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Does partial difficult search help difficult search?

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Olds, Cowan, and Jolicœur (2000a, 2000b) showed that exposure to a display that affords *pop-out* search (a target among distractors of only one color) can assist processing of a related display that requires *difficult* search. They added distractors of an additional color to the initial simple display and analyzed response time distributions to show that exposure to the initial display aided subsequent search in the difficult portion (this finding was called *search assistance*). To test whether search assistance depends on perceptual grouping of the initial items, we presented initial items that were more difficult to group (two colors of distractors, instead of just one). The target appeared (on 50% of the trials) among distractors of two colors, and then after a delay, more distractors of those two colors were added to the display. Exposure to the initial easier portion of the display did not assist processing of the second portion of the display when the initial display contained a large number of items; we found tentative evidence for assistance with small numbers of initial items. In the Olds et al. (2000a, 2000b) studies, it was easy to group the initial distractor items, because they were all the same color. In contrast, in the present study, it was difficult to group the heterogeneous initial distractor items. Search assistance is found only when initial item grouping is relatively easy, and thus we conclude that search assistance depends on grouping.

People are constantly confronted with complex visual displays that they must quickly search for particular stimuli (targets). The difficulty of visual search often decreases when nontarget display items (distractors) can be perceptually grouped (Duncan & Humphreys, 1989). Grouping is easier when items are similar to each other; thus, a homogeneous set of items groups better perceptually than do heterogeneous items.

There are a number of ways in which search difficulty has been categorized. Although a number of researchers have shown that search difficulty is best represented as falling on a continuum, rather than into a dichotomy (see, e.g., Duncan & Humphreys, 1989; Nakayama & Joseph, 1998; Wolfe, 1998), it is still useful to consider the categories that were initially proposed and to compare searches of different difficulties and the cognitive mechanisms that might be responsible for them. When search is fast and response time (RT) does not depend on the number of items in the display (the *set size*), this pattern is called *pop-out search*; when performance is relatively slow and RT depends on the number of items in the display, this pattern is called *difficult search* (see Treisman & Gelade, 1980, for the introduction of these terms). Treisman initially classified search performance on the basis of how many features had to be considered in order to detect the target. There are feature searches in which the target can be discriminated from distractors on the basis of just one feature. These produce *pop-out* (e.g., Figure 1A). In conjunction search, on the other hand, the target is defined by the combination of multiple features (e.g., Figure 1C). Treisman and Gelade proposed that all conjunction searches were difficult searches, but subsequent research has shown that some conjunction searches are quite easy (Nakayama & Silverman, 1986; Wolfe, Cave, & Franzel, 1989).

There are other ways to make search difficult, even within one single feature dimension. Another way of predicting when pop-out versus difficult search will occur involves the concept of linear separability (Bauer, Jolicœur, & Cowan, 1996, 1999; D'Zmura, 1991; see also Arguin & Saumier, 2000), which can apply to situations in which the target differs from the distractors on the basis of just one dimension (e.g., color). In a display that is *linearly separable* (Figure 1B), it is possible to classify each item's color on one side or the other of a linear separator, which is a task-specific straight line through color space; for such stimuli, pop-out search is possible (Bauer et al., 1996, 1999; D'Zmura, 1991). If the target is *not linearly separable* from the distractors (Figure 1D), difficult search occurs. A third, related way of predicting search difficulty is in terms of item heterogeneity versus homogeneity. Duncan and Humphreys (1989) showed that search is relatively easy when distractors are more homogeneous and argued that distractor rejection by "spreading suppression" among a set of homogeneous distractors could explain such results (Humphreys & Muller, 1993; see also Rosenholtz, 1999).

Although the specific mechanisms responsible for pop-out and difficult search are not known, there must be

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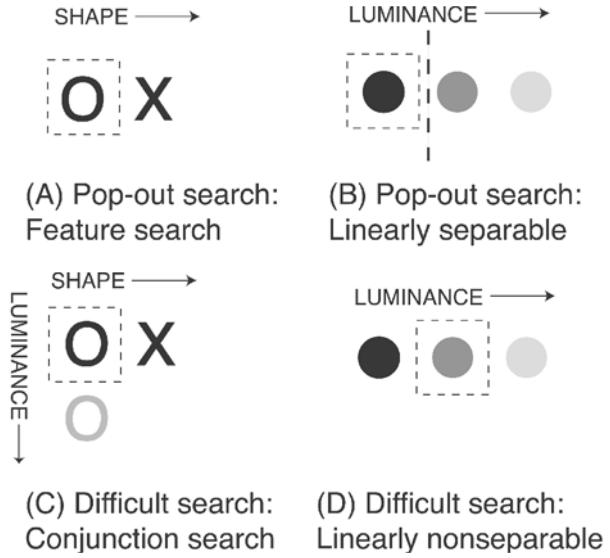

Figure 1. In each stimulus feature configuration showing the dimension of shape and/or luminance, the target is surrounded by a dashed box; the distractors are not. (A) Pop-out search: feature search. (B) Pop-out search: linearly separable, where the target representation in luminance space can be separated from the representations of all distractors by a straight line (the linear separator). (C) Difficult search: conjunction search. (D) Difficult search: linearly nonseparable configuration, where the target cannot be separated from all distractors by one straight line (the target lies between the the distractors along the dimension of luminance).

some differences: The former mechanisms operate more quickly and are capable only of making simple discriminations, for example. Something in addition to the mechanisms that are active during the easiest searches is necessary when search is very difficult. However, there must also be some overlap between these sets of mechanisms; at the very least, they are both capable of guiding selection. Even the reasonable proposal that there is one search mechanism, performing tasks of differing difficulties, should allow for different levels of involvement of different *sub*processes for the different types of displays.

With regard to the issue of whether pop-out versus difficult search performance lies on a continuum, rather than a dichotomy, this too could be compatible with at least some differentiation in the cognitive mechanisms responsible for search performance. Perhaps there is a simple mechanism analyzing the features of *all* displays, plus a separate, more complicated mechanism that is used as well for more complex displays—to different degrees, depending on the complexity of the display (i.e., a continuum). This possibility would involve two mechanisms and a continuum—that is, two separable mechanisms do not rule out a continuum.

Search Assistance

Olds, Cowan, and Jolicœur (2000b) reported an experiment in which search of a simple display was interrupted by the presentation of additional distractors (see Figure 2A). Observers began to search a display in which the target (present on half the trials) was linearly separable from homogeneous distractors of just one color. This display afforded pop-out, but search was then interrupted when additional distractors of a second color were added to the display after a brief delay. The color of the additional distractors was chosen so that the target color was not linearly separable from the pair of distractor colors (as in Figure 1D; however, in the experiment, the target and distractors differed in equiluminant color, rather than in luminance). There was a delay (stimulus onset asynchrony, or SOA) between the onset of the initial set of stimuli and the onset of the second set. Thus, processing of the pop-out display was interrupted after different amounts of progress. Using a technique described below in the Results section, Olds et al. (2000b) showed that partial computations made during exposure to the initial, simple display were used to help search of the second, difficult portion of the display ("search assistance") for both target-present and target-absent trials. Thus, partial information—gathered from a display with homogeneous distractors that afforded pop-out search—can be used to increase the efficiency of search of a subsequent display with heterogeneous distractors (difficult search).

Before we turn to the purpose of the present study, we will consider more thoroughly the question of what "search assistance" means. Like "pop-out" and "difficult

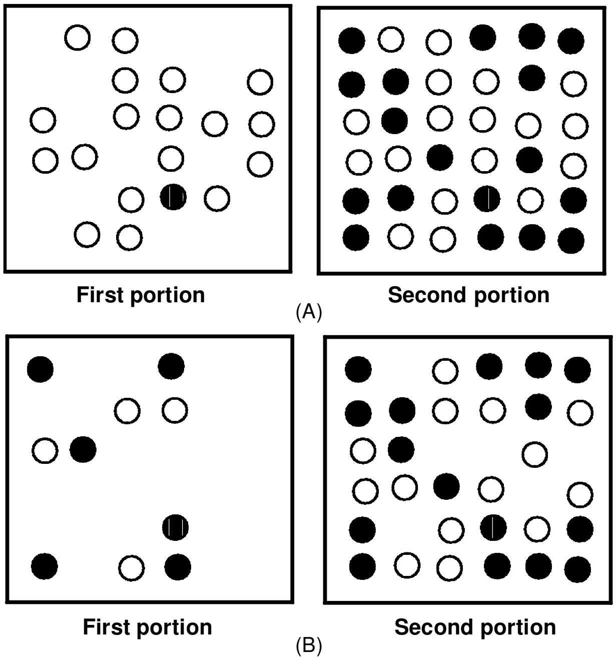

Figure 2. (A) Illustration of the sequence of events in a trial for Olds, Cowan, and Jolicœur (2000a, 2000b). (B) Illustration of the sequence of events in a trial for Experiment 1. Note that in both these previous studies and the present study, the target and distractors differed in equiluminant color rather than luminance.

search," it is a term we will use to describe a pattern in data. Pop-out refers to fast RTs that do not increase substantially with increases in set size; difficult search refers to slower RTs that do increase with increases in set size. Search assistance consists of fewer slow RTs than would be expected, given a preview of a partial display; this pattern will be discussed in more detail in the Results section. Thus, search assistance is a pattern in performance data (which of course occurs only when a display with a preview is shown), and we have sought to understand the cognitive mechanisms responsible for this pattern.

