The preview benefit in single-feature and conjunction search: Constraints of visual marking

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Previewing distracters enhances the efficiency of visual search. Watson and Humphreys (1997) proposed that the preview benefit rests on visual marking, a mechanism which actively encodes distracter locations at preview and inhibits them afterwards at search. As Watson and Humphreys did, we used a letter–color search task to study constraints of visual marking in conjunction search and near-efficient single-feature search with single-colored and homogeneous distracter letters. Search performance was measured for fixed target and distracter features (block design) and for randomly changed features across trials (random design). In single-feature search there was a full preview benefit for both block and random designs. In conjunction search a full preview benefit was obtained only for the block design; randomly changing target and distracter features disrupted the preview benefit. However, the preview benefit was restored when the distracters were organized in spatially coherent blocks. These findings imply that the temporal segregation of old and new items is sufficient for visual marking in near-efficient single-feature search, while in conjunction search it is not. We propose a supplanting grouping principle for the preview benefit: When the new items add a new color, conjunction search is initialized and attentional resources are withdrawn from the marking mechanism. Visual marking can be restored by a second grouping principle that joins with temporal asynchrony. This principle can be either spatial or feature based. In the case of the latter, repetition priming is necessary to establish joint grouping by color and temporal asynchrony.

Introduction

Watson and Humphreys (1997) found evidence that the visual system employs efficient tools to prioritize new objects over old ones. They had participants search

feature conjunction targets formed by letter–color conjunctions (finding a blue H among green Hs and blue As). Tasks of this kind are attention demanding and are highly sensitive to the number of search elements in the display (set size). The function of reaction time versus set size (search function) was found to be linear, with a slope (search rate) of about 26 ms/item. In single-feature search (e.g., searching for a blue H among blue As), the search function was relatively flat, with a slope of about 14 ms/item. When all green Hs were presented (which accounted for half of all distracter elements) 1 s before all the blue elements were added to the display, a linear search function with half the search rate of that in single-feature search was observed.

A straightforward interpretation of this result is that distracter preview enabled the observers to ignore the previewed (old) elements in the search display. Note that, in the preview conjunction search task, the set of distracters falls into two halves. The previewed distracters all have color A, while the new elements which complement the display all have color B. If the observer is able to mark and ignore the old elements at later search, she or he will be able to perform a single-feature search on only the new elements, which are half the search elements of the display (see Figure 1). Given the linear search function

$$RT_{single} = a\,x + b \qquad (1)$$

for single-feature search, where x denotes the number of search elements, the search function for conjunction search with preview should be

$$RT_{conj}^{prev} = a\,\frac{x}{2} + c \qquad (2)$$

if the old elements are omitted from search and only the set of new items is scanned. The slope of the search function for preview search (Equation 2) is half the
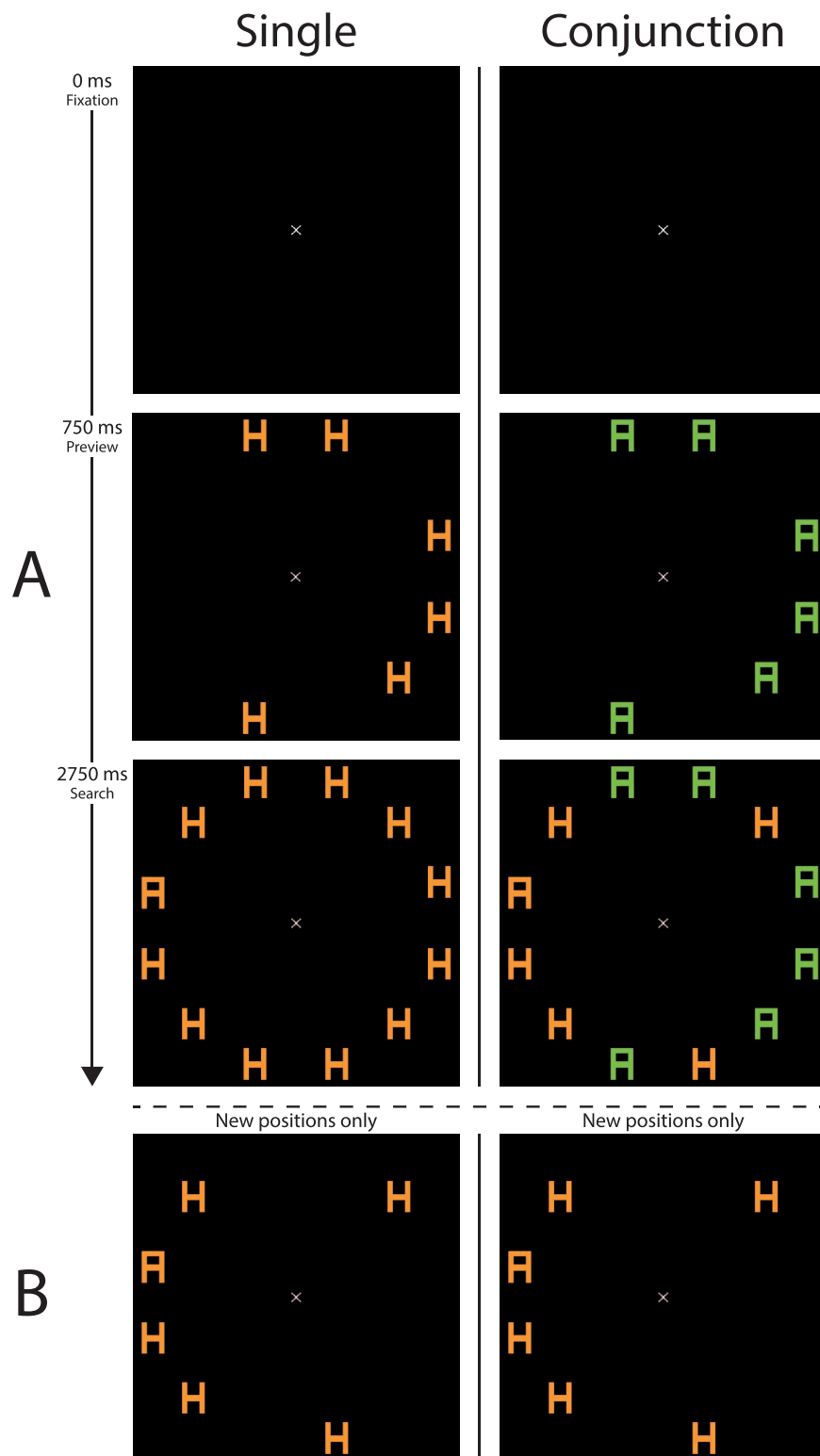
Figure 1. (A) Examples of a single trial with a set size of 12 items for single-feature preview search (left panel) and conjunction preview search (right panel). In both types of search an orange A is the target. In Experiment I, the preselected target items—and consequently the distracter items—were constantly the same across trials. In Experiment II, the definition of target and distracter items varied randomly from trial to trial. (B) The items in the new positions, which are identical for single-feature (left) and conjunction search (right), are half the search elements of the display. For the purpose of better illustration, the items were doubled in size compared to the original stimuli.

slope of the search function for single-feature search without preview (Equation 1).

In control experiments, Watson and Humphreys revealed a variety of constraints for the preview benefit. The distracters must be shown for at least 400 ms before the search display, which suggests active distracter stimulus processing in the preview period (Watson & Humphreys, 1997). Moreover, concurrent attention-demanding tasks were shown to interfere with the preview benefit, indicating that the underlying process demands resources and is not a simple cuing mechanism (Humphreys, Watson, & Jolicoeur, 2002; Watson & Humphreys, 1997). Further, results from a probe-dot task indicated active inhibitory processing at the previewed locations (Watson & Humphreys, 2000).

These findings led to the conclusion that the previewed items undergo *visual marking*, a routine in which local stimuli are first encoded and then actively inhibited (Watson & Humphreys, 1997; Watson, Humphreys, & Olivers, 2003). Support for visual marking was contributed by fMRI studies, which indicated enhanced activity at the preview stage in early feature-selective areas and in frontoparietal brain regions concerned with selection and attentional control. During the subsequent search stage the activity in early feature-selective areas was found to be reduced, while activity in higher level areas was maintained (Allen, Humphreys, & Matthews, 2007; Payne & Allen, 2011). Visual marking so conceived is an elegant and parsimonious account of the preview benefit.

Visual marking has a surprisingly large capacity, since it is, unlike short-term memory, able to handle about eight to 10 items at a time (Jiang, Chun, & Marks, 2002a; Theeuwes, Kramer, & Atchley, 1998). A possible reason for the large capacity of the marking mechanism is that old and new elements form well-separated groups with different temporal onsets (Jiang et al., 2002b) and, additionally, different colors (Braithwaite & Humphreys, 2003). Grouping along both dimensions is apparently involved in the preview benefit. When the temporal segregation of old and new items is disrupted—e.g., by shape changes or substantial luminance changes of the old items at the onset of the new items—the preview benefit declines sharply (Jiang et al., 2002b). If old and new items have similar colors, the preview benefit is attenuated (Braithwaite & Humphreys, 2003; Gibson & Jiang, 2001). This might indicate involvement of grouping along both the dimensions of color and time.

The attenuation of the preview benefit by color similarity of old and new elements suggests that not only locations but also distracter features are inhibited when the old items are processed. This has been supported by carryover effects based on feature similarity with previously ignored items at search (Braithwaite, Humphreys, & Hodsoll, 2003; Olivers &

Humphreys, 2002). Using moving stimuli, it has been shown that these stimuli could only be marked when there was a color difference of old and new items, while there was no preview benefit just on the basis of the temporal asynchrony of both item sets (Olivers, Watson, & Humphreys, 1999; Watson & Humphreys, 1998). Additionally, there is evidence that observers use the preview to anticipate possible target features. Braithwaite and Humphreys (2003) showed that the negative effects of color similarity of old and new items could be compensated by foreknowledge of target color. Watson and Humphreys (2005) found that adding irrelevant color disks to the old items had no detrimental effects on the preview benefit when they had the same color as the old items or introduced a new color to the display. However, when they shared color with the new items, the preview benefit was disrupted. Apparently, search is no longer facilitated if new feature information enters which reduces the predictive value of the old items for anticipating the target. These findings suggest that not only active encoding and ignoring of locations but also active feature processing is involved in the preview benefit.

While distracter feature inhibition and target feature anticipation are mechanisms that may complement a spatial-marking mechanism, Donk and colleagues (Donk & Theeuwes, 2001, 2003; Donk & Verburg, 2004) have suggested an alternative account of the preview benefit that disapproved involvement of any active distracter processing. Instead, they explained the preview benefit by a parsimonious bottom-up mechanism that automatically directs attention to only the new items at the moment they appear. Early work on spatial selection showed that new items that enter the display with a sudden luminance onset capture attention in an automatic fashion (Yantis & Jonides, 1984). Donk and Theeuwes (2001) showed with an elegant paradigm that abrupt onsets of new items can trigger prioritization of whole sets of new items in search. Orthogonally varying the number of old and new items, they observed that reaction time as a function of the number of new items was independent of the number of old items when the items had a luminance gradient to the background. With items that were isoluminant with the background, the search function critically depended on the number of old items. These results suggest that the subject visited only the new items when they came in abruptly, while without abrupt onsets, old and new elements were scanned during search. Subsequent experiments showed that subjects tended to prioritize new items even when target presence was more likely in the set of old items than in the set of new items (Donk & Theeuwes, 2003).

