 95%) from search tasks in which 100-ms and 500-ms displays were followed by blank displays of 2,000 ms and 1,600 ms, respectively (total epoch

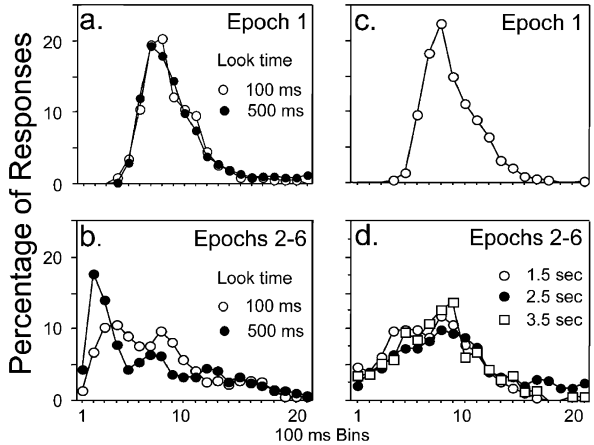

Fig. 3. Normalized reaction time distributions for correct responses in Experiments 3 and 4. Distributions for Epoch 1 (a) and Epochs 2 through 6 (b) in Experiment 3 are shown separately for display durations of 100 ms and 500 ms. The graphs in (c) and (d) present the distributions for Epoch 1 and Epochs 2 through 6, respectively, in Experiment 4; in this experiment, the duration of the blank displays was unpredictable, and epoch cycle time was 1,500 ms, 2,500 ms, or 3,500 ms.

time = 2,100 ms). Although search was very similar in the first epoch for the two tasks (Fig. 3a), RR was more pronounced for 500-ms looks than for 100-ms looks (44% and 29%, respectively, of responses in Epochs 2–4 occurred in the first 500 ms of these epochs; see Fig. 3b), $\chi^2(1, N = 2{,}317) = 52.52, p < .001$. The distributions for display durations of 100 ms and 500 ms in Epochs 2 through 4 were also significantly different from each other, $\chi^2(20, N = 2{,}317) = 161.13, p < .001$, Cramer's $V = .26$. The results suggest that memory is stronger when there is more time to accumulate visual evidence.

EXPERIMENT 4: EFFECT OF BLANK DURATION

Experiment 4 was designed to rule out the possibility that RR is caused by participants' anticipation of the display's reappearance. Figures 3c and 3d show normalized RT distributions from 20 participants performing a search task in which the blank intervals between the displays were randomly 1,400 ms, 2,400 ms, or 3,400 ms (mean accuracy = 91%). Following the expected start-up time in Epoch 1 (Fig. 3c), RR was equally strong regardless of the amount of time that elapsed before the reappearance of the display (Fig. 3d). These results indicate both that the effect does not depend on precise temporal predictability and that the benefits of memory in this task can survive longer than 3 s.

EXPERIMENT 5: RULING OUT A CONFIRMATION BIAS

We next investigated whether participants might have been using a "confirmation" strategy in which they would withhold a correct response while waiting to confirm their decision with an additional look at the following display. If so, it would be possible to present the display only once and to extract a correct response by forcing participants to respond. To test this possibility, we ran an experiment in which search and blank displays alternated on 80% of the trials and the search display appeared only once on the remaining 20%. On these latter trials, participants were forced to respond once they realized the display was not going to reappear. Data were collected from 18 participants. The display timings were those used in Experiment 1.

The results were clear. The first epoch in both conditions led to the usual RT distribution in which responses began 500 ms after display onset. When this first epoch was followed by an alternating display, the usual RR was observed (Fig. 4a). However, following a single presentation of the display, the RT distributions were quite similar for correct responses (Fig. 4b) and incorrect responses (Fig. 4c), indicating that participants were simply guessing the target's color: After 1,000 ms, 48% of responses were correct and 52% were incorrect, a nonsignificant difference as revealed by a sign test, $n+ = 431$, $n- = 461$, $p = .332$ (bins between 1,000 ms and 6,000 ms). Clearly, participants were not merely withholding a correct response in anticipation of a second look.