It is possible that the search assistance found in previous studies occurred because observers perceptually grouped the initial items. Thus, in the present study, we investigated the role of perceptual grouping in search assistance. We did this by using a different kind of preview from those used in previous experiments.

Purpose

We set out to determine whether partial processing of an initial difficult search display facilitates subsequent processing of a more difficult display. In the partial pop-out experiments of Olds et al. (2000a, 2000b), the initial distractors were homogeneous (and linearly separable; Figure 2A), and search was easy in the initial portion of the display. The present experiments followed a similar delay format, but the initial distractors were heterogeneous (and not linearly separable; Figure 2B), and initial search was expected to be difficult. In other words, there was a small-set-size difficult search display, and then more distractors of both colors were added after a variable delay. One effect of initial distractor heterogeneity was clearly expected: RTs should be longer, overall, than those for the partial pop-out experiments because, of course, pop-out was not possible in the initial portion of the display. More important, we tested whether search assistance would occur with this heterogeneous initial display.

One possible prediction would be that there should be no search assistance with a difficult preview, because the initial items (including the target, when present) would be difficult to perceptually group and, thus, would be difficult to differentiate from the extra distractors. Another possible prediction would be that there should be *more* search assistance with heterogeneous initial items that afford difficult search than with homogeneous initial items that afford pop-out search, because with heterogeneous initial items, both the first portion of the display and the second portion of the display require difficult search. In the present experiments, the initial display and the second portion of the display both required difficult search. Therefore, the relevant processes might be able to share information particularly well, and thus, exposure to the initial display should be particularly helpful.

We also varied set size, in order to examine search efficiency overall and to determine whether the set size of the initial display would affect search assistance with a difficult preview. Set size affects the speed of difficult search, and researchers have interpreted this effect as indicating something about capacity limitations (Treisman & Gelade, 1980). Does set size also affect search assistance with a difficult preview? If the perceptual grouping prediction, mentioned first above, is correct, large set sizes of heterogeneous items should be particularly disadvantaged (relative to small set sizes); on the other hand, if the second prediction is correct, set size might have little or no effect on search assistance in the present experiments.

EXPERIMENT 1

The first portion of the stimulus contained 10 or 4 distractors (Experiments 1A and 1B, respectively) of two different colors (referred to here as D1 and D2). On half the trials, the target replaced one of these distractors. After a delay, 20 additional D1 and D2 distractors appeared, while the items from the first portion remained unchanged. The intermediate SOAs gave the observer a temporally limited opportunity to search the small-set-size display before it became a larger set-size display.

Method

Observers. All the observers had normal color vision as measured by Ishihara color plates. One of the authors participated, and 5 others were paid for participation. Observers M.D., N.O., and R.P. participated in Experiment 1A before Experiment 1B; Observers B.L., J.N., and N.D. participated in Experiment 1B first.

Equipment. Stimuli were displayed on a Sony Trinitron Multiscan 220GS monitor using a Macintosh G3 computer. The experiment was programmed using MATLAB and Brainard's (1997) Psychophysics Toolbox routines. The monitor was calibrated using a Minolta CS-100 Chroma Meter and the technique described by Olds, Cowan, and Jolicœur (1999a).

Stimuli. The items were colored disks with a diameter of 8 mm (0.75° of visual angle). All potential stimuli were located on a 6×6 virtual matrix that was positioned in the center of the screen. The actual locations of the items were perturbed randomly by up to one seventh of a disk diameter, both horizontally and vertically. The background and all colored disks were equiluminant (20 candelas/m^2). For all the observers, the orange target *CIE x, y* chromaticity was (0.416, 0.364), and the background chromaticity was (0.327, 0.332). In *CIELuv* color space, where distances correspond roughly to perceived color differences, the gray background had coordinates of (92, 0.207, 0.472); the target color had coordinates of (92, 0.255, 0.501). The distractors D1 and D2 were of a pinkish-orange and yellowish-orange hue, respectively. The target was not linearly separable from the distractors; in other words, its coordinates and those of the two distractor colors fell on the same line in *CIELuv* color space, and the target color was intermediate between these distractor colors. The particular color coordinates for the distractors were chosen for each observer individually, so as to maximize the RT difference between homogenous search (search in D1 distractors only or search in D2 distractors only) and heterogeneous search (search in both D1 and D2 distractors; see Olds, Cowan, & Jolicœur, 1999b, for more description of this technique).

Initially, 10 items (5 D1 distractors and 5 D2 distractors, with the target replacing one randomly selected item on 50% of the trials) were displayed for Experiment 1A (as in Figure 2B); 4 items were displayed initially for Experiment 1B. The SOAs were 0 (i.e., all items came on at the same time), 53, 107, 160, 213 msec and ∞ (i.e., the second set of items never appeared). The 0-msec SOA condition was a control condition measuring performance on displays with a relatively large set size (30 items for Experiment 1A, 24 items for Experiment 1B). The ∞ SOA condition was a second control condition measuring performance on displays with a relatively small set size (10 items for Experiment 1A, 4 items for Experiment 1B). In the intermediate conditions, after the SOA, 20 items (10 D1 distractors and 10 D2 distractors) were added to the display. The target could appear in any location except the four corner locations.

Design and Procedure. Each trial started with the presentation of a fixation symbol, which had the dual purpose of indicating the center of the stimulus matrix on the screen and providing the observer with feedback about the previous trial. The fixation symbol was a "+" for the first trial; on subsequent trials, a "+" was presented following a correct response, and a "−" was presented following an error. The fixation symbol remained on the screen for 400 msec; following the fixation symbol, the screen was blank for 400 msec. The search items then appeared and remained on the screen until the observer responded by pressing one of two marked keys on the keyboard, to indicate target presence or absence. At increments of 50 trials, the observer was given a break and could initiate the next trial, whenever ready, by pressing a key. The observers adapted to the dimly lit room for several minutes before testing began. Following each session, the observers were encouraged to reduce their error rate, if it was above 10% for any conditions.

Each session consisted of 384 trials: 64 trials (32 target positions crossed with present/absent) for each of the six SOAs. Each session began with 10 practice trials, from which data were not analyzed. All aspects were randomized within sessions. In each experiment, each observer completed four sessions, for a total of 1,536 experimental trials.

Results and Discussion

RT outliers more than three standard deviations from the mean were removed (separately for each observer, SOA, and present/absent). For Experiment 1A, 2.3%, 1.0%, 1.2%, 1.0%, 1.6%, and 1.2% of the RTs overall were removed for observers B.L., J.N., M.D., N.D., N.O., and R.P., respectively; for Experiment 1B, 1.8%, 1.4%, 1.2%, 1.3%, 1.2%, and 1.2% were removed.

Errors were low, so we focus on RTs for correct responses (see Figure 3). Target-present RTs decreased with increasing exposure to the initial display; the initial display was easier to search because it had fewer items than the final display. Target-absent RTs remained elevated until the longest SOA (the smaller set size difficult search control condition, SOA = ∞). Note that because the same number of items were always added at the SOA, set size in the second portion of the display varied between experiments; RT for SOA = 0 was higher for Experiment 1A (set size of 30) than for Experiment 1B (set size of 24). Mean RT for SOA = ∞ was, of course, also higher for Experiment 1A than for Experiment 1B (set sizes of 10 and 4, respectively). Although errors for target-present trials were generally higher than errors for target-absent trials, this was not the case for SOA = ∞ in Experiment 1B. However, since the errors were quite low (below 5%) overall, this difference is not likely to be important.

The method for measuring search assistance. In the experiments mentioned previously, the aim of Olds et al. (2000a, 2000b) was to determine "whether partial pop-out helped difficult search." Here, our aim was to measure whether information from partial *difficult* search (of the initial small-set-size display) would help subsequent difficult search (of the second, larger set-size display). We might expect such an effect, unless there is amnesia within this portion of the system (see, e.g., Horowitz & Wolfe, 1998b). We addressed this question by using the following method.

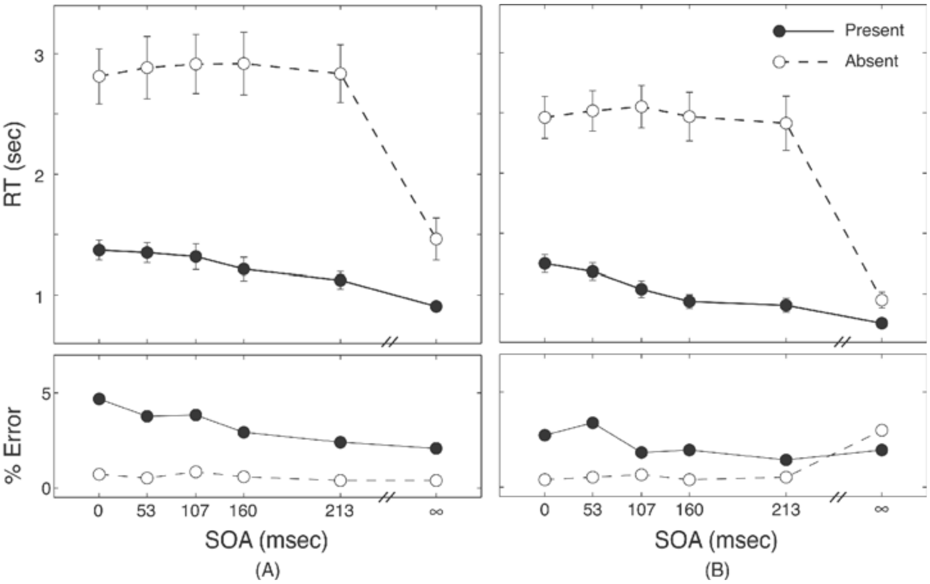

Figure 3. Mean response time (RT) and percentage of error plotted against stimulus onset asynchrony (SOA) separately for target-present trials and target-absent trials for (A) Experiment 1A and (B) Experiment 1B.