In the ongoing debate about the relevant mechanism for the preview benefit, there is some agreement that

inhibition of locations, feature-based inhibition, feature-based target foreknowledge, and onset capture are all potentially relevant mechanisms for the prioritization of old over new items, which might also act in concert depending on the constraints of the stimuli and the task (Donk, 2006; von Mühlenen, Watson, & Gunnel, 2013). The task constraints are important, since the instruction given to the observers that only the new items contain the target likely triggers active preprocessing of the distracter set; thus a possible bottom-up capture mechanism and active distracter preprocessing may act in parallel to maintain segregation of old and new items during the search period, which may last more than 2 s in an inefficient conjunction search task.

It is striking that studies on the preview benefit have so far used a constrained arrangement of conjunction search that might favor segregation into old and new items by a further implicit mechanism. The target item is defined a priori, and the distracters remain constantly the same across all trials of the experimental test (Watson & Humphreys, 1997, 2000, 2002, 2005).[1] With these constraints (block design), it might be that highly overlearned color-to-letter assignments for the target and the distracters support segregation. The constraints of the block design have strong implications for testing current accounts of the preview benefit. Visual marking suggests that the preview period before the search display is sufficient to encode and mark the distracter items—no reference is made to a long-term memory mechanism. If the preview benefit is critically dependent on repetition priming (Geyer, Müller, & Krummenacher, 2006; Kristjansson, Wang, & Nakayama, 2002), then this would be evidence that the short-term spatial-marking mechanism must be complemented by a long-term memory component for features.

Attentional capture should not depend on repetition priming at all, since it is irrelevant for a capture mechanism whether new items change their nature from trial to trial or remain the same. We conclude that a test whether the preview benefit in conjunction search needs repetition priming or is robust against randomly changing color-to-letter assignments across trials is highly desirable, since such a test would reveal whether memory for features is necessarily involved in the preview benefit. To contribute this test was the first motivation of the present study.

Second, comparing the preview benefit in single-feature and conjunction search offers another critical test for current theoretical accounts. If the preview benefit solely rests on a spatial-marking mechanism or just on attentional capture, then preview search should be *equally efficient* for single-feature search and conjunction search. This follows, since the elements which remain in the to-be-searched representation after visual marking are the same for both kinds of preview

search, allowing a true single-feature search (see Figure 1). Consequently, a search function according to

$$RT_{\text{single}}^{\text{prev}} = a\,\frac{x}{2} + d \qquad (3)$$

should be observed if all old elements are omitted in single-feature preview search, which again is the half-slope prediction (Equation 2) up to the intersection parameter, which may differ among preview search with single features or feature conjunctions.

In looking at preview search from the perspective of possibly involved feature processing, the prerequisites for the preview benefit are notably different in single-feature and conjunction search. While only the temporal asynchrony of old and new items can be used as a grouping cue in single-feature search, old and new items are separated by time *and* color in conjunction search (Theeuwes et al., 1998). Hence, although the search display looks more complicated in conjunction search, the conditions for memorizing the locations that can be excluded from search are better. Even if the observer imperfectly encodes the distracter locations in the preview period, the fact that all the previewed items are green and the new items are all blue should help her or him to distinguish them in the search display and aid in attending just the blue items. In single-feature search, however, imperfectly encoding distracter items in the preview period lets the subject unnecessarily visit old locations, which should lead to a decline in the preview benefit compared to the prediction in Equation 3. Hence, a prediction from visual marking that is complemented by inhibition of distracter features—e.g., inhibition of the old items' color (Olivers et al., 1999; Watson & Humphreys, 1998) or by an anticipatory feature set for the target (Braithwaite & Humphreys, 2003)—would be that the preview benefit in conjunction search should be at least as strong as in single-feature search. In contrast, the attentional-capture account would predict an equal preview benefit for single-feature and conjunction search if it is ascertained that the luminance onsets of the new items are equally strong in both types of search. Testing and comparing the preview benefit for single-feature and conjunction search was the second major objective of the present study.

We report three experiments here. In Experiment I we replicated the preview benefit in its original experimental arrangement using the block design and compared the effect for single-feature and conjunction search. In Experiment IIa we used the random design, randomly varying the color-to-letter assignment from trial to trial. Further, we used preview displays that enabled marking of (a) only spatial and (b) spatial and featural information. In Experiment IIb we tested the effects of spatial blocking of distracters under otherwise the same conditions as in Experiment IIa. In Experi-

ment III we tested the effect of target foreknowledge, again using the random design. To ensure equal onsets of the new items in all experiments, we used colors that were calibrated for equiluminance, as did Donk and Theeuwes (2003).

The results of the three experiments reveal new constraints of visual marking in single-feature and conjunction search.

General method

General experimental outline

In all experiments, subjects performed a classical letter-search task. Two letters (A and H), in either orange or green color, were used as stimulus items. The colors were calibrated for equiluminance (see later). As Allen and Humphreys (2007) did, we used a search array with circular arrangement, comprising either 8, 12, or 16 items. In the preview conditions, half of the distracters were presented 2 s before the remaining items were added to the display. Participants were asked to indicate whether the target was present or not. Target-present and target-absent trials were equally frequent. In single-feature search, the target was an odd letter presented among a homogeneous set of distracter letters (all distracter letters were the same). In conjunction search, the distracters consisted of two homogeneous sets of alternative letters in alternative colors (e.g., blue As and green Hs). The target was one of these two letters but in the alternative color to the same distracter letter (e.g., a blue H). Reaction times (RTs) of correct responses and accuracy (proportion of correct responses) were measured. All experiments followed the same Search type (single, conjunction) $\times$ Preview (variable types) $\times$ Trial type (present, absent) $\times$ Set size (8, 12, 16) design. In all experiments, search functions were determined and the search rates were estimated.

Apparatus and stimuli

The experiment was executed with Inquisit 4 (Millisecond LLC, Seattle, WA). Patterns were displayed in a darkened room on NEC Spectra View 2090 TFT displays at 1600 $\times$ 1200 resolution with a refresh rate of 60 Hz. The luminance of the black background of the screen was 0.11 cd/m^2. The stimulus colors of light green and orange were calibrated to be equiluminant at 59 cd/m^2 using a ColorCal colorimeter (Cambridge Research Systems, Rochester, UK). This ensured a strong luminance contrast of stimulus items and background, letting the participants perceive clear luminance onsets when preview (old) and new items complementing the search display were presented. No gamma correction was used.

Stimuli were viewed binocularly at a distance of 70 cm. The letters A and H had physical dimensions of 21 $\times$ 29 pixels (width $\times$ height), corresponding to 0.44° $\times$ 0.6° of visual angle. Line thickness for all lines in each letter was 5 pixels, or 0.1° of visual angle. To create the preview and search arrays, letters were placed on the vertices of a regular n-gon ($n = [8, 12, 16]$). The center distance of each vertex was 288 pixels, or 5.98° of visual angle. The topmost vertex was always placed at the 12 o'clock position. The polygon center was always marked with a fixation cross.

Participants used a distance marker but no chin rest. They gave responses on an external Cedrus RB-830 response pad with a built-in clock for precise RT measurements. Acoustical feedback was given via headphones. A brief "tack" tone indicated that the response was correct; a "tack-tack" tone signaled an error.

Experiment I: Fixed color-to-letter assignment (block design)

Experiment I investigated the equivalence of the preview benefit in single-feature and conjunction search when color-to-letter assignments were predefined and constant across trials (block design).

Method

Experimental outline

The target item to be used in single-feature and conjunction search was the same and defined in advance, individually for each subject. It could either be an orange A, an orange H, a light-green A, or a light-green H. Defining the same target for single-feature and conjunction search implied that the composition of the new item sets was equivalent in both types of search. For example, if the target was selected to be an orange A, an orange A was among orange Hs in the new item set in target-present trials of single-feature and conjunction search (see Figure 1).

Experimental conditions

Both single-feature and conjunction search were tested with and without distracter preview, resulting in four experimental conditions. For each of these four

A

Single Feature Search
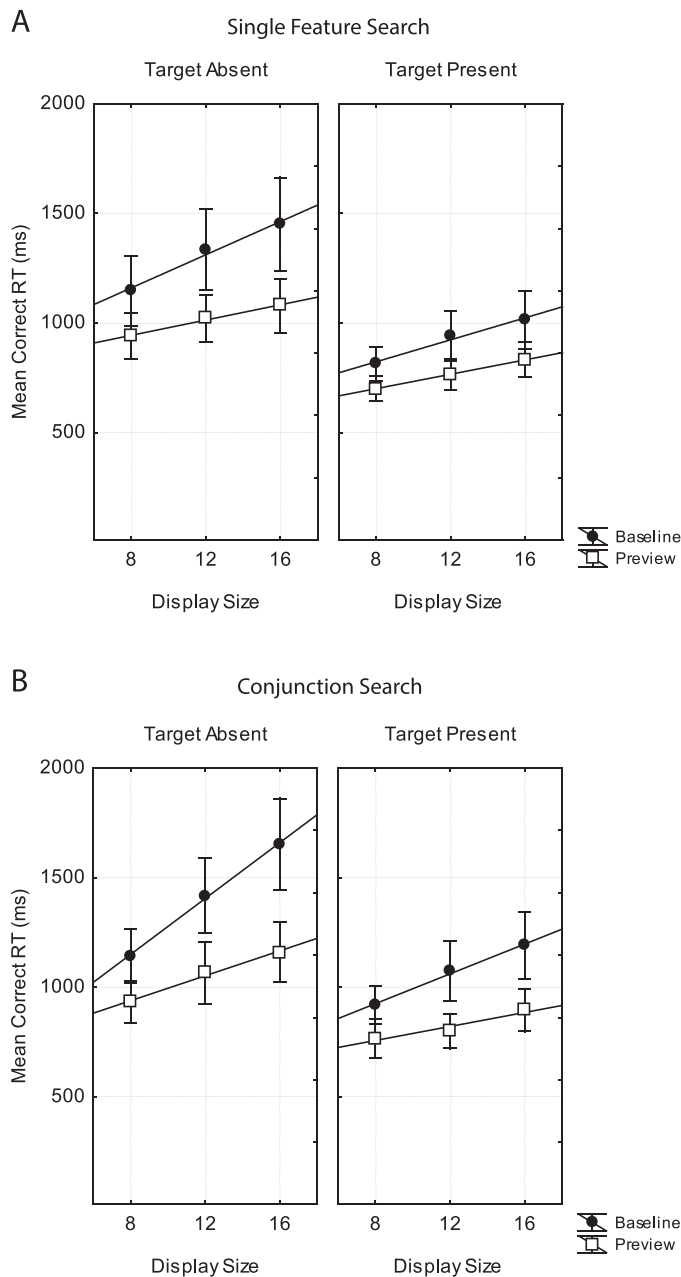

B

Conjunction Search

Figure 2. Results for Experiment I. Mean correct reaction times are shown as a function of set size for single-feature search (A) and conjunction search (B). Mean reaction times with preview are indicated by open symbols, without preview by filled symbols. Error bars indicate 95% confidence limits of the means. The straight lines indicate linear regression functions.

conditions, a search function was measured for present and absent trials.

Participants

Eighteen undergraduate students of psychology participated (mean age: 22.8 years; range: 20–26), 11 of them women. The participants were paid for partici-

pation or given course credit. All participants had normal or corrected-to-normal visual acuity.

