

# Color-based grouping and inhibition in visual search: Evidence from a probe detection analysis of preview search

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In four experiments, we examined selection processes in visual search using a probe detection task to measure the allocation of attention. Under preview search conditions, probes were harder to detect on old relative to new distractors (Experiment 1). This cannot be attributed solely to low-level sensory factors (Experiment 2). In addition, probe detection was sensitive to color-based grouping of old distractors and to color similarity between old distractors (Experiments 3 and 4). These effects were dissociated when the color of the old distractors changed but probe detection effects remained. Collectively, the data indicate both group-based suppression of distractors and the separate inhibition of distractor features in search.

The objects and events that make up our visual environment provide a constant flow of dynamic visual information. It has long been acknowledged that the capacity of the nervous system is exceeded by such a rich, detailed, and continuous source of information (Broadbent, 1958; Neisser, 1967). As a consequence, certain items, objects, and events must be selected at the expense of others. Therefore, to ensure the emergence of coherent behavior, stimuli that are relevant to current goals must be selected and irrelevant distractors rejected. However, what is less clear is just how attention determines what to select in a given context.

One major debate concerns whether selection represents only facilitatory processing of important and relevant information (Folk & Remington, 1996; Folk, Remington, & Johnston, 1992, 1993; Folk, Remington, & Wright, 1994; Murphy & Eriksen, 1987; Posner, 1980; Posner, Snyder, & Davidson, 1980; Shih & Sperling, 1996; Treisman & Gelade, 1980), only the inhibition of irrelevant information (Cave, 1999, 2001; Koshino, 2001; Neill & Valdes, 1996; Tipper, 1985), or a combination of both these processes (Posner & Dehaene, 1994; Watson & Humphreys, 1997, 1998, 2000). Behaviorally, distinguishing between facilitatory and inhibitory processes in selection is problematic, since target selection can often be redescribed in terms of either distractor inhibition or target facilitation.

A persuasive argument has been made that selection does indeed involve only excitation and, hence, facilitation

of target signals. This argument seems to be based largely on the notions of capacity limitation and computational efficiency. For instance, it may require less processing effort to increase the priority of salient or task-relevant stimuli than to inhibit activation associated with distractor items. Why go through the trouble of trying to ignore all the irrelevant items (presumably using up important resources) when simply increasing excitation would lead to successful selection (see Neisser, 1976)? Against this, it can be argued that any effects of selective target enhancement would be further enhanced by also biasing selection against irrelevant, competing information (see Bundesen, 1990, for a mathematical account). In this view, a dual inhibitory/excitatory system can make for a more efficient selection process. Contrary to a purely "facilitatory" account of selection, there is a growing body of evidence for the involvement of inhibitory components (or dual inhibitory/facilitatory components) in selection (Cave, 1999, 2001; LaBerge, 1995, 1997).

For instance, a purely facilitatory selection process has difficulty explaining why reaction times (RTs) are lengthened when (1) a target appears at a previously inspected location (e.g., inhibition of return: Klein, 1988, 2000), (2) a target on trial  $n+1$  was previously a distractor rejected on trial  $n$  (e.g., negative priming; see Neill & Valdes, 1996, for a review), or (3) probes fall at distractor locations that share few features with a target (*feature-based distractor inhibition*; see Cave, 1999, 2001, for reviews). These results suggest that selection involves inhibition of irrelevant information as well as excitation of relevant target information.

## Preview Search

In preview search, sets of distractors are presented across distinct time intervals. Preview search was first examined by Watson and Humphreys (1997), who took a

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standard color–form conjunction search task (see, e.g., Treisman & Gelade, 1980) and presented distractors in one color 1 sec before the presentation of the target and the second set of distractors. Even though the final combined display matched the standard conjunction condition, search in the preview condition was as efficient as when only the new items appeared alone (e.g., in a single feature baseline, when only the target and the second set of distractors appeared). Preview search was also considerably more efficient than it was in a conjunction baseline, when both sets of stimuli were presented simultaneously. To account for these findings, Watson and Humphreys (1997) argued that the search advantage in the preview condition occurred in part because the old items were actively inhibited (via a process they termed *visual marking*) and rejected en masse. For static items, this inhibition was argued to be location based and not concerned with the featural properties of the old items. In other words, the inhibition was “feature blind.” Inhibition could be applied to the features of old distractors, but this would occur only when they moved (e.g., when location-based inhibition would be ineffective; Watson & Humphreys, 1998).

Evidence supporting the idea that old distractors are inhibited comes from studies in which a *probe detection* procedure was used. Probe detection has been employed in combination with search tasks to study where attention is deployed (see Klein, 1988). For instance, in a standard conjunction search task Kim and Cave (1995) showed that probes were particularly difficult to detect if they appeared on distractors that differed from the target in both color and shape. Apparently, attention is guided away from such stimuli during the search process, and they may even be inhibited relative to a baseline level (see also Cave, 1999, 2001).