We sought to measure how much large-set-size difficult search (meaning, performance that is like that for search of a 30- or 24-item display; hereafter, referred to as *large–difficult search*) was occurring at each SOA. Our method involved examining how the right tail of the RT distribution (the slowest RTs) for each SOA compared with its mean. The measure described below is useful because it allows each distribution to be summarized by a small number of parameters.

First, we characterized the RT distribution for each SOA by four numbers: mean RT, mean of the squared RTs, mean of the cubed RTs, and mean of RT^4. These descriptors are the first four moments of a distribution (the first moment is mean RT, the second moment is mean RT^2, etc.). For each intermediate SOA distribution, we calculated proportion of large–difficult search (λ) separately for each moment; thus, we characterized each distribution by four λs. For each individual observer, the proportion of large–difficult search trials is 1.0 at SOA = 0, the large–difficult search control condition; there is no search of a small-set-size display in that condition, so the RT distribution reflects 100% large-set-size difficult search trials. Proportion of large–difficult search is 0.0 at SOA = ∞, the small-set-size control condition (by definition). For each observer, for each intermediate SOA distribution, for each moment, we solved the following equation to calculate λ:

$$\overline{x^j}_{(\mathrm{SOA})} = \lambda_{(j)(\mathrm{SOA})} * \overline{x^j}_{(\mathrm{SOA}=0)} + (1-\lambda_{(j)(\mathrm{SOA})}) * \overline{x^j}_{(\mathrm{SOA}=\infty)}, \quad (1)$$

where $\overline{x^j}_{(\mathrm{SOA})}$ is the jth moment for a particular intermediate SOA's RT distribution and $\lambda_{(j)(\mathrm{SOA})}$ is the proportion of large–difficult search for that moment and for that SOA. Thus, Equation 1 simply says that for a given SOA, the jth moment is a weighted sum of the jth moment for the SOA = 0 distribution (with weight $\lambda_{(j)(\mathrm{SOA})}$; note that this is the jth λ, and that this weighting parameter will be different for each of the four moments) and the jth moment for the SOA = ∞ distribution [with weight $(1-\lambda_{(j)(\mathrm{SOA})})$]. For the first moment, for example, mean RT for this intermediate SOA would be a weighted sum of the mean RT for SOA = 0 and the mean RT for SOA = ∞. The weight λ would indicate which control distribution the intermediate distribution most resembled.

We will focus this introduction to the graphs on the results from the previous experiments (Olds et al., 2000a, 2000b), where the control distributions were that for pop-out (SOA = ∞) and that for difficult search (SOA = 0), as in Figure 2A. If the exposure to the initial, simple display did not influence subsequent difficult search, the RT distributions for the intermediate SOA conditions would simply be linear combinations of the two control RT distributions (SOA = 0, SOA = ∞) at some unspecified weighting.[1] On each trial, an RT would be sampled from one or the other control distribution, corresponding to either pop-out or difficult search (a mixture model). If this were the case, then for each intermediate RT distribution, the λs derived from the four moments would all coincide (i.e., triangles on top of circles, etc.; see Figure 4A for a hypothetical illustration). For example, in Figure 4A, for SOA = 53, the first moment indicates evidence of 80% large–difficult search in this RT distribution; the second moment also indicates 80% large–difficult search, and the third and fourth moments as well. This is the prediction of the *independent mixture model*, which says that the intermediate SOA distribution was indeed formed by randomly sampling from the two control distributions. This pattern would show that if initial processing failed, its partial computations could not be used to guide subsequent processes to the target (i.e., that the two control distributions were combined linearly).

When the λs do *not* coincide at each SOA, as in Figures 4B–4C, this indicates an effect of processing the first display on the processing of the second display. Previous work using an initial easy display (Olds et al., 2000a, 2000b) found this interaction to be facilitatory (i.e., search assistance). The higher moments reflect properties of the tails of the distributions (generally the right tail, in RT distributions). Figure 4B illustrates what the λs look like when the right tail of the RT distributions shrinks, with increasing SOA, faster than the mean does—if the estimates of proportion of difficult search obtained from higher moments (e.g., the fourth moment) are closer to their SOA = ∞ values than are the estimates obtained from lower moments (e.g., mean RT). This pattern is similar to that found by Olds et al. (2000a, 2000b) when the initial display afforded pop-out. It is evidence that partial processing of the initial display helps search of the second display, because it means that, as compared with a linear combination, the intermediate RT distribution has too short a right tail. The RTs in the right tail represent the slowest trials, and these RTs have a large effect on the higher moments (i.e., $3{,}000^4$ is very large). If the right tail is too short, something must have helped search of the difficult display (the longest RTs), and it must have been partial processing of the initial display. Note that *completed* pop-out search could not be wholly responsible for this speed-up. If it were, this would be reflected in mean RT—simply more pop-out RTs on the order of 500 msec—as well as in the tail of the distribution, which would simply decrease all the λs for a given SOA, rather than preferentially decreasing the high-moment λs. This pattern is reflected in the mean RTs (see, e.g., the mean RT for SOA = 160 in Figure 3A vs. Figure 3B).

Finally, the opposite pattern would occur if partial initial processing *hindered* subsequent processing (Figure 4C) and the intermediate RT distributions had disproportionately long right tails.

Having described the logic for reading these graphs, we turn to the present data. We discuss target-present trials and target-absent trials separately because Olds and Punambolam (2002) found different effects of luminance interruption on search assistance for the two types of trials. In addition, although the observer does not know whether the target is present or not until the end of the

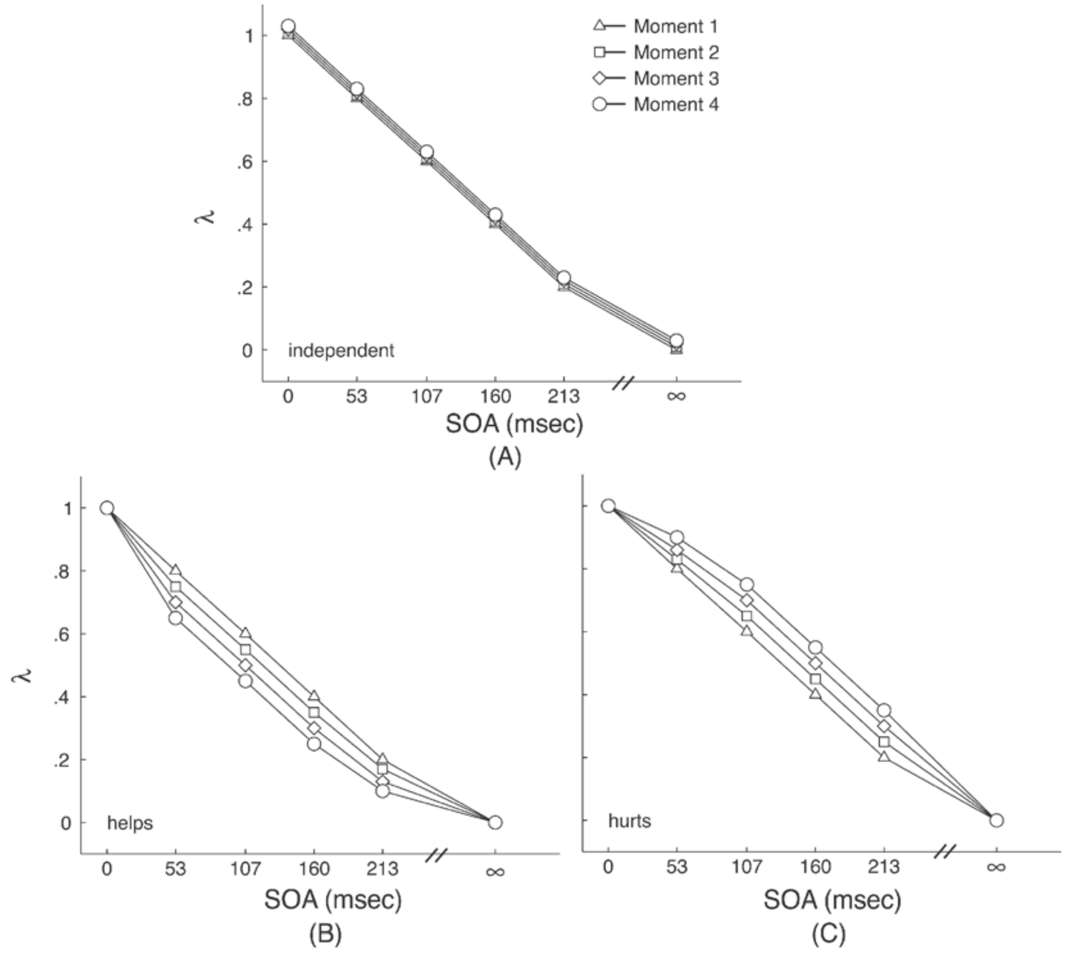

Figure 4. (A) Illustration of what the λs would look like if the two control distributions did not interact. At each stimulus onset asynchrony (SOA), proportion of large-set-size difficult search (λ) is the same no matter what moment it is calculated from. Note that in the figure, the symbols for each moment are shifted upward slightly so that they are all visible; however, this is just for purposes of illustration, and they are meant to overlap. (B) Illustration of what the λs would look like if partial processing of the initial display helped processing of the second display. The λs calculated from higher moments are smaller than those calculated from lower moments (see the text for further description). (C) Illustration of what the λs would look like if partial processing of the initial display hindered processing of the second display.