Procedure

A yes/no forced-choice search task was used. The four experimental conditions, each with three set sizes, were run in eight blocks, each comprising 36 target-absent trials and 36 target-present trials and presented randomly interleaved. The participants were informed which of the four possible targets was chosen for the experiment. They were told that the target would never appear at previewed locations, that set size would vary randomly across trials, and that trials containing the predefined target and trials not containing it would be equally likely. The participants were instructed to decide on target presence or absence, if possible, after one search round over the circular stimulus array, and were alerted to be both fast and accurate. Further, they were instructed to act more cautious if the acoustical feedback signaled frequent errors. Before a new experimental condition started, a block of 12 practice trials was administered to ensure that the task was understood. The temporal order of events in a preview trial was as follows: fixation mark (500 ms), then preview (2000 ms), then search array (until response). In the baseline conditions the search array was presented immediately after the fixation interval. Each participant had to go through 624 trials, which took about three quarters of an hour. The order of the experimental blocks was randomized for each partici-pant. Participants were alerted to make brief pauses between the experimental blocks.

Results of Experiment I

RTs

Figure 2 shows the mean RTs of correct responses as functions of the set size (search function), for target-absent (left panels) and target-present trials (right panels). Linear regression functions gave almost perfect fitting results, with a ratio of explained variance beyond $R^2 = 0.98$ in all conditions except for preview search with feature conjunctions, where a value of $R^2 = 0.938$ was reached. The slopes of the linear functions are given in Table 1. The slope estimates reveal consistently shallower search functions for target-present compared to target-absent trials. In near-efficient single-feature search, the search rates for target-present trials were smaller than for target-absent trials but did not reach the ideal of half the search time per item. In conjunction search the slopes ratios came close to this ideal, indicating that the target was found, on average, after half the item set was scanned. The table also gives

Search	Preview	Target absent			Target present		
		Slope a	a/a_{single}	a/a_{conj}	Slope a	a/a_{single}	a/a_{conj}
Single-feature	NO	37.9			25.1		
Single-feature	PREV	17.4	0.46		16.5	0.66	
Conjunction	NO	63.7	1.68		34.0	1.35	
Conjunction	PREV	28.4	0.75	0.45	16.0	0.64	0.47

Table 1. Slope estimates a for the linear fit of the search functions (Experiment I). *Notes*: Estimates and slope ratios are given with the single-feature baseline and the conjunction baseline.

the slope ratio a/a_{single} of each preview condition relative to the single-feature baseline. For single-feature search, a slope ratio of about 0.5 was obtained for target-absent trials and a slightly larger one for target-present trials, indicating that the search rates for single-feature search fairly well complied with the half-slope prediction (Equation 3) in both trial types. In conjunction search, the slope ratios for preview relative to the single-feature baseline were 0.75 for target-absent trials and 0.64 for target-present trials, indicating that a full preview benefit in terms of the half-slope prediction (Equation 2) was just slightly failed.

To evaluate whether the preview benefit could be substantiated by significant deviations from parallelism of the preview search functions and the single-feature baseline, we analyzed the RT data for each preview condition and the single-feature baseline with separate ANOVAs, and tested the Preview × Set size interaction. This is commonly used as the standard test for parallelism (Watson & Humphreys, 2002). These tests revealed significant Preview × Set size interactions for single-feature search, both in target-present trials, $F(2, 34) = 3.77$, $p < 0.05$, and in target-absent trials, $F(2, 34) = 19.48$, $p < 0.001$. For conjunction search, a significant interaction was found for target-present trials, $F(2, 34) = 4.17$, $p < 0.05$, but not for target-absent trials, $F(2, 34) = 2.01$, $p = 0.15$. Testing search functions for preview conjunction search for parallelism with the conjunction baseline showed strong deviations in both trial types—target-absent trials: $F(2, 34) = 29.35$, $p < 0.001$; target-present trials: $F(2, 34) = 10.23$, $p < 0.001$—corresponding to the finding that the rates for preview were halved relative to the conjunction baseline (see Table 1).

Overall ANOVA for the general design (see General method) indicated the expected main effects of set size, $F(2, 34) = 90.43$, $p < 0.001$; trial type, $F(1, 17) = 84.70$, $p < 0.001$; search type, $F(1, 17) = 7.07$, $p < 0.02$; and preview, $F(1, 17) = 92.79$, $p < 0.001$.

Accuracy

Mean accuracy rates were generally high: 98.4% in target-absent trials but lower (92.5%) in target-present trials, $F(1, 17) = 27.7$, $p < 0.001$. To moderate degrees, accuracy was modulated by search type (single-feature: 95.9%, conjunction: 95.0%), $F(1, 17) = 7.02$, $p < 0.05$. Accuracy was not different with and without preview (baseline: 95.8%, preview: 95.1%), $F(1, 17) = 2.18$, $p = 0.159$. Subjects tended to operate less accurately with increasing set size (8: 96.5%, 12: 95.9%, 16: 93.9%), $F(2, 24) = 14.83$, $p < 0.001$. However, the main effect of set size had its origin in a differential effect for both trial types, since accuracy remained at constant and high levels across set size for target-absent trials and tended to fall with increasing set size only in target-present trials (Set size × Trial type), $F(2, 34) = 28.97$, $p < 0.001$. Further, a significant Search type × Preview interaction substantiated the proposition that subjects reached slightly higher accuracy rates in the single-feature search baseline than in the conjunction search baseline, but accuracy was at the same levels for both types of search in the preview condition. Critically, the Set size × Preview interaction did not reach significance, $F(2, 34) = 1.65$, $p = 0.21$, indicating that the preview benefit was not affected by a speed–accuracy trade-off. The accuracy rates for all conditions of Experiment I are given in Table 2.

Search	Preview	Target absent			Target present		
		8	12	16	8	12	16
Single-feature	NO	98.7	99.5	99.1	95.8	94.2	93.4
Single-feature	PREV	96.7	98.7	98.0	95.7	92.6	88.2
Conjunction	NO	96.9	98.6	99.4	94.3	92.3	87.1
Conjunction	PREV	98.0	99.3	97.4	95.7	91.9	88.6

Table 2. Mean percentage accuracy rates from Experiment I.

Discussion of Experiment I

The search functions measured for single-feature search and conjunction search reflected a strong preview benefit in both types of search. For single-feature search, the search rates complied with the half-slope prediction derived from visual marking for both trial types. In conjunction search, the slope ratios a/a_{single} indicated agreement with the half-slope prediction in target-present trials, while in target-absent trials, efficiency was not as high as predicted. Since the search rates for preview were approximately the same for single-feature and conjunction search in target-present trials, the results are compatible with assuming a visual-marking mechanism that inhibited the previewed items and thus let the subjects scan mostly the new items.

Comparing our results with the results of the seminal experiment by Watson and Humphreys (1997) shows that the search rates obtained here for the conjunction search baseline were about 10 ms/item larger. However, for all the other conditions our slope estimates comply fairly well with the estimates reported by those authors (see Watson & Humphreys, 1997, table 1).[2] A look at the error rates reported by Watson and Humphreys (1997, table 2) confirms highly similar search performance compared to the data reported here. They also reported more errors for target-present trials than for target-absent trials, and declining accuracy with increasing set size only in target-present trials, on about the same order of magnitude reported here. Taken together, Experiment I replicated the results of Watson and Humphreys on the preview benefit fairly well. The only notable difference in our results compared to their findings is a lower search efficiency in the conjunction search baseline. This may be due to the circular search array, which we used to enforce a strictly serial scan strategy.

Experiment II: Variable color-to-letter assignment (random design)

While Experiment I replicated the preview benefit for a fixed color-to-letter assignment and with target foreknowledge (block design), Experiment II investigated the preview benefit for randomly varying color-to-letter assignments, and without foreknowledge of the target (random design). In the random design, finding the target amounts to finding the odd element in the display. Because the preview display reveals the target features (e.g., if the preview display shows orange Hs, the subject can infer that the target will be a green H), we devised a preview condition that revealed distracter locations but not their color. To control the

effect of this condition, we used it for single-feature search as well. There, color information is irrelevant, since all items have the same color. Further, we added conditions where the preview items were arranged in spatially coherent blocks to ease encoding and recall of previewed distracter locations. Although the experimental blocks with spatially random and blocked preview-item presentation were administered in random order to the subjects, we present the results separately, with Experiment IIa referring to spatially random presentation and Experiment IIb to spatial blocking.

Method

Experimental conditions

As in Experiment I, baseline performance without preview and performance with preview were measured for single-feature search and conjunction search. In the color item-preview condition, the preview items were presented in light green or in orange, which was randomly chosen for each trial. In the neutral-color preview condition, the preview items were presented in a color that was the average of light green and orange. This color was obtained by using light green and orange in alternation for neighboring pixels (see Figure 3). The same equiluminant colors were used as in Experiment I. In the neutral-color preview condition, all preview items changed into color items at the moment when the search items were displayed. There was neither a luminance change nor a form change at the old positions when the search items were added. Just a color change occurred, without any onset capture at the old positions (see Figure 3). Because in this preview condition the observer had valid distracter position information but could not guess the color of the target, we termed it "POS," whereas the normal preview with colored items was termed "POS+C."