EXPERIMENT 6: RANDOM RESHUFFLING BETWEEN VIEWS

Finally, we tested whether RR requires the items in the scene to be stable. In this experiment, the display configuration remained

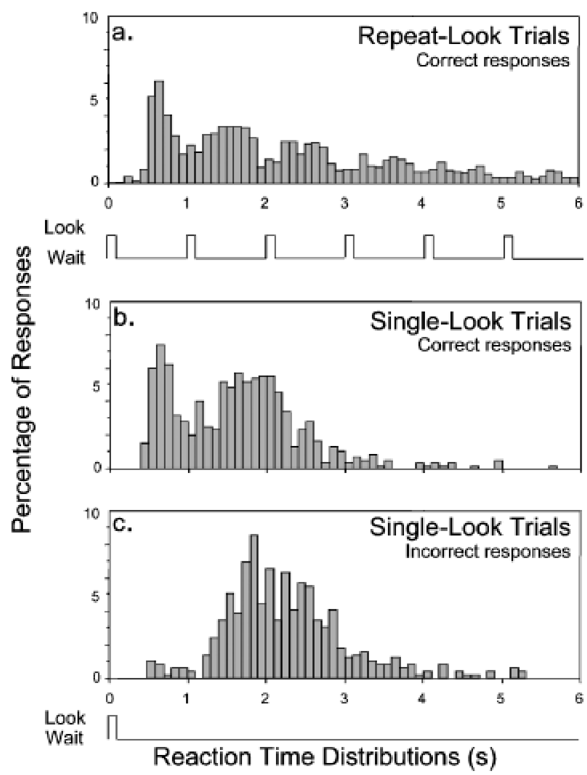

Fig. 4. Results from Experiment 5. In this experiment, the search display reappeared on 80% of trials (repeat-look trials) and did not reappear on the remaining 20% of trials (single-look trials). The graphs show reaction time distributions for repeat-look trials with correct responses (a), single-look trials with correct responses (b), and single-look trials with incorrect responses (c).

the same on each presentation, but the assignment of the individual search item (including the target) to each location was randomly reshuffled on each re-presentation. The display timings were those used in Experiment 1. Under these conditions, RR was eliminated, and the search task began anew in each epoch (see Fig. 1c; $n = 12$, mean accuracy = 93%, display size = 16). Thus, the resulting RT distribution was significantly different from the RT distribution when RR was present (Fig. 1b), $\chi^2(55, N = 9{,}247) = 1{,}351.95$, $p < .001$, Cramer's $V = .30$ (bins between 500 ms and 6,000 ms).

GENERAL DISCUSSION

These experiments show that humans are able to resume an interrupted visual search much more quickly than they are able to begin a new search. The speed of resumption is comparable to the speed with which they can discriminate a target in the absence of any distracting items (Fig. 1f). These findings are consistent with the proposal that visual perception consists of an iterative sequence of hypothesis generation and hypothesis testing, as we have proposed elsewhere (see Di Lollo et al., 2000). Given a single glance at a scene, a hypothesis about it must first be generated and then can be tested (confirmed or rejected). Hypotheses based on an initial glance can be tested very rapidly in a second glance, simply because the initial generation step has already been accomplished. According to this account, only a limited portion of a scene—namely, that involving the hypothesis—needs to be remembered during the interruption. Without further studies, it is difficult to say exactly what is represented in the hypothesis, but we anticipate that a perceptual hypothesis may include information about the shape of a few display items, their response relevance, and their spatial location (see Lleras & Enns, 2004, for a related discussion).

Many details of the present study are consistent with iterative hypothesis testing. The fact that an increase in the number of display items leads to target detection in a later epoch but has no effect on the RT distribution within the epoch (Fig. 1g) is consistent with testing a succession of hypotheses about individual items (or small regions). The finding that a longer first look results in a greater likelihood of RR (Fig. 3c) is consistent with greater success in hypothesis formation during a longer initial glance. The finding that reshuffling the display items between presentations eliminates RR (Fig. 1c) is consistent with the need to reconnect a hypothesis stored in memory with actual sensory information. Future studies will be needed to fully uncover the rich interactions at play in RR and, more generally, when vision and memory operate under conditions that more closely resemble the world in which they evolved.

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