trial (until a response is selected) and, thus, cannot choose a different strategy for each type of trial (especially with the brief SOAs in our experiment), there will be *developing processing of the target stimulus* on a target-present trial, but not on a target-absent trial, and thus some differences might be expected.

Experiment 1A, target-present trials. For target-present trials in Experiment 1A, search assistance did not occur with the difficult preview. In Figure 5A, for each observer (bottom panels), the triangles show how mean RT changes from large–difficult search RT (SOA = 0, where λ is 1.0) to small–difficult search RT (SOA = ∞, where λ is 0.0) with increases in SOA. For example, for Observer B.L., at SOA = 160, mean search RT is about 60% of the way in between that for small–difficult search and that for large–difficult search (i.e., in Figure 5, Observer B.L.'s SOA = 160 triangle is at approximately a .6 proportion of large–difficult search). The same holds for the other curves included in this graph: The squares illustrate how the proportion of large–difficult search, as measured by mean RT^2, decreases as a function of SOA. On average (top panel), the λs are close to overlapping, and in fact, at SOA = 107, they go in the *opposite* direction to that which indicates assistance; it looks as if partial processing *hurts* subsequent difficult search in the SOA = 107 condition. What this means is that there are some RTs in the intermediate distribution that are longer than a linear combination of control distributions would predict. Whether or not it hurts subsequent processing, it is clear from these results that partial processing does not appear to *help* subsequent difficult search in Experiment 1, except possibly

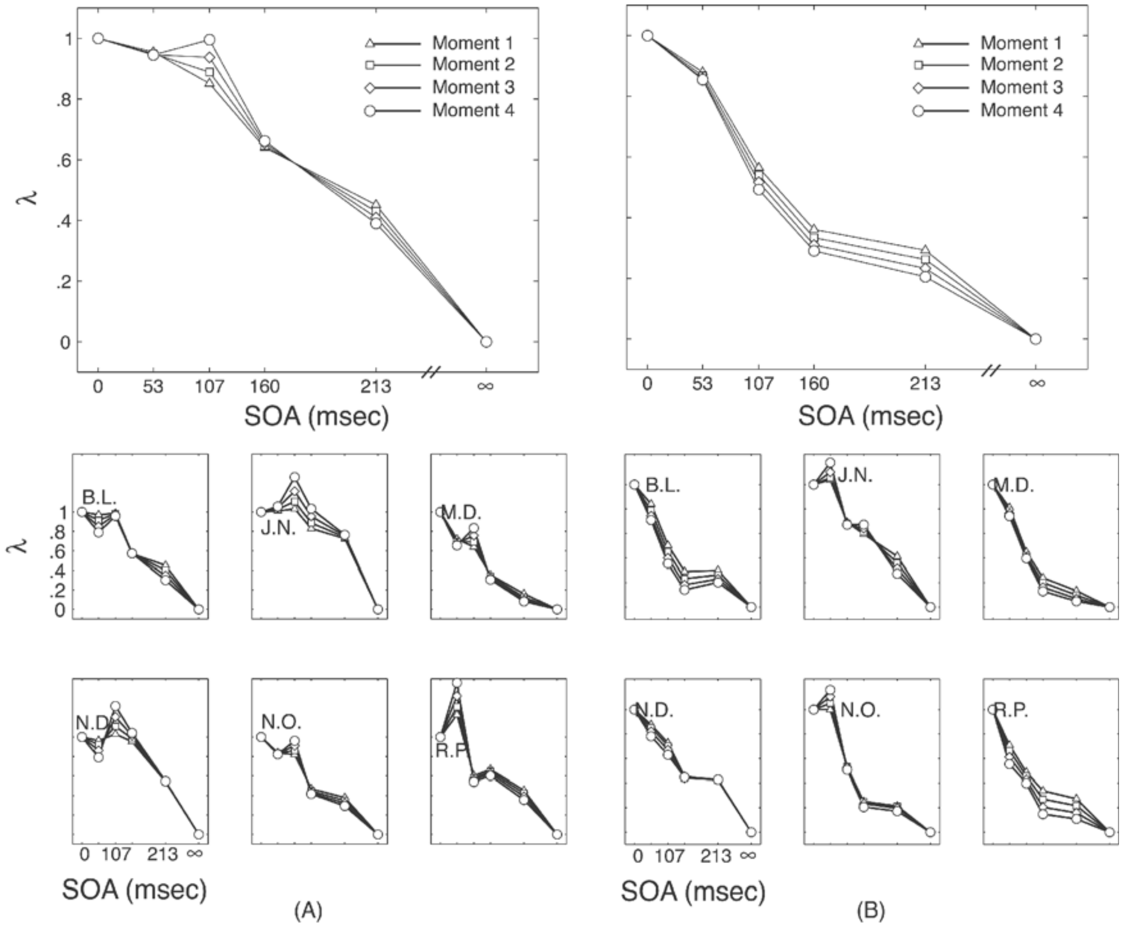

Figure 5. Proportion of large–difficult search (λ) plotted against stimulus onset asynchrony (SOA), separately for the first four moments of the target-present response time distributions for (A) Experiment 1A and (B) Experiment 1B. The top panel shows the average of the individual graphs; the bottom panels are the individual graphs, which illustrate the variability between observers. Note that if only a circle is visible, this indicates that the four estimates coincided (i.e., they were the same). See the text for a further description.

for SOA = 213. There is some variability between observers; this is likely due to noise, since the two control RT distributions are more similar than those for the previous partial pop-out experiments (difficult search with a small set size is slower than pop-out search).

It is possible to discern this effect less quantitatively by examining the RT distributions directly. The simple cartoon distributions in Figure 6A illustrate how the intermediate SOA condition RT distributions might look if there had been no assistance (and no negative influence from processing the first display on processing the second). The top panel of Figure 6A is a simplified large–difficult search RT distribution; the bottom panel is a simplified small–difficult search RT distribution. Each intermediate "distribution" (middle panels) has been created by sampling from each control distribution in different proportions (i.e., simply combining scaled copies of the two control distributions). Figure 6B shows the actual RT distributions for one observer (B.L.). Comparison of Figure 6A and Figure 6B illustrates that for this observer, the empirical intermediate distributions are, in fact, roughly linear combinations of the control distributions (we cannot prove that they are, but we can contrast these data with those of previous experiments). In the intermediate distributions shown in Figure 6B—for example, that for SOA = 107—one can cover up the RTs that appear to represent successful small–difficult search (i.e., RTs below around 1.5 sec that would fall within the bulk of the control distribution at the bottom of the figure). The remaining uncovered set of RTs (the above–1.5-sec RTs for SOA = 107) does look like a scaled copy of the difficult search RT distribution at the top. In other words, the non–small-set-size RTs in that distribution could simply be large-set-size RTs (i.e., a scaled copy of the large–difficult search RT distribution). Note that the corresponding λ plot for this observer (in Figure 5A) shows the same thing; this is generally the case.