The experiment comprised two search conditions (single-feature, conjunction), two preview conditions (POS, POS+C), and baseline measurements without preview. As in Experiment I, the conditions were administered in experimental blocks with randomly interleaved presentation of the three set sizes and randomly chosen distracter positions on the search array. The preview conditions POS and POS+C were also measured with spatially blocked presentation of distracters. For conjunction search a new baseline was added, where the two families of distracters were presented in spatially coherent blocks. For single-feature search an additional baseline condition was not necessary, since there was only one family of distracters, which naturally forms one coherent block of items.
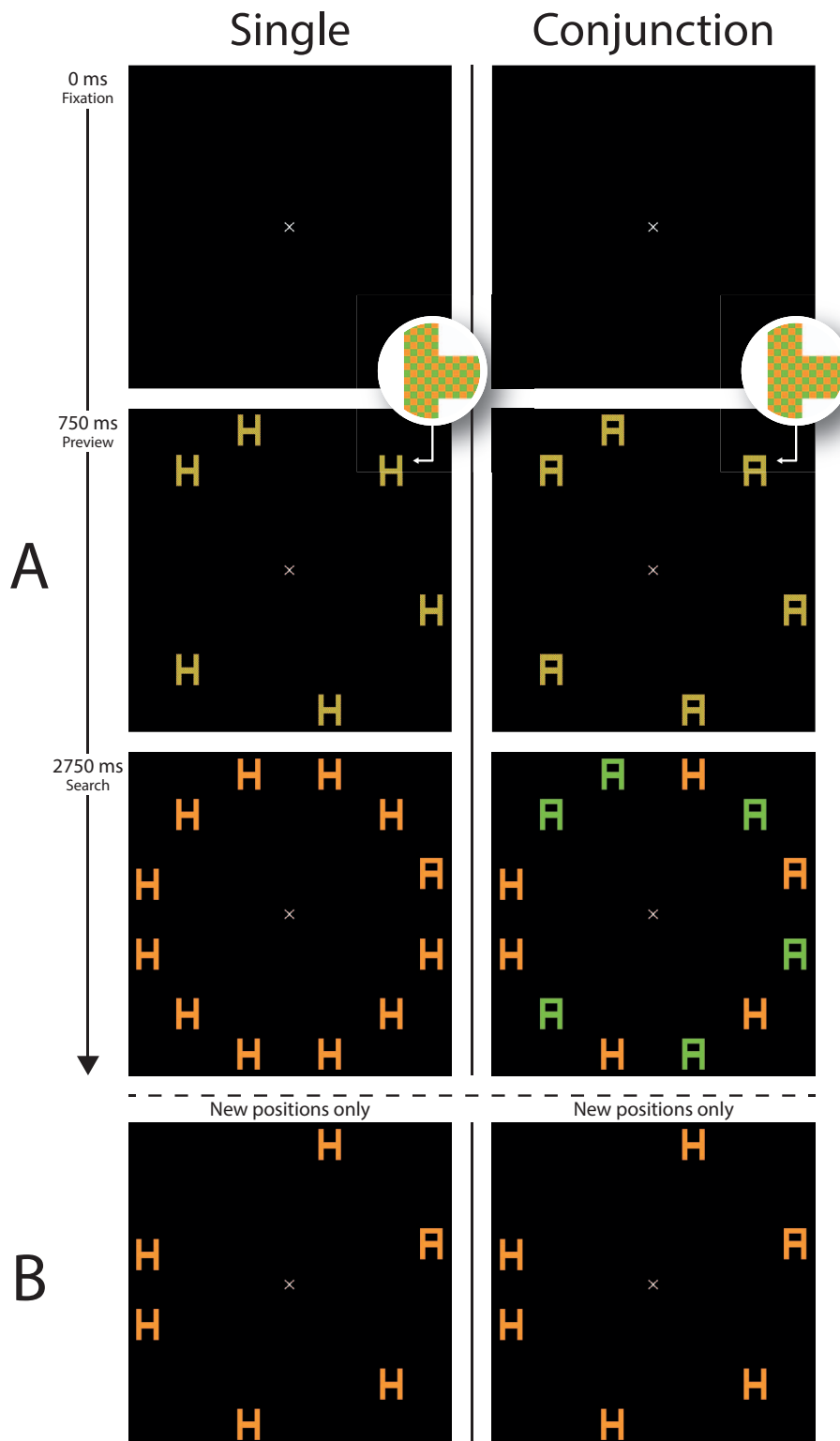
Figure 3. (A) Illustration of the POS preview condition, which did not reveal the color of the preview items. The letters were composed of pixels alternating orange and light green, which perceptually results in the spatial average color. At the onset of the search display, the preview items changed to their true color, which was the color of the new items in single-feature search (left) or the alternative color of the new items in conjunction search (right). (B) The items in the new positions. For the purpose of better illustration, the item were doubled in size compared to the original stimuli.
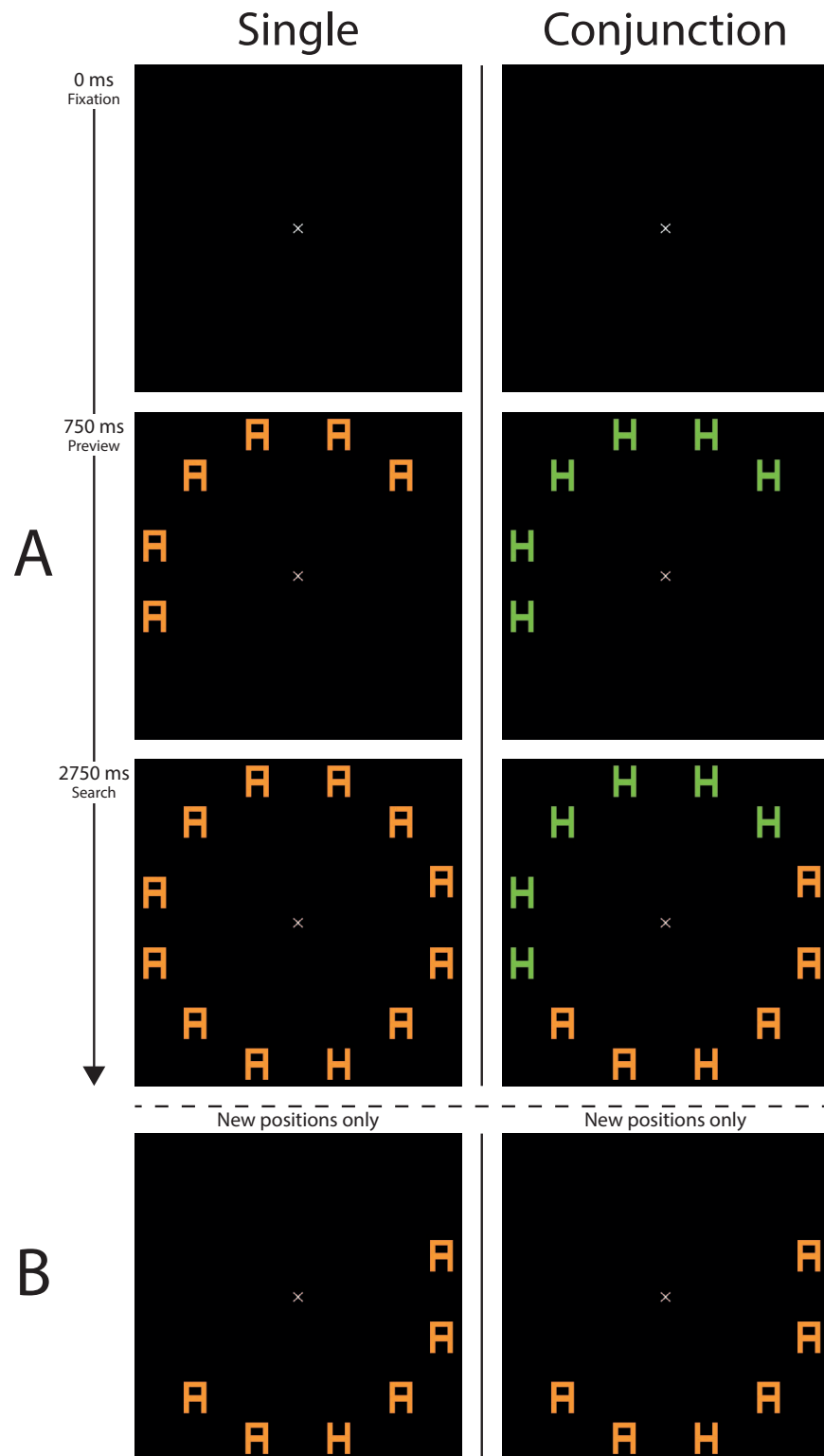
Figure 4. (A) Example of spatial blocking of the preview items (Experiment IIb) in single-feature search (left) and conjunction search (right). (B) The items in the new positions. The target is an orange H. For the purpose of better illustration, the items were doubled in size compared to the original stimuli.

A

Single Feature Search
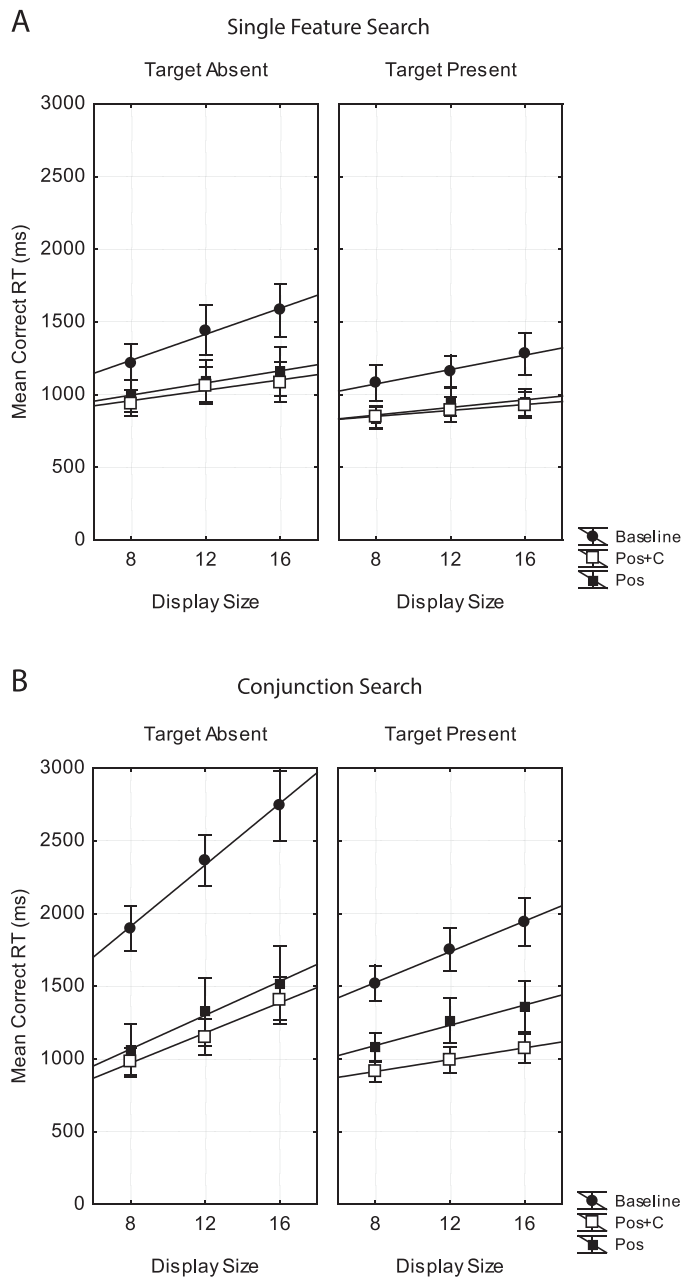
B

Conjunction Search

Figure 5. Results for Experiment IIa (randomly positioned distracters). Mean correct reaction times are shown as a function of set size for single-feature search (A) and conjunction search (B). Mean reaction times without preview (baseline) are indicated by filled circles; open squares indicate the means for full preview (POS+C), and filled squares indicate the means for just location preview. Other conventions are as in Figure 2.

Participants

Twenty-one undergraduate students of psychology participated (mean age: 22.4 years; range: 20–28), 14 of them women. The participants were paid for participation or given course credit. All had normal or corrected-to-normal visual acuity. None of the subjects participated also in Experiment I.

Apparatus and stimuli

Experiment II used the same apparatus, stimuli, display parameters, and event timings as Experiment I. The blocked arrangement of preview items is illustrated in Figure 4.

Procedure

As in Experiment I, each experimental block comprised 36 target-absent trials and 36 target-present trials. The participants received the same general instructions as in Experiment I. In particular, they were told that a target item would never appear at the previewed locations. The subjects were carefully introduced to odd-item (deviant) conjunction search with demonstrations of probe trials, having the experimenter point to target stimuli in the display. For the POS+C condition, the subjects were told that the preview distracter items would be complemented by new search items in the alternative color. For the POS condition, they were told that preview distracter items would appear in the average color and that all items would change into true-color items at the moment when the new search items complemented the display. The six experimental conditions with spatially random arrangement of preview items were divided into 12 experimental blocks. These blocks were complemented by 10 experimental blocks, which realized spatially blocked arrangement of preview items, and the conjunction baseline with blocked presentation of the two distracter families. The order of the experimental blocks was randomized for each participant. Before a new experimental condition started, a block of 12 practice trials was administered to ensure that the task was understood. Participants were alerted to make brief pauses between the experimental blocks. In total, subjects went through 1,716 trials. The experiment was executed over three consecutive days.

Results of Experiment IIa (randomly positioned distracters)

RTs

Figure 5 shows the mean RTs of correct responses as functions of the set size (search functions), and Table 3 gives the search rates of the linear regression functions. As in Experiment I, deviations from linearity were small ($R^2 > 0.96$), and the slope ratios for target-present trials to target-absent trials were about one half, indicating a serial scan strategy. In single-feature search, the slopes in both preview conditions were about half the slopes for the baseline, both in target-present and target-absent trials. As in Experiment I, we analyzed the RT data for each preview condition (POS, POS+C) and the single-feature baseline with separate

Search	Preview	Target absent			Target present		
		Slope a	a/a_{single}	a/a_{conj}	Slope a	a/a_{single}	a/a_{conj}
Single-feature	NO	44.8			24.8		
Single-feature	POS+C	17.9	0.40		10.2	0.41	
Single-feature	POS	20.9	0.47		13.0	0.53	
Conjunction	NO	105.7	2.36		52.7	2.13	
Conjunction	POS+C	51.9	1.16	0.49	21.3	0.86	0.40
Conjunction	POS	58.2	1.30	0.55	34.7	1.40	0.66

Table 3. Slope estimates a for the search-function data of Experiment IIa. *Notes*: Conventions are as in Table 1.