Olivers and Humphreys (2002) and Watson and Humphreys (2000) have both used probe detection procedures in preview search. On a majority of trials, participants would search for a target in the new display. However, on a minority of trials a tone would indicate that a probe detection task had to be performed instead of a search. Detection was less accurate when probes fell near old distractors relative to when they fell near new distractors. Indeed, in Watson and Humphreys (2000), probes near old distractors were more difficult to detect than probes that fell near distractors in a conjunction baseline. This is consistent with old items’ being inhibited in preview search, and more pronouncedly so than in conjunction search.

Although there is evidence of a role of inhibitory processes in preview search, the exact nature of such processes is unclear. For example, old distractors may be grouped on the basis of their common and separate onset signals, which are distinct from the onset signal associated with the target set, so that inhibition is applied in this case to a separate temporal group (see Jiang, Marks, & Chun, 2002a, 2002b). On the other hand, inhibition may be inherently spatial in nature, based on the locations of the old distractors, without the distractors’ necessar-

ily being grouped (Watson & Humphreys, 1997, 2002). In the present study, we examined the nature of how old distractors are rejected in search by varying the color relations between items in the preview display and between items in the preview and search displays. These manipulations were combined with a luminance-probe procedure to study attentional deployment as a function of the color-grouping relations.

In addition to any effects due to grouping of old distractors, preview search also provides evidence of inhibition of the features of old distractors. For example, Olivers, Watson, and Humphreys (1999) and Watson and Humphreys (1998) have shown that color differences between old and new displays help to generate a preview benefit when all the stimuli move. They proposed that, in this circumstance, old items are deprioritized in search by feature map inhibition (as in Treisman & Sato, 1990). Olivers and Humphreys (2002, 2003) and Braithwaite and Humphreys (2003; see also Braithwaite, Humphreys, & Hodsoll, 2003, 2004) have also observed negative effects of color similarity between old and new items in preview search. Olivers and Humphreys (2003) examined the effects of having a singleton target or distractor, defined as one having an odd color, in the search display. They found that the effects of the color singletons on search were moderated when previews had the same color. The strength of the moderating effect increased as the preview duration lengthened. They suggested that there was inhibition of the color of the preview stimuli and that this affected the subsequent processing of new stimuli of the same color. Braithwaite et al. (2003) showed that color similarity between old and new items influenced the tendency of observers to search items in a “minority” color group. Usually, in displays where all the stimuli appear simultaneously, observers tend to be biased in their search to the smaller of the two color groups (Bacon & Egeth, 1997; Egeth, Virzi, & Garbart, 1984; Kaptein, Theeuwes, & van der Heijden, 1995; Moore & Egeth, 1998; Poisson & Wilkinson, 1992). Braithwaite et al. (2003) presented search displays with 66% of the letters in one color (e.g., green) and 33% in another (e.g., red). These displays were preceded by previews with the opposite color ratios (in this example 33% green and 66% red). Thus, in the final display, both color groups were represented equally. In this case, rather than RTs’ being shorter to targets in the new minority color (red), RTs were lengthened to these targets relative to targets in the new majority color (green). Braithwaite et al. (2003) attributed this reversal of the standard result to the negative carryover of color inhibition from the preview to the search display. If there is stronger inhibition for properties of the group that is dominant in the preview (e.g., for the color red in our example), then RTs will be delayed for targets of this color than for targets of the former minority color.

These results clearly indicate that color relations between old and new items influence preview search. However, the true nature of these effects remains unclear. Although Braithwaite et al. (2003) and Olivers and Humphreys

(2002, 2003) have attributed their results to the carry-over of color inhibition across displays, this is by no means certain. For example, the similarity effects could reflect grouping of the new items with the larger preview group. If the preview group is inhibited or even simply coded as old (cf. Jiang et al., 2002a, 2002b), then RTs to targets carrying the group's color may be delayed. Therefore, although color-based effects have now been well documented for static items, the underlying processes are largely underspecified. One mechanism that could generate negative color carryover effects is inhibition of a whole feature map coding a distractor feature (Treisman & Sato, 1990). Feature map inhibition could reduce the need for serial binding in order to find a conjunctive target, since distractors may be inhibited together through a common feature. Alternatively, Duncan and Humphreys (1989, 1992) argued that search is determined by grouping relations between the stimuli and the strength of match between any dominant group and a "memory template" for the target. Distractors, by definition, do not match the template and may be rejected (*en masse*) by a process of spreading suppression. In this process, stimuli are assigned an attentional weight, which determines their likelihood of being matched to the template. Spreading suppression reduces the perceptual weight of stimuli within a distractor group, and the degree of suppression may even be proportional to the size of the group (e.g., if the suppression operates in a multiplicative fashion; see also Koshino, 2001).