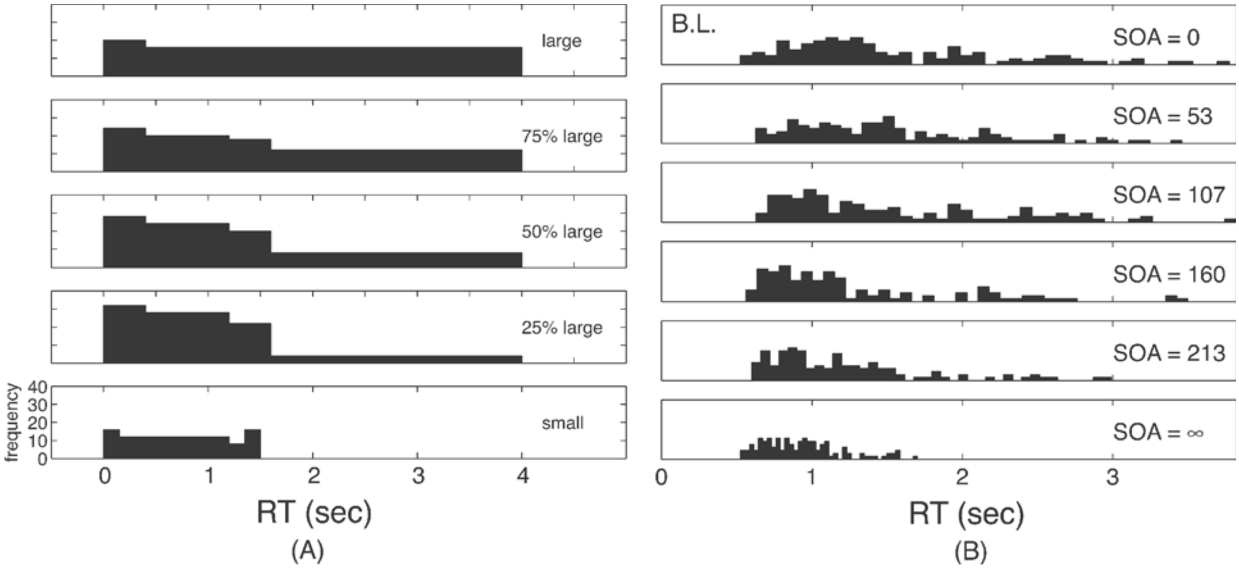

Figure 6. This figure illustrates a hypothetical case in which control distributions add in different proportions to produce intermediate distributions, along with an example of a set of empirical distributions. (A) The top distribution (hypothetical *large-set size difficult search control distribution*) consists of the numbers 1 to 5, taken every 0.1 (i.e., [1:.1:5]); this set of numbers is repeated four times, and the resulting set is plotted in the top histogram. The bottom distribution (hypothetical *small-set size difficult search control distribution*) consists of the numbers 1 to 2.5, taken every 0.05; this set of numbers is repeated four times, and that set is plotted in the bottom histogram. The intermediate histograms represent different combinations of the two control distributions. For example, the second histogram consists of three copies of the 1-to-5 numbers and one copy of the 1-to-2.5 numbers (i.e., it consists of 75% large set size and 25% small set size control response times [RTs]). (B) Actual RT distributions for Experiment 1A, target-present trials (Observer B.L.).

See the Appendix for a description of Monte Carlo simulations that illustrate the predictions of two possible independence models.

Experiment 1B, target-present trials. Figure 5B shows that for target-present trials in Experiment 1B, when there were only four items in the initial display, search assistance did occur for SOAs beyond 53 msec (unlike in Experiment 1A). On average, λ calculated from high moments was smaller than λ calculated from lower moments. Partial processing of the smaller initial display appears to have been used to assist processing of the subsequent modified display.

Target-absent trials. For target-absent trials (Figure 7), search assistance did not occur for Experiment 1A or 1B. In fact, it looks as if partial processing may have *hurt* subsequent difficult search on the target-absent trials. Our main focus is on target-present trials, so we do not show target-absent λs for individual observers.[2]

Removal of outliers. For the analyses reported in this paper, outliers beyond three standard deviations from the mean were removed from each condition, and the present method of analysis is based on what happens with the long RTs. Thus, it is reasonable to be concerned about what would have happened if outliers had been left in (because the outliers will generally be long RTs for these distributions). Past work has analyzed RT data both in its entirety and with outliers removed (see, e.g., Olds et al., 2000b); results have tended to be consistent for both cases, although outliers tend to add noise. Because such a small percentage of trials were removed in the outlier screening process and because abnormally long RTs, which could be due to sneezes or looking away, should be removed, we are inclined to focus on the outlier-free data.

Nevertheless, we also analyzed the data with these outliers included (i.e., all the RTs for each distribution). For target-present trials in Experiment 1A, when outliers were included, there was still no search assistance—in fact, the pattern in the λs for all intermediate SOAs went in the direction that indicates hindrance rather than assistance. Thus, whether or not outliers are included, for Experiment 1A, search assistance did not occur. For Experiment 1B, however, when outliers were included, the evidence for search assistance was much less strong than it was when outliers had been removed. For most intermediate SOAs, the λs were close to overlapping; for SOA = 213 msec only, the λs weakly indicate assistance (i.e., they are ordered as they are in Figure 5B, but they lie much closer together). Thus, the results for a set size of four are not entirely conclusive. Future research can examine whether this kind of inconsistency tends to be due to a relatively substantial right tail in some RT distributions or to a small number of very long RTs (but note that the mean proportion of outliers removed for Experiment 1A, 1.38%, is not very different from that removed for Experiment 1B, 1.35%).

EXPERIMENT 2

Experiment 2 was similar to Experiment 1, but four initial set sizes of 4, 6, 8, and 10 were included, in order

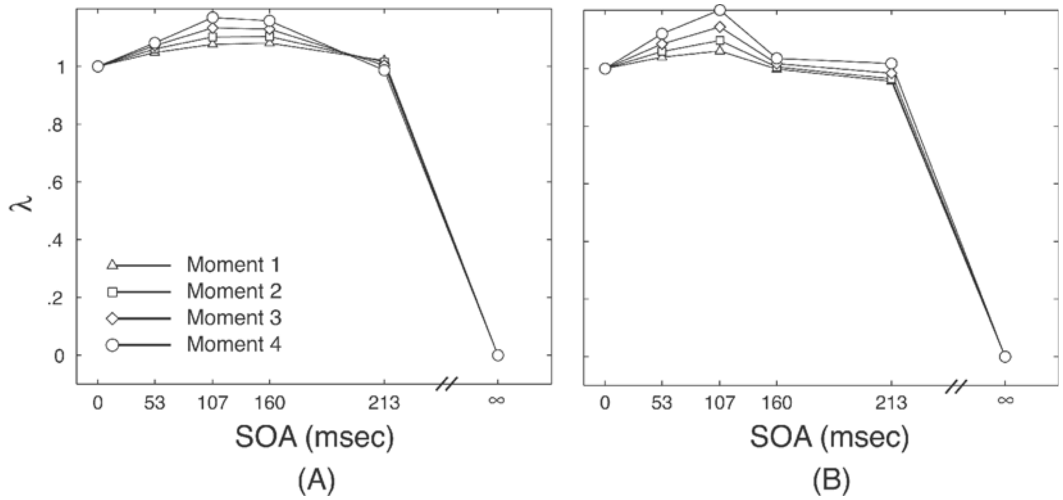

Figure 7. λ for target-absent trials, plotted against stimulus onset asynchrony (SOA) and averaged across observers, for (A) Experiment 1A and (B) Experiment 1B.

to seek further evidence for small-set-size assistance and in order to determine at what point that assistance, if present, breaks down.

Method

Observers. Observers B.W., E.O., M.D., M.M., M.W., N.O., and R.P. participated. Observers M.D., N.O., and R.P. had participated in Experiment 1 first; author E.O. had participated in similar pilot experiments. Observers B.W., M.M., and M.W. had not participated in any search experiments in which a difficult display was followed by a subsequent larger set size difficult display.

Equipment. The same equipment was used as that used for Experiment 1.

Stimuli. The stimuli were the same as those for Experiment 1, except that initial set size was 4, 6, 8, or 10 items.

Design and Procedure. The design and procedure were the same as those for Experiment 1, except that the different initial set sizes were presented intermixed. Each session of 384 trials was preceded by 10 practice trials. All the observers completed eight sessions, for a total of 3,072 experimental trials each.

Results and Discussion

The outlier screening process resulted in the removal of 1.7%, 1.8%, 1.6%, 1.6%, 1.6%, 0.9%, and 1.4% of correct RTs overall, for observers B.W., E.O., M.D., M.M., M.W., N.O., and R.P., respectively (across the four set sizes; the RTs were divided by present/absent, SOA, and initial set size for the purposes of screening).

Figure 8 shows mean RT and error rate for Experiment 2, presented separately for the four initial set sizes. Figure 9 shows the λs. Although partial processing helped subsequent difficult search for a set size of four (SOA = 107 or longer) and for a set size 6 with a long SOA (SOA = 160 or 213), it did not help for the larger set sizes.

There is more noise in these data than in those of Experiment 1, because despite the large number of trials per observer, there are half the number of data points for each set size. Note, in fact, that for some observers for some SOAs, for the larger set sizes the λs do fall in the pattern

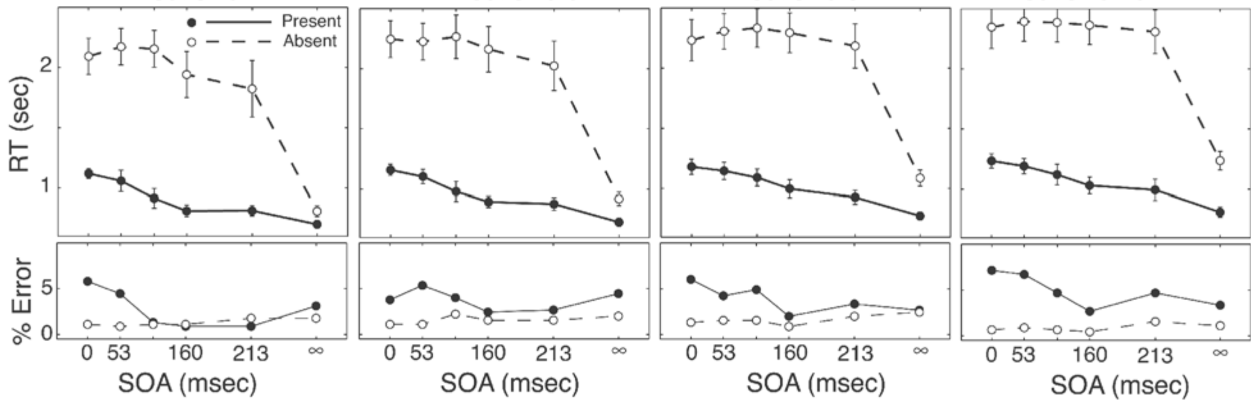

Figure 8. Mean response time (RT) and percentage of error plotted against stimulus onset asynchrony (SOA) separately for target-present trials and target-absent trials and separately for each initial set size for Experiment 2.