ANOVAs to evaluate significant deviations from parallelism of the preview search functions and the single-feature baseline. For POS, a significant Preview × Set size interaction indicated that the search functions for the single-feature baseline and preview were not parallel, neither in target-present trials, $F(2, 40) = 4.51$, $p < 0.05$, nor in target-absent trials, $F(2, 40) = 10.07$, $p < 0.001$. Also, for POS+C, a significant Preview × Set size interaction was found for each trial type—target-present trials: $F(2, 40) = 4.07$, $p < 0.05$; target-absent trials: $F(2, 40) = 14.57$, $p < 0.001$. Testing both preview conditions with ANOVA showed no significant Preview × Set size interaction—target-present trials: $F(2, 40) = 1.69$, $p = 0.197$; target-absent trials: $F(2, 40) = 1.59$, $p = 0.217$—indicating that parallelism of the two preview search functions could not be rejected. Reaction times in POS were moderately larger compared to POS+C in target-absent trials, $F(2, 40) = 4.52$, $p < 0.05$, but not in target-present trials, $F(2, 40) = 3.11$, $p = 0.093$.

Different results were obtained for conjunction search (see Table 3). The slope ratios a/a_{single} indicated values of about 1, suggesting that preview enhanced conjunction search to the time per item that was found for single-feature search, which was roughly half the time per item measured for the conjunction search baseline. The half-slope prediction (Equation 2) clearly failed in both POS and POS+C. Accordingly, testing the Preview × Set size interactions for single-feature baseline and POS showed no significance for either trial type—target-present trials: $F(2, 40) = 1.80$, $p = 0.178$; target-absent trials: $F(2, 40) = 2.29$, $p = 0.113$. For POS+C the same result was obtained—target-present trials: $F(2, 40) = 0.34$, $p = 0.714$; target-absent trials: $F(2, 40) = 2.81$, $p = 0.072$. In contrast to single-feature search, POS and POS+C preview had different effects in conjunction search. Testing with both preview conditions showed a significant Preview × Set size interaction for target-present trials, $F(2, 40) = 5.52$, $p < 0.01$, and a marginal, nonsignificant one for target-absent trials, $F(2, 40) = 2.89$, $p = 0.067$, substantiating a higher efficiency of search in POS+C compared to POS. Moreover, RTs in POS were larger compared to POS+C in target-present trials, $F(2, 40) = 34.06$, $p <$ 0.001, and target-absent trials (see Figure 5), but the latter effect was marginal and nonsignificant, $F(2, 40) = 3.10$, $p = 0.093$.

As in Experiment I, the overall ANOVA indicated the expected main effects of set size, $F(2, 40) = 130.52$; $p < 0.001$; trial type, $F(1, 20) = 48.12$, $p < 0.001$; search type, $F(1, 20) = 155.14$, $p < 0.001$; and preview, $F(2, 40) = 198.29$, $p < 0.001$.

Accuracy

Mean accuracy rates were 93.3% on the grand average, which was slightly smaller than in Experiment I (95.5%). Mean accuracy was 96.7% in target-absent trials and 90.0% in target-present trials, $F(1, 20) = 50.0$, $p < 0.001$. Accuracy was not modulated by search type (single-feature: 93.3%, conjunction: 93.3%), $F(1, 20) = 0.05$, $p = 0.822$. Accuracy was lower for the baseline conditions compared to the preview conditions (baseline: 92.1%, POS+C: 93.1%, POS: 94.7%), $F(2, 40) = 8.00$, $p < 0.001$. However, a significant Search type × Preview interaction indicated that this was true only for conjunction search, not for single-feature search, $F(2, 40) = 7.11$, $p < 0.01$. As was found in Experiment I, accuracy remained at a constant high level across set size for target-absent trials (96.7%) and tended to decline with increasing set size only in target-present trials: Set size × Trial type, $F(2, 40) = 15.73$, $p < 0.001$. Subjects reached higher accuracy rates in the single-feature search baseline than in the conjunction search baseline (single-feature: 93.6%, conjunction: 90.6%), $F(1, 20) = 9.07$, $p < 0.01$. In the preview conditions, subjects operated with about the same accuracy in both types of search—POS (single-feature: 93.8%, conjunction: 95.6%), $F(1, 20) = 4.09$, $p = 0.06$; POS+C (single-feature: 92.6%, conjunction: 93.6%), $F(1, 20) = 1.91$, $p = 0.182$. Testing whether preview benefit was affected by a speed–accuracy trade-off by evaluating the Set size × Preview interaction (Watson & Humphreys, 2002) showed statistical significance, $F(4, 80) = 2.95$, $p < 0.05$. However, this interaction reflected that subjects were *more* accurate in the preview conditions compared to the baseline without preview. The accuracy rates for Experiment II are given in Table 4.

Search	Preview	Target absent			Target present		
		8	12	16	8	12	16
Single-feature	NO	97.3	97.5	98.0	90.7	90.2	87.7
Single-feature	POS+C	96.7	97.2	98.1	95.0	88.0	80.8
Single-feature	POS	97.8	96.9	99.2	93.4	91.1	84.8
Conjunction	NO	97.0	91.8	93.1	89.5	87.7	84.3
Conjunction	POS+C	96.6	97.3	97.3	93.8	90.6	86.1
Conjunction	POS	96.8	96.8	95.4	92.2	96.8	95.4

Table 4. Mean percentage accuracy rates from Experiment IIa.

Discussion of Experiment IIa (randomly positioned distracters)

The slope estimates obtained for the search functions in Experiment IIa indicated that the half-slope prediction was valid in both preview conditions for single-feature search. In conjunction search, however, the half-slope prediction failed systematically: Larger slopes were observed in both types of preview and in both trial types. Slopes in conjunction preview search had at least double the value of the slopes in single-feature preview search, indicating clearly different kinds of search in both conditions. Another striking difference between single-feature search and conjunction search was the differential effect of the two preview types. The search functions for POS and POS+C nearly coincided in single-feature search, and only a tiny efficiency advantage was observed for POS+C compared to POS. This small advantage in POS+C may indicate that changes at old locations at the moment when the search items add to the display could not be completely ignored by the observers. However, the degree of disruption was so small that visual marking was practically not hampered, as indicated by the full agreement with the half-slope prediction in POS as well.

Comparing the search rates for single-feature search across Experiments I and IIa showed that search was equally efficient in both experiments, both in baseline and in preview (see Tables 1 and 3). The equal baseline slopes indicated that single-feature search was robust against randomly varying color-to-letter assignments. Apparently, the odd element was found with the same speed per item irrespective of whether the target and distracter item set were changing from trial to trial or were constantly the same. Also, preview search was equally efficient for both cases. Since we found full agreement with the half-slope prediction (Equation 3), we conclude that visual marking works with constant or randomly varying sets of target and distracter items in single-feature search.

Comparing the search rates for conjunction across Experiments I and IIa showed that search efficiency differed greatly between experiments. Baseline search rates in Experiment IIa were a bit under double the search rates in Experiment I. Also, preview search was notably less efficient. Comparing the slope ratios of conjunction search baseline to single-feature baseline in both experiments showed that efficiency of conjunction search was lower than that of single-feature search by about a factor of 1.5 in Experiment I, while in Experiment IIa this factor was larger than 2 (see Tables 1 and 3). This indicates that conjunction search is much harder under the conditions of the random design.

Comparison of the search rates for conjunction search baseline and the two preview search conditions showed that preview search was approximately twice as efficient as conjunction search without preview. Thus there was a preview benefit, but the effect was not as strong as expected from visual marking. The failure of the half-slope prediction suggests that subjects visited more items than actually necessary in the conjunction search preview conditions, indicating that it was hard for them to recall all the memorized distracter locations correctly when the screen was complemented with the items of the alternative color. Comparing the results for POS obtained for both types of search shows that a hypothetical spatial-marking mechanism, which leads to perfect segmentation of old and new items in single-feature search, fails in conjunction search. Moreover, in conjunction search, POS+C preview led to shallower search functions and smaller RTs than POS preview. Because color information is a valid segmentation cue and is task relevant in conjunction search, while in single-feature search it is not, the differential effects of POS+C and POS suggest that observers used the feature information provided by POS+C preview. Previewing color A may invoke feature-based attention serving to prioritize color B and deprioritize color A at later search. Thus the gain in efficiency of POS+C relative to POS may be due to feature-based attention adding to a spatial mechanism that operates to prioritize new items and deprioritize old items (see General discussion). However, the data show that even a mechanism that uses the coincident color and position information is not sufficient to achieve very high degrees of segmentation of old and new items in
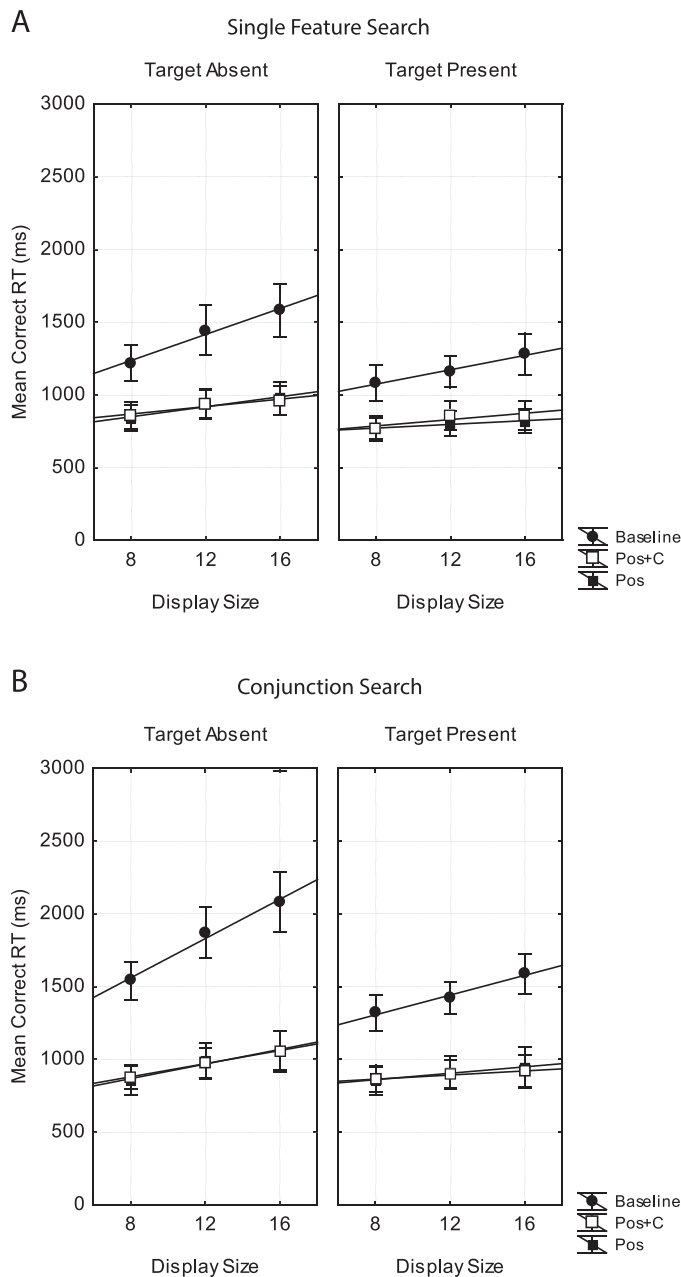
Figure 6. Results for Experiment IIb (blocked distracters). Conventions are as in Figure 5.

conjunction search tasks yielding RTs in the same range observed in our Experiment IIa. Nonetheless, a full preview benefit was observed, and in both types of search. These results indicate that absolute search times in Experiment IIa were still in a range where a full preview benefit can potentially be obtained.