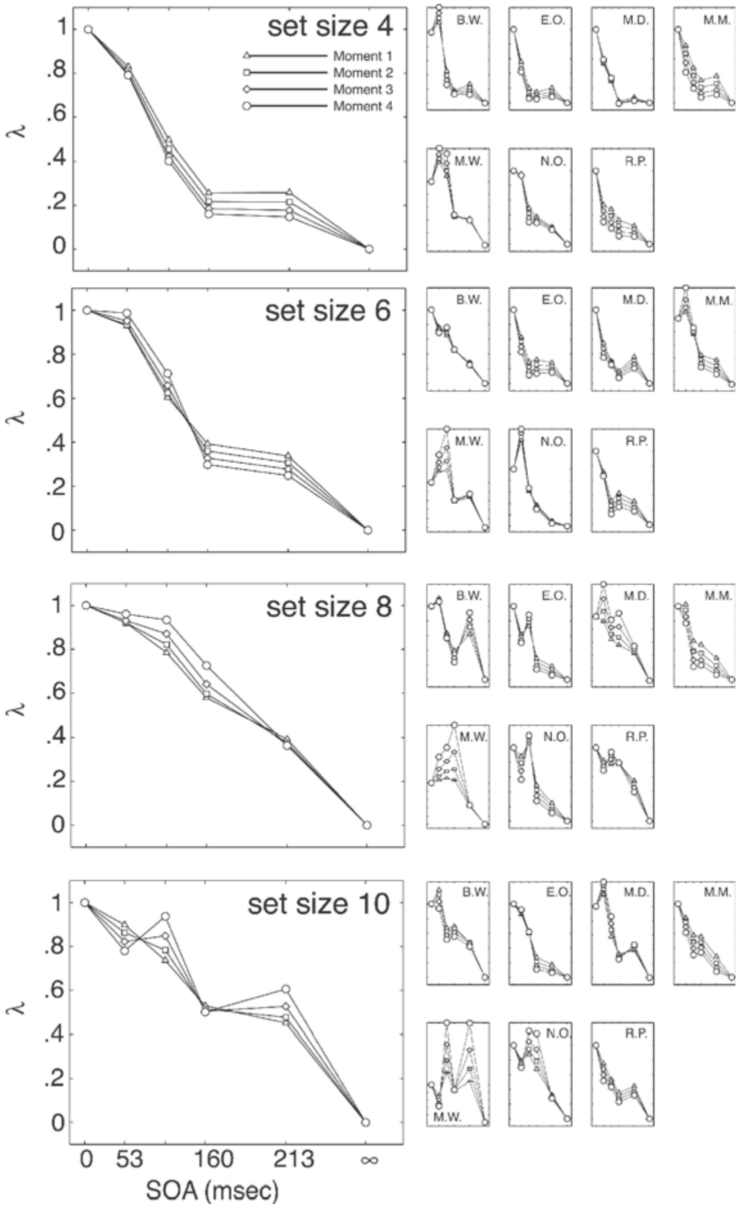

Figure 9. λ plotted against stimulus onset asynchrony (SOA) separately for the first four moments of the target-present response time distributions for Experiment 2. The left panels show the average of the individual graphs; the right panels are the individual graphs, which illustrate the variability between observers. See the text for further description. Note that for some of the individual observer graphs, the *y*-axis has shifted because of some large values of λ.

that indicates search assistance, but this is not consistent overall. It is clear that search assistance can occur with a difficult preview, but reliably only if set size is small. The data indicate that search assistance can occur with six initial items only if the SOA is sufficiently long, perhaps allowing for relevant information to build up gradually.

Removal of outliers. As was mentioned above, we have focused mainly on the outlier-free data. However, we did analyze the entire data set as well, including these outliers for target-present trials in Experiment 2. As was the case in Experiment 1, the only difference from the results reported above was that, for the smaller set sizes, the finding of search assistance did *not* hold. That is, our main conclusion holds, that for larger set sizes, there was no search assistance, whether or not outliers were removed. Difficulty in grouping impairs search assistance. However, our secondary conclusion that search assistance did occur for the smallest set sizes is again somewhat weakened, because it does not hold when outliers are included. Thus, the results for small set sizes are suggestive rather than conclusive. Current work in our lab is focusing on this discrepancy, using alternative modeling techniques.

For the sake of brevity, we do not present the target-absent λs; we will simply mention that for none of the set sizes was there any assistance.

GENERAL DISCUSSION

The purpose of this paper has been to examine the effect of partial processing of a difficult search display on subsequent processing. We tested whether search assistance for a difficult preview occurred and, if so, whether it depended on initial set size. Search assistance with a *pop-out* preview has been demonstrated for displays of different set sizes (Olds, Cowan, & Jolicœur, 2000c); the present experiments tested search assistance for different set size *difficult* preview displays.

Exposure to a difficult search display did *not* assist processing of a subsequent larger difficult search display. Tentative evidence was found for search assistance for the smallest set sizes tested, for target-present trials only. There was no search assistance for target-absent trials. Even though the first display and the second display both required difficult search (and thus would be expected to be processed by the same set of cognitive mechanisms), there was less search assistance in the present experiments than in the previous studies that tested assistance from pop-out to difficult search. This is striking because the mechanisms responsible for pop-out and the mechanisms responsible for difficult search are likely different, at least in part, and yet previous work has found search assistance with a pop-out preview. We now turn to several relevant issues that may explain the difference between the present results and previous findings of search assistance.

Grouping Is Better for Homogeneous Initial Items Than for Heterogeneous Initial Items

Palmer (1999, p. 259) has proposed *grouping by synchrony* as a new principle of perceptual grouping, whereby items that change together are grouped together. It is likely that this principle is relevant for search assistance experiments, since the appearance of an item can be seen as a change in that item. When the target and some of the distractors appear and then more distractors appear after a delay, performance will be improved if the observer can segment the two sets of items temporally—in effect, ignoring the "new" distractors.

In previous experiments testing search assistance with a pop-out display (Olds et al., 2000a, 2000b), initial distractors were homogeneous, and therefore, grouping by similarity (of color) would have been possible, along with grouping by synchrony. Perhaps we found less search assistance in the present experiments because temporal grouping is more difficult when the initial distractors (and the added distractors) are heterogeneous. Homogeneity of the initial distractors appears to be necessary for search assistance, at least for set sizes beyond the smallest that we tested. Duncan and Humphreys (1989) showed that distractor homogeneity facilitates search; the present experiments show that initial distractor homogeneity also facilitates search assistance, which is greater with a pop-out initial display than with a difficult initial display.

Temporal grouping was the same in the present experiments as in the previous partial pop-out experiments: In both sets of experiments, some of the distractors appeared first, with the target, and others appeared later. Comparing the present results with the previous results for search assistance with a pop-out display showed the extent to which ease of grouping by similarity affects the processes responsible for search assistance: Grouping by synchrony alone is worse than grouping by both synchrony and similarity (of color). This may be particularly true for target-absent trials (where we found no search assistance at all in the present experiments), which is consistent with Duncan and Humphreys's (1989) claims that homogeneity is particularly important when the target is absent. Thus, the present results can be seen as supporting Duncan and Humphreys's and Humphreys and Muller's (1993) claims about the importance of grouping in visual selection, although these previous papers, of course, did not address search assistance.

Why Might There Be Search Assistance for the Smallest Set Sizes?

Although search assistance did not occur for many of the conditions tested, the outlier-free analysis suggests that it may have occurred for the smallest set sizes tested. How might this have occurred? It is possible that a small number of initial items or item locations can be encoded and then preferentially searched during the second portion of the display. A number of researchers have discussed possible mechanisms for encoding small numbers of items or locations. For example, Pylyshyn (2000) has found that multiple-item tagging and tracking (using hypothesized *instantiation fingers*, or FINSTs) is possible for about four items, even when the items move and even in the presence of other, similar items. Another proposed mechanism, which could encode small numbers of items, is visual short-term memory (VSTM), described, for example, by Duncan and Humphreys (1989) as a limited capacity buffer. Input representations compete for access to this buffer. The decrease in search assistance between four and six to eight initial items (see Figure 9) indicates that an explanation based on such a limited capacity buffer is plausible.[3] Luck and Vogel (1997) also have provided evidence for a capacity limit of four items in search. Finally, Palmer (1995) has described data from spatial cuing experiments that show that the effective set size of a display can be reduced if observers are shown which subset of display item locations could contain a target. The initial displays in the present experiments could be considered to contain this kind of cuing information; they indicate possible target locations. Finally, although inhibition of return (IOR, a tendency not to reinspect previously attended items; Klein, 1988) is not a likely explanation for search assistance with a pop-out preview (because IOR does not occur in displays that do not require difficult search; Klein, 1988), it could possibly contribute to search assistance with a small set size difficult preview.

Note that search assistance with a *pop-out* preview (Olds et al., 2000a, 2000b) cannot be due to FINSTs or VSTM, since it occurs for an initial set size of 18, for both target-present and target-absent trials. This indicates that the search assistance the present experiments may have shown for small numbers of heterogeneous items must occur by a *different* mechanism than does search assistance with a homogeneous preview.

Memory in Search

Finally, we turn to an issue that has received a great deal of attention recently, that of the role of memory in search. Relevant to the issue of whether processing of one search display influences processing of another, related search display is the issue of whether search processes are influenced by their previous behavior and/or experiences (i.e., whether they have *memory*). The present experiments investigated whether search of a difficult display can assist subsequent search of a related larger display; without memory, this should not occur. Previous work (Olds et al., 2000a, 2000b) demonstrating search assistance with a pop-out preview showed that feature information *can* build up over the course of search and can guide subsequent processing.

Some researchers have presented evidence against memory in search—for example, a lack of decrease in efficiency when search items change positions every 111 msec (Horowitz & Wolfe, 1998b), which seems to make sense only if search does not normally keep track of what items it has considered (see also Horowitz & Wolfe, 2001; note, though, that the authors found that search may keep track of a limited number of previously attended locations). Others have presented evidence for memory in search: a decrease in efficiency when search items change positions (Kristjansson, 2000), a tendency not to reinspect previously attended items, or IOR (Klein, 1988; Klein & MacInnes, 1999), implicit memory for spatial layout from trial to trial (Chun & Jiang, 1999), and priming of item features and positions from trial to trial (Maljkovic & Nakayama, 1996). A full discussion of these studies is beyond the scope of this paper (see, e.g., Shore & Klein, 2000, for a review). Furthermore, there are different ways in which the word *memory* has been used; for example, it can mean priming from one trial to the next, or it can mean inhibition (which implies encoding) of previously attended locations within a trial.

The Guided Search model. We now will turn to one model of search and consider how it could possibly account for the present results and how this account would relate to the issue of memory in search. The model we will consider here is not the only model of search worth considering, and in fact, there is a debate about whether difficult search is subserved by serial processing or by a parallel limited-capacity mechanism (see, e.g., Eckstein, Thomas, Palmer, & Shimozaki, 2000). We will discuss this model and accept, for our present purposes, the serial difficult search it proposes, because it lends itself well to the issue of memory.

The Guided Search model (Wolfe, 1994; Wolfe et al., 1989) consists of a parallel stage followed by a serial stage. The first stage calculates how much each item in the display matches the known target features (such as shape and color), in parallel across the entire display; the representation of each item becomes highly activated to the extent that it matches these target features. The next, more spatially focused stage considers display items serially, and it considers first items that have high activations at the parallel stage. This sequence of parallel and then serial processing, with information from the parallel process influencing the order of serial processing, could be seen as involving "memory" in two ways. First, activation builds up from moment to moment in the first, parallel stage (similar perhaps to priming), and this activation would presumably take time to decay. Second, within the serial process in the original Guided Search model, inspected items are not returned to (similar, perhaps, to IOR; Klein, 1988). A strong version of this second sense of "memory" is the one Horowitz and Wolfe (1998b) argued against in their initial "amnesic search" work.

It is the first sense of "memory" that we will focus on here: the accumulation of feature information in the parallel stage. We consider first whether amnesic search is incompatible with Guided Search. The T-in-L difficult search, which Horowitz and Wolfe (1998b) found not to be disrupted by moving items (but see Kristjansson, 2000; Shore & Klein, 2000), is not a conventional conjunction search (e.g., target defined by a combination of shape and color). Thus, it does not appear to involve the guidance of serial search by parallel processing, described above as a feature of the Guided Search model, at lease not in the same way as conjunction search does. More recent work (Horowitz & Wolfe, 1998a) has shown that *conjunction* search (which, according to Guided Search, does involve parallel processing's guiding serial search) *is* disrupted by moving items. Therefore, Horowitz and Wolfe's "amnesic search" argument does not deny the guidance of serial by parallel processes; this guidance is disrupted by moving items. That means that these researchers' general "amnesic" argument is, in fact, compatible with the first kind of "memory" mentioned above, that of building and accumulating activation (at the parallel feature level) as processing continues. This accumulation must be connected to particular locations and, thus, *would* be disrupted by constantly repositioned items (as Horowitz & Wolfe, 1998a, found). To summarize, Horowitz and Wolfe's amnesic search hypothesis argues only against memory for previous deployments of attention, whereas it does not argue against the build-up of activation at the feature (parallel) level. This is particularly interesting because it implies that information build-up is quite different at the feature and the conjunction levels.

Guided Search and search assistance with a pop-out preview. How does Guided Search relate to search assistance? The Guided Search model, with information from the first, parallel process influencing the order of serial processing, provides one possible explanation of how search assistance could occur with a *pop-out* preview (as in Olds et al., 2000a, 2000b), for target-present trials, as follows. Activation gradually builds up most at the target location during parallel processing of the first portion of the display, because the target matches the desired feature(s) more than the distractors do. Once search starts to consider the second portion of the display, the target representation maintains its relatively high activation (and may build additional activation as well), which causes it to be prioritized highly and, thus, found more quickly than in pure difficult search. Note that the Guided Search model is based on conjunction difficult search, rather than non–linearly-separable difficult search. However, since search assistance has been demonstrated for conjunction search, as well as for non–linearly-separable search (Olds, Jolicœur, & Cowan, 2001), it is likely that an extension of Guided Search that incorporates non–linearly-separable difficult search would provide a useful way of interpreting these previous search assistance results.[4]

Note that the Guided Search model could illustrate one way of having two distinct (but related) component mechanisms for search and a continuum as well. The parallel stage is involved in all searches, whereas the serial stage is more active the more difficult the search is. That is, for pop-out, the serial stage considers only the target (first). When search is more difficult, the second stage serially considers more items and, thus, is more actively involved; this activity/involvement could fall on a continuum related to task difficulty. Whether one considers the two stages as two mechanisms or as two subprocesses within one search mechanism, there is some separation. This is why previous work (Olds et al., 2000a, 2000b) discussed search assistance as involving influence from *the mechanisms responsible for pop-out* (mainly the first, parallel stage, in Guided Search terms) on *the mechanisms responsible for difficult search* (both parallel and serial stages, in Guided Search terms).

Guided Search and search assistance with a difficult preview. Assuming that a modification of Guided Search that could account for non–linearly-separable difficult search would be relatively straightforward, and keeping in mind that the model was not created to explain the present results, we ask whether Guided Search could explain why search assistance may have occurred for the small set size of *heterogeneous* initial items. This interaction would not involve assistance from the parallel stage to the serial stage in the same way as that for homogeneous initial items; the target is not linearly separable from the distractors in the first portion of the display, and thus, pop-out does not operate (i.e., the feature map alone will not directly help in search assistance with a difficult preview). The interaction/feedback that is currently included *within* the serial process in Guided Search is the fact that inspected items are not returned to. If several items were inspected during the first portion of the display and were found to be distractors, they could then be avoided during processing of the second portion. Note that this explanation is based on a lingering encoding of where serial search has been, rather than on gradually building activations at the feature level; if Guided Search is modified to serially search *with* replacement, this explanation will not hold. However, a mildly amnesic modification of Guided Search could explain why search assistance may have occurred for the small set size, but *not* for the large set size, difficult preview: Possibly, there is a very limited memory for previously considered locations (see Horowitz & Wolfe, 2001), and thus, the effect manifests itself only for very small set sizes.

Thus, Guided Search may be consistent with the present results, with some modification. Guided Search began as an extension of Treisman's feature integration theory (Treisman & Gelade, 1980), and thus, some of our conclusions relate to feature integration theory as well. Further work is necessary to consider whether parallel models (e.g., Eckstein et al., 2000) could also account for search assistance results.

To return to the first sense of "memory" discussed above, the results of the present experiments show that for most set sizes, memory for whatever was done in the first phase of difficult search did not help when the rest of the distractors were presented in the second phase.

Conclusion

Only some information can be selected for detailed processing by the visual system. Previous work (Olds et al., 2000a, 2000b) has measured the effects of initial processing of a simple display on subsequent processing of a related display and has shown that simple feature information can indeed guide subsequent search. The present experiments were designed to measure whether exposure to a more complicated display could also guide subsequent search. A more varied set of items was present in the initial display, and the observer had to avoid being distracted by new items in order to efficiently consider the task-relevant old items.