Results of Experiment IIb (blocked distracters)

RTs

Figure 6 shows the search-function data, and Table 5 gives the search rates of the linear regression functions for Experiment IIb. The baseline for single-feature search was the same as in Experiment IIa. For single-feature search, the search functions became a bit flatter due to blocked presentation of preview items, and slope ratios fell below the half-slope prediction (Equation 3). Testing the Preview × Set size interaction for blocked versus random presentation indicated no significance for POS+C—target-present trials: $F(2, 40) = 1.03$, $p = 0.367$; target-absent trials: $F(2, 40) = 1.17$, $p = 0.319$—and none for POS in target-absent trials, $F(2, 40) = 0.43$, $p = 0.648$, but one in target-present trials, $F(2, 40) = 3.43$, $p < 0.05$.

For conjunction search, the search functions became notably flatter due to blocked presentation. The half-slope prediction (Equation 2) succeeded for both preview conditions and for each trial type (see Table 1). Testing the Preview × Set size interaction for blocked versus random presentation indicated significance for POS+C—target-present trials: $F(2, 40) = 7.79$, $p < 0.001$; target-absent trials: $F(2, 40) = 35.28$, $p < 0.001$—and also for POS—target-present trials: $F(2, 40) = 8.62$, $p < 0.001$; target-absent trials: $F(2, 40) = 17.23$, $p < 0.001$. Comparing the search rates for single-feature and conjunction preview search showed that approximately the same speed per item was reached for both search types in target-present trials. Search was highly efficient, with a slope of about 10 ms/item. The Preview × Set size interaction for single-feature versus conjunction search indicated no significance—POS+C: $F(2, 40) = 1.22$, $p = 0.304$; POS: $F(2, 40) = 0.83$, $p = 0.441$. For target-absent trials, a comparison of slope coefficients suggested that conjunction search was seemingly less efficient than single-feature search, particularly in POS+C (see Table 5). However, the Preview × Set size interaction did not reach significance for either preview condition—POS+C: $F(2, 40) = 2.54$, $p = 0.091$; POS: $F(2, 40) = 1.44$, $p = 0.248$. Testing the absolute levels of performance showed that single-feature search was still faster than conjunction search in all preview conditions in target-present trials—POS+C: $F(1, 20) = 12.07$, $p < 0.01$; POS: $F(1, 20) = 13.64$, $p < 0.01$—substantiating the upward shift of the conjunction search functions relative to the search function for single-feature search (see right panels of Figure 6). In target-absent trials the

conjunction search when the random design is used and distracters are randomly positioned in the search array.

Comparing conjunction search across Experiments I and IIa also reveals a strong difference not only in efficiency but also in absolute search times. It could therefore be that absolute search times were in a range where maintaining item positions in memory became critical. However, a full preview benefit has been obtained even in more exhaustive search tasks with up to 30 items (Theeuwes et al., 1998). In that study, RTs were in about the same range of our Experiment IIa. Olivers et al. (1999) used difficult single-feature and

Search	Preview	Target absent			Target present		
		Slope a	a/a_{single}	a/a_{conj}	Slope a	a/a_{single}	a/a_{conj}
Single-feature	NO	44.8			24.8		
Single-feature	POS+C	12.8	0.29		10.9	0.44	
Single-feature	POS	17.3	0.39		6.4	0.26	
Conjunction	NO	67.5	1.51		34.0	1.37	
Conjunction	POS+C	22.6	0.51	0.33	7.1	0.29	0.21
Conjunction	POS	25.1	0.56	0.37	11.0	0.44	0.32

Table 5. Slope estimates a for the search-function data of Experiment IIb. *Notes*: Conventions are as in Table 1.

single-feature search advantage was less pronounced—POS+C: $F(1, 20) = 3.39$, $p = 0.08$; POS: $F(1, 20) = 4.37$, $p < 0.05$.

Comparing search efficiency across Experiments IIb and I showed nearly identical search rates for the baselines in both target-absent and target-present trials (see Tables 1 and 5). Correspondingly, the Preview × Set size interaction for the baselines in Experiments I and IIb indicated no significance—target-present trials: $F(2, 74) = 0.78$, $p = 0.461$; target-absent trials: $F(2, 74) = 0.46$, $p = 0.629$. In the preview condition (POS+C), the search rates agreed in target-absent trials, but search was more efficient in Experiment IIb for target-present trials—target-absent trials: $F(2, 74) = 0.46$, $p = 0.632$; target-present trials: $F(2, 74) = 3.54$, $p < 0.05$.

For spatially blocked distracters, all expected main effects of the overall ANOVA were found: set size, $F(2, 40) = 84.64$, $p < 0.001$; trial type, $F(1, 20) = 67.56$, $p < 0.001$; search type, $F(1, 20) = 75.16$, $p < 0.001$; and preview, $F(2, 40) = 515.45$, $p < 0.001$.

Accuracy

Mean accuracy rates were 94.0% on the grand average, which was slightly better than in Experiment IIa (93.3%). Mean accuracy was 97.0% in target-absent trials and 90.9% in target-present trials, $F(1, 20) = 47.8$, $p < 0.001$, which fairly well matched the results of Experiment IIa. Accuracy was not modulated by search type (single-feature: 94.2%, conjunction: 93.7%), $F(1, 20) = 1.26$, $p = 0.274$. Different from Experiment IIa, there was no Search type × Preview interaction, $F(2, 40) = 0.38$, $p = 0.687$, only a main effect of preview, indicating lower accuracy for the baseline conditions compared to the preview conditions (baseline: 93.6%, POS+C: 94.4%, POS: 94.4%), $F(2, 40) = 4.07$, $p < 0.05$. As was found in Experiments I and IIa, accuracy remained at a constant high level across set size for target-absent trials and tended to decline with increasing set size only in target-present trials—Set size × Trial type: $F(2, 40) = 4.30$, $p < 0.05$. However, this interaction was smaller in Experiment IIb than Experiment IIa.

Subjects reached no higher accuracy rates in the single-feature search baseline than in the conjunction search baseline (single-feature: 93.6%, conjunction: 92.7%), $F(1, 20) = 1.83$, $p = 0.191$. In the preview conditions, subjects operated with about the same accuracy in both types of search—POS (single-feature: 94.6%, conjunction: 94.2%), $F(1, 20) = 0.518$, $p = 0.479$; POS+C (single-feature: 94.5%, conjunction: 94.3%), $F(1, 20) = 0.06$, $p = 0.805$. Generally, accuracy was less strongly modulated across experimental conditions in Experiment IIb than in Experiment IIa. Testing the Set size × Preview interaction as an indicator for a potential speed–accuracy trade-off in the preview benefit showed no statistical significance, $F(4, 80) = 1.17$, $p = 0.33$. The accuracy rates for Experiment IIb are given in Table 6.

Discussion of Experiment IIb (blocked distracters)

The search-function data show that spatial blocking of distracters made preview search equally efficient in single-feature and conjunction search. In target-present trials, the search functions had the same slopes in both preview conditions and for both search types. Moreover, the half-slope prediction of visual marking succeeded in all four conditions. In target-absent trials, however, the search functions for conjunction preview search were slightly steeper and upward shifted relative to the corresponding search functions for single-feature preview search.

Comparison with the results of Experiment IIa (randomly positioned distracters) showed that there was just moderate improvement due to spatial blocking of distracters in single-feature search, in both efficiency and absolute RTs. In conjunction preview search, however, search efficiency improved greatly, by about a factor of 2.5, due to spatial blocking of distracters. Overall RT level was lowered and the RT difference of POS+C and POS, which was pronounced for randomly positioned distracters, vanished. Comparing across Experiments IIb and I

		Target absent			Target present		
Search	Preview	8	12	16	8	12	16
Single-feature	NO	97.3	97.5	98.0	90.7	90.2	87.7
Single-feature	POS+C	96.9	96.7	97.1	93.0	93.2	90.1
Single-feature	POS	96.9	95.6	98.4	94.3	92.0	90.2
Conjunction	NO	98.3	95.6	95.9	89.5	88.7	87.9
Conjunction	POS+C	96.5	96.8	97.2	90.8	94.1	90.5
Conjunction	POS	97.4	97.1	97.5	93.8	91.0	88.5

Table 6. Mean percentage accuracy rates from Experiment IIb.

showed that about equal conjunction search efficiency was reached in target-absent trials, while in target-present trials, preview search was more efficient in Experiment IIb.

These results indicate that spatial blocking of distracters enabled the observers to ignore the old items and scan only the new ones in the search display while performing a conjunction search. In single-feature search, spatial blocking did add some improvement, but not much. Comparing the results for conjunction search across Experiments IIa and IIb suggests that visual marking is enabled by spatial blocking. Fore-knowledge of the target and a fixed color-to-letter assignment across trials (Experiment I) is apparently not necessary for a full preview benefit in terms of visual marking, since the effect is completely restored by spatial blocking.

A potential reason for the failure to find evidence for visual marking in conjunction search for POS+C preview in Experiment IIa is that the subjects possibly tried to infer the target from the preview. Note that, if the observer previews, for example, orange Hs, she or he can conclude that the target will be a light-green H. However, inferring like this would be resource demanding. Watson and Humphreys (1997) showed that performing a resource-demanding task in parallel to the preview, or withdrawing attention from the preview, disrupts the preview benefit. Therefore, we decided to remove the load of a hypothetical target inference from the preview by informing the observers about the target by an advance cue. The observers should thus be enabled to fully concentrate on distracter positions.

Experiment III: Variable color-to-letter assignment and target cue

Experiment III investigated the preview benefit in conjunction search using the random design but with target foreknowledge, provided by an advance cue.

Method

Experimental conditions

Because the half-slope prediction of visual marking succeeded for single-feature search in Experiment IIa, the effect of an advance target cue was tested only for conjunction preview search (POS+C). The experimental arrangements for measuring the single-feature search baseline and the conjunction search baseline were the same as in Experiment IIa.

Participants

Seventeen undergraduate students of psychology participated (mean age: 21.8 years; range: 20–24), 11 of them women. The participants were paid for participation or given course credit. All had normal or corrected-to-normal visual acuity. None of the subjects participated also in Experiments I or II.

Apparatus and stimuli

Experiment III used the same apparatus, stimuli, display parameters, and event timings as Experiment II.

Procedure

As in Experiment I, each experimental block comprised 36 target-absent trials and 36 target-present trials. The participants received the same general instructions and the same introduction to conjunction search as in Experiment II. For the POS+C preview condition, they were informed that the fixation mark at the screen center would be replaced by the target item at the beginning of the trial, that this item had to be searched, and that the preview display would reveal the positions where this item would never appear.

The temporal order of events in a preview trial was the following: fixation mark (500 ms), target cue (750 ms), fixation mark (500 ms), preview (2000 ms), and search array (until response). Hence, compared to Experiment II, a fixation period and a cue period were added before the standard event sequence for a preview trial started.
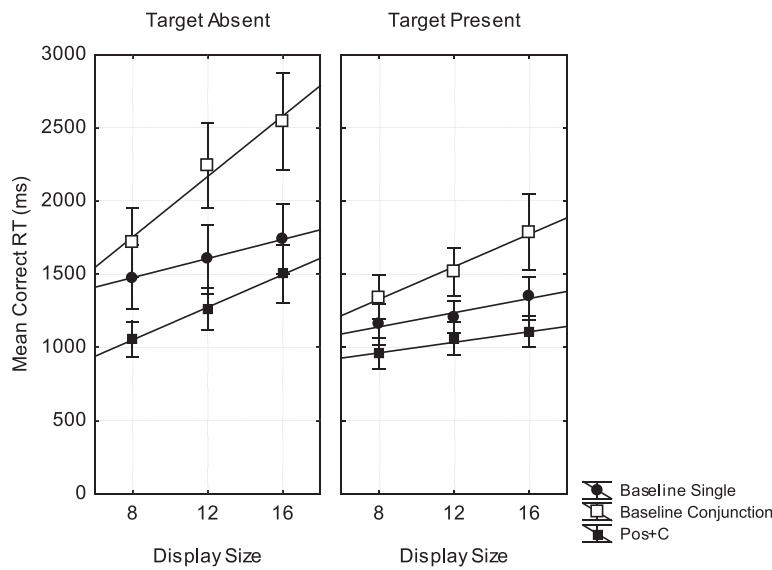
Figure 7. Results for Experiment III. Mean reaction times for conjunction search are indicated by solid squares for preview and by open squares for the baseline. The data for single-feature search are indicated by filled circles. Other conventions are as in Figure 2.

The three experimental conditions were divided into six experimental blocks. The order of the experimental blocks was randomized for each participant. Before a new experimental condition started, a block of 12 practice trials was administered to ensure that the task was understood. Participants were alerted to make brief pauses between the experimental blocks.

Results of Experiment III

RTs

Figure 7 shows the search-function data for Experiment III, and Table 7 gives the slope estimates. The slope ratios a/a_{single} indicate that the preview search function had a larger slope than the single-feature search function in target-absent trials and a slightly shallower slope in target-present trials. Thus the half-slope prediction (Equation 2) was not reached for preview with an additional target cue in either trial type. Testing parallelism by evaluating the Preview × Set size interaction for single-feature baseline and preview gave nonsignificant results in both trial types—target-present: $F(2, 32) = 2.02$, $p = 0.148$; target-absent: $F(2, 32) = 2.13$, $p = 0.135$. Overall ANOVA indicated the expected main effects of set size, $F(2, 32) = 112.75$, p < 0.001; trial type, $F(1, 16) = 100.97$, $p < 0.001$; and search type, $F(2, 32) = 50.31$, $p < 0.001$.

To further evaluate the effect of the additional target cue, we compared the RT data of Experiment III with the corresponding search conditions of Experiment IIa. For the overall ANOVA, the Search type and Preview factors were agglomerated into one Condition factor with three levels: single-feature search baseline, conjunction search baseline and preview search POS+C. The overall ANOVA indicated no main effect of experiment, $F(1, 36) = 0.03$, $p = 0.957$, substantiating no faster responses in Experiment III. There was only one significant interaction involving experiment—Condition × Experiment: $F(2, 72) = 7.07$, $p < 0.001$—reflecting a crossing scheme of larger RTs in Experiment III in the single-feature search baseline but smaller RTs in Experiment III in the conjunction search baseline. However, exploring this interaction with pair-wise tests showed no significant RTs across the two experiments in either search condition—single-feature search baseline: $F(1, 36) = 1.85$, $p = 0.182$; conjunction search baseline: $F(1, 36) = 1.95$, $p = 0.171$; preview search POS+C: $F(1, 36) = 0.74$, $p = 0.397$.

Comparing single-feature search conditions across experiments with ANOVAs revealed a slightly shallower slope in Experiment III in target-absent trials but

Search	Preview	Target absent			Target present		
		Slope a	a/a_{single}	a/a_{conj}	Slope a	a/a_{single}	a/a_{conj}
Single-feature	NO	37.7			24.2		
Conjunction	NO	103.4	2.74		55.6	2.30	
Conjunction	POS+C	55.8	1.48	0.54	19.5	0.81	0.35

Table 7. Slope estimates a for the search-function data of Experiment III. *Notes*: Conventions are as in Table 1.

Search	Preview	Target absent			Target present		
		8	12	16	8	12	16
Single-feature	NO	97.9	98.4	95.4	93.1	94.4	90.0
Conjunction	NO	95.4	97.4	96.4	92.6	89.7	88.7
Conjunction	POS+C	98.4	96.1	97.4	91.8	90.8	85.6

Table 8. Mean percentage accuracy rates from Experiment III.

equal slopes in target-present trials for the single-feature search baseline—Search type × Set size interaction: target-present trials: $F(2, 72) = 0.20$, $p = 0.816$; target-absent trials: $F(2, 72) = 3.45$, $p < 0.05$. Testing the same interaction revealed nonsignificant results for the conjunction search baseline—target-present trials: $F(2, 72) = 0.75$, $p = 0.478$; target-absent trials: $F(2, 72) = 0.46$, $p = 0.630$—and also for preview search—target-present trials: $F(2, 72) = 1.48$, $p = 0.233$; target-absent trials: $F(2, 72) = 0.32$, $p = 0.727$—corresponding to the fairly equal slope coefficients obtained in both experiments (see Tables 3 and 7).

Accuracy

Mean accuracy rates were 93.9% on the grand average, which was at exactly at the levels of Experiment II. Mean accuracy was 97.0% in target-absent trials and 90.8% in target-present trials, $F(1, 16) = 38.91$, $p < 0.001$, which precisely matched the results of Experiment IIb. Accuracy was not modulated by search type (single-feature baseline: 94.9%, conjunction baseline: 93.4%, POS+C: 93.4%), $F(2, 32) = 1.72$, $p = 0.195$, but declined with increasing set size, $F(2, 32) = 6.38$, $p < 0.01$. There were no first- or higher order interactions among set size, trial type, and search condition. As was found in Experiments I and II, accuracy remained at constantly high levels across set size for target-absent trials and tended to decline with increasing set size in target-present trials, but the Set size × Trial type interaction did not reach significance, $F(2, 32) = 3.00$, $p = 0.064$. The accuracy rates for Experiment III are given in Table 8.

Discussion of Experiment III

Showing the target in advance while the target and distracter item definition varied randomly from trial to trial did not restore the preview benefit in terms of the half-slope prediction for conjunction search. For both trial types, conjunction preview search (POS+C) was at the same speed per item with (Experiment III) and without (Experiment IIa) target foreknowledge, provided by an advance cue. Further, absolute RTs did not differ for Experiments III and IIa. Therefore, we conclude that the failure to find evidence for visual marking in Experiment IIa is not due to a possible resource expenditure on target inference, which might interfere with the attentional resources for spatial memory. On the other hand, preprocessing the target in Experiment III had no detrimental effects on search time or efficiency. The fairly equal results for search with and without target foreknowledge indicate that target foreknowledge seemingly did not change the nature of search.

General discussion

In three experiments we found evidence that the preview benefit in single-feature and conjunction search has different constraints. In conjunction search, the half-slope prediction of visual marking was found to be compatible with the search-function data when (a) target and distracter items were constantly the same across trials (block design) or (b) grouping into old and new items was supported by spatial blocking, such that observers had to attend only one half of the display. Agreement with the half-slope prediction was reached in target-present trials, while in target-absent trials the search rates tended to be larger. In the random design, where target and distracter features varied randomly from trial to trial, the half-slope prediction of visual marking failed. Further, POS+C preview led to shallower search functions and smaller RTs compared to POS preview. Revealing the target to the observer by an advance cue did not restore the preview benefit.

In single-feature search, the search rates agreed with the half-slope prediction of visual marking for fixed and randomly varying target and distracter definitions, and consistently for both trial types. POS+C and POS preview yielded practically the same search functions. Spatial blocking of old items enhanced search efficiency strongly, with search rates that were even smaller than predicted by visual marking. Further, the slope ratios a/a_{single} agreed fairly well among target-present and target-absent trials, which indicated an equally strong preview benefit in both trial types.

In the following, the implications of the different constraints of the preview benefit in single-feature and conjunction search are discussed with respect to the

potential underlying mechanisms in both types of visual search.

The onset-capture account

In the Introduction it was outlined that an attentional-capture account predicts an equal preview benefit for single-feature and conjunction search, once it is ascertained that the saliency of the luminance onset is the same for all color items. Since in Experiments I through III the same equiluminant color stimuli were used, the finding that the random design disrupted the preview benefit in conjunction search but not in single-feature search poses problems for the assumption that the luminance onset of the new items is sufficient to trigger a search just on the new items. An attentional-capture mechanism is blind to a repetition of the same color-to-letter assignments across trials. Whether target and distracter randomly change or stay the same across trials does not matter for the capture elicited by the onset of the new elements. Hence, the finding that the preview benefit is disrupted without repetition priming in conjunction search is crucial for the onset-capture account.

Further critical findings are the effects of spatial blocking, the differential effects of POS+C and POS preview in single-feature and conjunction search, and the different strengths of the preview benefit in target-absent and target-present trials, which were found only in conjunction search, not in single-feature search. The spatial order of the items does not change the amplitude of the luminance onsets at the new positions, but it is apparently much easier for the subjects to attend only the new items when they appear together as one coherent spatial block, which allows for grouping along both space and time (see also the next section). The finding that conjunction search is faster and more efficient with POS+C preview compared to POS preview, while single-feature search is not, points to benefits of active processing of color information in conjunction search. This effect is not covered by an onset-capture account, since it derives from different information provided to the subjects at the preview stage. The finding that the preview benefit is consistently stronger in target-present trials than in target-absent trials in conjunction search may point to a confound with absolute search duration. Donk (2006) noted that onset capture is maximally effective only in the first several hundred milliseconds after presentation of the new elements, which forces subjects to rely on additional mechanisms in exhaustive, longer lasting search. Given such a short-term decay characteristic of onset capture, a reduced preview benefit in target-absent compared to target-present trials should result. Indeed, Donk found that RTs did not depend on the number of old items, but only for target-present trials, not target-absent trials. This indicates that subjects in those experiments scanned first the new positions and then the old position if the target was not among the new items. In the experiments reported here, the differential findings for the slope ratios a/a_{single} in single-feature and conjunction search indicate that the subjects behaved similarly as in Donk's studies in conjunction search but not in single-feature search. In the latter, equal slope ratios a/a_{single} for both trial types, which complied with the half-slope prediction, suggest that only the new positions were visited in target-present *and* target-absent trials. We return to this point later.

Temporal asynchrony

Jiang and colleagues (Jiang et al., 2002b; Jiang & Wang, 2004) have claimed that the temporal grouping of old and new items, induced by delayed temporal onset (asynchrony), is sufficient to explain the preview benefit. In various experiments, they demonstrated that item manipulations that leave untouched the asynchronous temporal-grouping relationship among old and new items maintain the preview benefit, while manipulations that add spatiotemporal changes to old items at the moment when the new elements enter are disruptive. Later experiments showed that this principle held for shape changes of old items but not for small changes in luminance or color (Kunar, Humphreys, & Smith, 2003; Watson & Humphreys, 2002). Even adding luminance increments to the old items at a ratio of 1:4 was found to not be disruptive if old and new items were still segmented by color (Watson, Braithwaite, & Humphreys, 2008).