With the heterogeneous initial items tested here, search assistance did not occur for larger set sizes. This result is consistent with the idea of amnesic search. The only evidence for search assistance occurred for target-present trials, for small set sizes; this tentative result could indicate a role for some sort of limited memory. The lack of search assistance for any but the smallest set sizes of difficult preview shows, first, that search assistance occurs differently if and when it occurs for heterogeneous initial items than when it occurs for homogeneous initial items. Second, this result shows that when search assistance does occur for homogeneous initial items, perceptual grouping is involved. In the face of new distractors, two criteria (onset time and color, in the previous search assistance experiments with homogeneous initial distractors) are better than one (onset time only, in the present experiments). These results are surprising, given that in the present experiments, both the first portion of the display and the second portion of the display afforded difficult search and, therefore, exposure to the first portion might have been expected to have a helpful influence on processing of the second portion.

In conclusion, grouping is important not only in search in conventional displays, but also in the guidance of search in temporally more complicated displays.

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NOTES

1. The independent mixture model dictates that the RT distributions in each intermediate SOA condition should consist of a proportion of RTs that reflect successful detection by pop-out mechanisms, and the remainder, which reflect successful detection by difficult mechanisms (i.e., obtained by randomly sampling a proportion of trials from the popout control distribution and the remainder from the difficult search control distribution). Olds et al. (2000b) discussed different kinds of combinations of such RT distributions in more detail.

2. Note that Olds and Punambolam (2002) also failed to find *pop-out* search assistance for target-absent trials in which all of the items became black disks for 100 msec between the first and the second portions of the display (i.e., the sequence of events was as in Figure 2A, except that, between the first and the second portions of the trial, all 36 potential item locations briefly contained black disks). This result shows that even pop-out search assistance has previously manifested itself less consistently for target-absent trials than for target-present trials.

3. This brings us to an interesting difference between target-present trials and target-absent trials, in our study. Assume that only a small subset of initial items (e.g., 4 items) can be tagged as initial items (potential target locations). These items would be prioritized for search even once the 20 extra distractors are added to the display. For target-present trials, on average this tagging will produce an advantage for search in the second portion of the display, even for initial set sizes greater than 4. For an initial set size of 8, for example, half the time the target will be one of the 4 items that has ended up being tagged as an

initial item, and it will be found earlier than normal. For target-absent trials, all of the initial items must be considered and determined not to be the target, so if only 4 have been tagged for prioritization, once the extra distractors are added there is no information about which are the other 4 initial items. Therefore, all of the 20 new distractors must be considered during search of the second portion, in case each one was one of the 4 untagged initial items. Tagging 4 of the 8 initial items will not help search on a target-absent trial. The current target-absent results are consistent with this idea—there is no assistance for target-absent trials. Looking at the present target-present results, however, we see that for initial set sizes above 4–6, there does not seem to be any consistent assistance. Even if the number of initial items were larger than a capacity of 4, we would still expect some help on target-present trials, and we do not see that. However, it is possible that our technique is not sensitive enough to pick up such a small effect, so we cannot use these results to rule out a role for FINSTs or VSTM in the search of these displays.

4. It remains to be seen how a limited-capacity parallel model of difficult search would compare with the serial version proposed by Guided Search.

APPENDIX
Monte Carlo Simulations

Olds et al. (2000a, 2000b) have shown that nonoverlapping distributions, when combined in a mixture, produce overlapping λs. Pop-out and difficult search RT distributions do not tend to overlap much (at the very least, there are many difficult RTs that do not overlap at all with the pop-out RTs). However, for the different set size difficult search control distributions in the present experiments, there is greater overlap (see Olds, Jolicœur, & Cowan, 2001, for another case in which the two control distributions tended to overlap). Therefore, we performed Monte Carlo simulations (similar to those of Olds et al., 2000a, 2000b) with combinations of the two control distributions, for Experiments 1A and 1B, in order to see what the λs for independent mixtures of the pairs of control distributions would look like.

Simple Mixture Model

In the simplest mixture model, on each trial, one process is chosen at random, and it provides the RT for the trial. In this model, the two processes do not interact, and the λs are predicted to coincide. To demonstrate this prediction of overlapping λs for the simple mixture model, we combined boot-strapping methods with Monte Carlo simulation in the following way. For observer B.L., for example, the empirically obtained small–difficult control RT distribution (SOA $= \infty$) contained 125 data points, and the large–difficult control distribution (SOA $= 0$) contained 123 data points (after outliers were removed). We sampled 60 RTs with replacement from the small–difficult distribution and 60 RTs from the large–difficult distribution; these 120 data points were combined for a predicted intermediate distribution. This arbitrarily chosen sampling was meant to simulate roughly a situation in which the mechanisms responsible for small–difficult search detected the target on 50% of the trials. The first four moments for the actual control distributions and for the simulated intermediate distribution were calculated. Then λ was calculated for each moment. This procedure was repeated 1,000 times. The mean λs are presented in Figure A1A (the point representing 50% sampling from the easier distribution); for both Experiments 1A and 1B, the λs from the different moments overlapped. The results are shown only for observer B.L.; the results for the other observers were very similar.

Thus, using the data from our control conditions, we have shown what linear combinations of these control distributions would tend to produce. Note that this simulation result is similar to the overall results from Experiment 1A with a set size of 10 (Figure 5A), but not to the longer SOA results from Experiment 1B with set size of 4 (Figure 5B). In other words, the simulation of the simple mixture model produces λs similar to those found for the larger initial set size, supporting the conclusion that there was no interaction (search assistance) for the larger initial set size.

Mixture Model With Delay

However, the simple mixture model is not the only possible instantiation of *independence*. Therefore, we considered another model. The second simulation we created was based on another plausible mixture model, one in which large–difficult search does not begin until small–difficult search has failed (i.e., at the SOA). In this simulation, large–difficult search (the cognitive mechanisms responsible for performance in the SOA $=$ 0 condition) is deployed only in response to the failure of small–difficult search (the cognitive mechanisms responsible for performance in the SOA $= \infty$ condition) to locate the target during the time that the display is small. As in the first simulation, small–difficult and large–difficult search each detected the target on half the trials. However, on the trials for which large–difficult search detected the target, the response time for large–difficult search was delayed by 160 msec (i.e., the RT was increased by 160 msec; this is because, for SOA $=$ 160, that is the appropriate delay). This delay of 160 msec caused λs calculated from higher moments to lie somewhat above those calculated from lower moments, but not by much, for Experiments 1A and 1B (Figure A1B). The simulation results for the other observers looked quite similar, except that for a couple of observers in Experiment 1B, the λs for the higher moments were higher than those from lower moments by

APPENDIX (Continued)

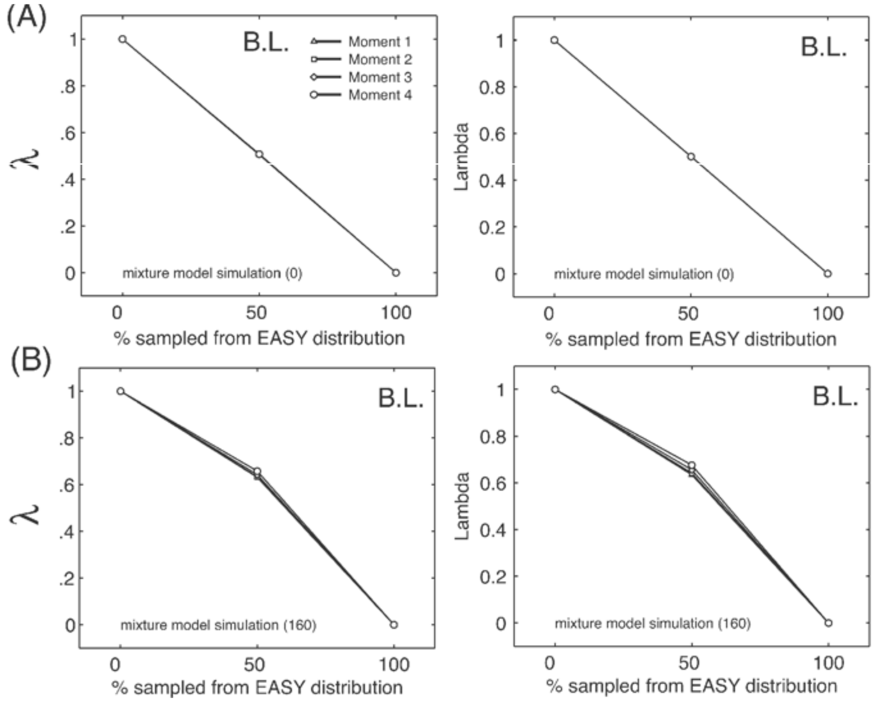

Figure A1. Results from Monte Carlo simulations: (A) simple mixture model and (B) mixture model with delay. The left column is Experiment 1A; the right column is Experiment 1B. See the text for further explanation.

more than is shown for B.L. (i.e., the circles were higher than the triangles by about two times as much). Note that this mixture model with delay is the one most similar to amnesic search: Search simply begins again at the SOA if the response has not already been selected. This model cannot explain the data from Experiment 1B with a set size of four (where λs were ordered in the opposite direction).

Thus, with either of the preceding models of independence (and given the control RT distributions obtained in Experiment 1), the larger set size produces λs consistent with independence, whereas the smaller set size produces λs that do not indicate independence (i.e., that indicate interaction).

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