The results of this study support the claim of Jiang and colleagues that the temporal segregation of old and new items is sufficient for the preview benefit in near-efficient single-feature search, but not in conjunction search. Although perfect temporal segmentation of old and new items was provided in POS+C preview, trial-to-trial variation of the color-to-letter assignment disrupted the preview benefit in conjunction search (Experiments IIa and III). The same efficiency as in single-feature search was reached only when constraints (a) or (b) from the beginning of the General discussion were met. Particularly, in constraint (b) the segregation of old and new items was both temporal and spatial, suggesting that a second grouping cue was necessary to reach effective grouping of old and new items. In addition to the spatial grouping, there was segregation by color in constraint (b), with a color border dividing the two halves of the display. A color border is perceived immediately and preattentively, within the first 100 ms of processing (Kubovy & Cohen, 2001).

Hence, it is not surprising that the subjects were able to attend only the new items when old and new items were segregated by an early preattentive grouping principle in the later search display (Schuboe & Meinecke, 2007).

Our findings imply that temporal asynchrony alone is *not* sufficient for efficient visual marking in conjunction search. Only with further experimental constraints (a and b), which involve other potential grouping mechanisms, does distracter preview enable observers to ignore the old items and perform a single-feature search on just the new ones.

We conclude from the discussion of attentional capture and temporal asynchrony that the differential findings of this study with respect to search type, trial type, and nature of the preview can only be understood by an account which refers to active preprocessing of the old items with respect to position and feature information. Such an account could be visual marking if the marking mechanism is complemented by active color processing (Braithwaite et al., 2003; Braithwaite & Humphreys, 2003; Olivers & Humphreys, 2002; Watson & Humphreys, 2005). In the following sections we outline the constraints of visual marking by the differential preview benefits in both types of search, and suggest a supplantation principle for visual marking in conjunction search.

Spatial memory is necessary for the preview benefit only in single-feature search

Theeuwes et al. (1998) pointed out that there is a confound of temporal asynchrony and color when the preview benefit is studied with the conjunction search task, since all old elements have color A and all new elements have color B. Grouping need not be temporal in this situation and does not necessarily involve memory for old items, since both item families differ by a salient feature in the search display, which is sufficient for segmentation. The subjects may learn to scan just the items of color B, using feature-based attention. Indeed, this has been observed in conjunction search tasks that used a block design with fixed target and distracter features across trials (Egeth, Virzi, & Garbart, 1984; Kaptein, Theeuwes, & van der Heijden, 1995; Olds & Fockler, 2004).

In single-feature search, however, the preview benefit is a phenomenon that necessarily involves memory, since old and new distracters are indistinguishable at the moment when the new items enter (Jiang & Wang, 2004). Hence, observers have to recall the locations of either the old items or the new items from memory to deprioritize old and prioritize new items at search. Jiang and Wang (2004) found evidence that processing of old items assists the isolation of new items, which are memorized in visual short-term memory, aided by a

fast-decaying memory for asynchrony. Watson and Humphreys (1997) claimed that old items are memorized and inhibited, which is supported by their later finding that parallel probe-dot detection tasks at the old locations were impaired at the previewed locations (Watson & Humphreys, 2000). Regardless of whether memory of the old or the new items mediates prioritization and deprioritization of locations on the search array, single-feature preview search involves memory and is the same in nature both with and without preview. Supporting our results for single-feature preview search, Theeuwes et al. (1998) found evidence that observers are able to effectively exclude the old positions and mostly scan only the new positions in a serial single-feature letter-search task with a known target but heterogeneous distracters.

Why is distracter preview less effective in conjunction search?

We have outlined (see Introduction) that the prerequisites for the preview benefit are, in principle, better in conjunction search than in single-feature search. The separation of old and new items is redundantly defined—i.e., by asynchrony and by color—and memory for old locations or tagging of the likely new positions can, but need not, be involved, since old and new items are distinguished by a salient color difference in the search display. Therefore, it is surprising that search on the set of new items, which was the same for single-feature and conjunction preview search in Experiments I through III, was more efficient in single-feature search in the random design.

The fact that random variation of target and distracter item definition disrupted the preview benefit in conjunction search but not in single-feature search indicates that the preview benefit is mediated by different processes in the two types of search. If the preview benefit rests just on spatial memory, it should not make a difference whether the target and distracter features change or remain the same across trials. Also, foreknowledge of the target should not matter for the ability to ignore old locations and visit just new one. This was found to be the case in single-feature search. There, search efficiency was the same in the blocked (Experiment I) and the random design (Experiment IIa). The half-slope prediction was perfectly met, and POS and POS+C preview had the same effects. Thus, the preview effect in single-feature search can be explained by a spatial-memory-based mechanism that mediates prioritization of new and deprioritization of old locations during search.

Since a spatial-memory mechanism should work independent of constancy or trial-by-trial changes of distracter features, disruption of the preview benefit in

the random design shows that a purely spatial mechanism is *not* sufficient to explain the findings for conjunction search. Instead, the different results for blocked and random design indicate involvement of active feature processing in the preview benefit for conjunction search. In conjunction search, POS and POS+C had different effects, indicating that the observers extracted not only item positions but also item features. The search functions for POS+C were both more flat and downward shifted relative to the search functions for POS, indicating that subjects benefited from the additional valid color information. For blocked presentation (Exp. IIb), however, the search functions for POS and POS+C coincided, and coincided with the single-feature search functions, at least in target-present trials. Apparently, spatial blocking made active feature processing of the pre-viewed items superfluous: The subjects just had to attend the opposite half of the display tagged by the preview items, and could perform a true single-feature search in this half. However, in target-absent trials the search rates for conjunction preview search were still larger compared to single-feature preview search. This indicates that the subjects were more uncertain about possibly missed targets, calling forth additional re-checking of items at least on the edge points of the old item set (Treisman & Gelade, 1980).

The differential effects of POS and POS+C in single-feature and conjunction search in Experiment IIa indicate that color information is actively used in conjunction preview search. Comparing Experiments IIa and III showed that additionally revealing the target did not add much—the same slopes were found in POS+C preview. This is a hint that the subjects did not try to perform a guided search for a letter in a definite color, but tried instead to segment the old and new items in the search display by combining spatial memory and feature-based attention to color.

But why do the observers engage in active color processing when it would be sufficient and more effective to rely just on spatial memory, like in single-feature search? The likely reason for this is that the onset of the second color instantly initializes conjunction search routines. These bind attentional resources necessary to jointly evaluate color and shape at each position. Attentional resources are therefore withdrawn from the spatial-marking mechanism, resulting in a disruption of the local encoding results achieved in the preview period. A supplanting grouping mechanism is then necessary to reduce search to evaluating only the shape attribute.

An effective supplanting grouping mechanism is spatial segmentation. When old and new items are in different halves of the display, the observers are able to attend only one half and can perform a true single-feature search there. Another supplanting grouping

mechanism can take effect when the same colors are constantly used for targets and distracters across trials. Studies on feature-based attention have shown that repeating the same target and distracter features in a block design accelerates conjunction search remarkably (Kristjansson et al., 2002). Repetition priming has been shown to concern mostly distracter features rather than target features (Geyer et al., 2006). Color showed particularly strong and robust repetition priming effects, which were stronger than for orientation and were present in multiple simultaneous cross-trial priming even when color was not task relevant (Kristjansson, 2006).

While repetition priming is not necessary for a feature cue to guide target selection in conjunction search (Anderson, Heinke, & Humphreys, 2010; Wolfe, Horowitz, Kenner, Hyle, & Vasan, 2004; Zhuang & Papathomas, 2012), the fact that there was a full preview benefit in the blocked design (Experiment I) but not in the random design (Experiment IIa) shows that repetition priming is necessary for visual marking if there is no other strong grouping cue adding to temporal asynchrony.

The search functions obtained for random target or distracter item variation (Experiment IIa) show that the preview benefit is notably disrupted, such that the data are no more compatible with the half-slope prediction of visual marking. However, there is still a preview benefit. Preview search is approximately as good as the single-feature baseline, which is approximately double the speed per item found for the conjunction baseline. Together with the evidence for active feature processing in preview conjunction search, these results indicate that the preview helps both to prioritize target features and to deprioritize distracter features, as well as prioritizing new item positions and deprioritizing old ones. However, the mechanisms do not work perfectly when target and distracter features vary randomly across trials. Perfect item class segmentation in conjunction preview search is reached only when a supplanting grouping mechanism enters.

The interpretation that the appearance of the second color automatically initializes conjunction search, which in turn may be changed to a virtual single-feature search by the help of supplanting grouping mechanisms, is supported by the differential effects for target-absent and target-present trials in single-feature and conjunction search. For single-feature search, the half-slope prediction of visual marking was met for both target-absent and target-present trials, and the slope ratios a/a_{single} were comparable for both trial types. In conjunction search we found consistently larger slope ratios a/a_{single} in target-absent trials than in target-present trials, and in all experiments. This was true even in the conditions where the half-slope prediction of visual marking

succeeded (Experiments I and IIb). In target-absent trials, search lasts longer, since all item positions have to be scanned. The longer the search, the more likely that observers will forget old item positions—i.e., visual marking likely becomes imperfect with increasing search time. Once some old item positions are no longer marked, subjects will visit them in performing an exhaustive search. However, this means that the subjects can no longer perform a single-feature search, attending letter shape only, and search turns into a true conjunction search where the color attribute matters. This shows that not only additional security checks on potentially missed targets enter in target-absent trials. Imperfect marking—which is more likely in target-absent trials compared to target-present trials, due to the longer absolute search time—is a likely reason why the constitution of true single-feature search on the new items was fragile, and not as natural as in the case of a true single-feature search, which is generally faster and more efficient.[3]

Conclusion: The constraints of visual marking in conjunction search

Studying the preview benefit for randomly varying and constant target and distracter features showed that the half-slope prediction of visual marking was compatible with the efficiency estimates in single-feature search without further constraints, suggesting that the temporal asynchrony of old and new items is sufficient to segment both item sets such that the observer is able to scan only the new items. A spatial-memory-based mechanism is sufficient to account for this finding. In conjunction search, however, the preview benefit was disrupted for randomly varying target and distracter features but agreed with the half-slope prediction of visual marking for cross-trial replication of the same target and distracter features. For randomly varying target and distracter features, the preview benefit could be restored by spatial blocking of distracter items. Foreknowledge of the target provided by an advance cue did not restore the preview benefit. These findings suggest that the temporal asynchrony of old and new items is not sufficient for effective segmentation of both item sets in conjunction search. A second, supplanting grouping principle must be added in order to accomplish robust separation of both item sets at search. The supplanting grouping mechanism can be spatial or grounded in feature-based attention. In case of the latter, repetition

priming is necessary for efficient item grouping via asynchrony along with the feature cue.

Keywords: visual search, preview benefit, conjunction search, visual marking, active ignoring

Footnotes

[1] The task favored in the experiments of Watson and Humphreys was finding a green H among blue Hs and blue As. Other authors have used different stimulus sets—e.g., Ts in different orientations (Olivers & Humphreys, 2002) or Ts and Ls (Jiang et al., 2002b; Jiang & Wang, 2004)—but target and distracter definitions are always constant across the trials of the experimental test.

[2] Note that, for comparison with our slope estimates, the slopes reported for the single-feature search baseline by Watson and Humphreys must be doubled, because they used half the set size shown in the diagrams to measure the search function for the single-feature baseline (Watson & Humphreys, 1997, p. 94).

[3] We thank two anonymous reviewers for drawing our attention to this point.

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