These influential yet contrasting accounts of search performance have proved difficult to evaluate, often because factors such as distractor-distractor and target-distractor groupings covary with whether targets and distractors are distinguished by a conjunction of features. One way around this is to present distractors over different time intervals, as in preview search, isolating the coding of the first set from that of a second set and any subsequent target. This can enable effects of grouping, and effects of inhibition of a common distractor feature applied to the preview, to be studied independently of grouping between the target and the second set of distractors. We adopted this procedure in the present study to examine the relations between group-based rejection of distractors and inhibition of distractors via a common feature.

### The Present Study

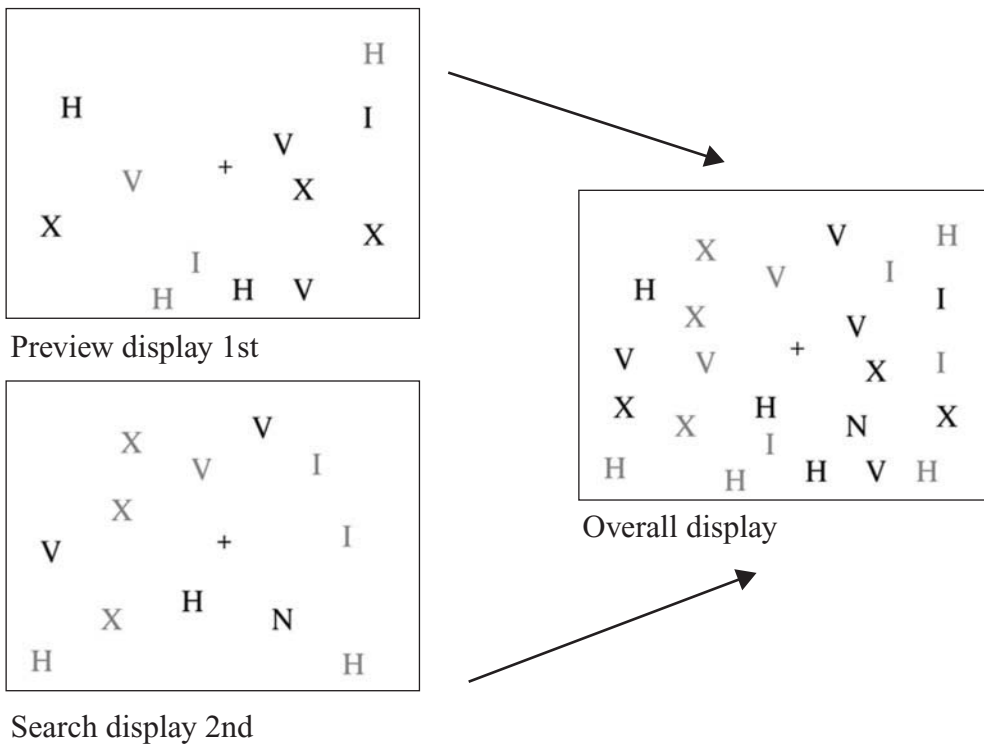
In the present study, we used a letter search task interspersed with a luminance-probe detection task. The probe was a letter that differed in brightness from that of the other items present (either one new letter was brighter than the others or one of the old letters brightened when the new items appeared). Thus, the probe was a *luminance singleton*.<sup>1</sup> The appearance of the probe was cued by an auditory beep 20 msec before the second search display, and the participants then had to identify the different (probed) letter rather than continue their search for a particular letter target. Letter search was performed on 66% of the trials and probe detection, on the remaining 33%. This

was to ensure that the participants were engaged in prioritizing search toward the new items, even on probe trials.

In Experiment 1, we used displays with letters in a single color (green) and demonstrated increased RTs when the luminance probe was an old item relative to when it was a new item. This is consistent with prior studies in which probe-dot procedures were used under preview search conditions (Olivers & Humphreys, 2002; Watson & Humphreys, 2000), and it confirms a cost on detection for old items under the present search conditions. Experiment 2 was a control study to test whether the cost was due to factors such as low-level masking or neural fatigue. In this experiment, we varied the duration of the previews and the attentional set of the observers. Collectively, the findings showed that the magnitude of the effect on probe detection could not be explained by sensory factors alone. Experiments 3 and 4 then provided tests of the nature of distractor inhibition in preview search. In Experiment 3, we used previews with a color bias across the letters (e.g., 66% of the preview letters were green and 33% red; these proportions were reversed in the search display, so that there were equal numbers of letters in each color on the screen). Probes were letters in either the majority or the minority color, in either the old or the new set (see Figure 1 for an example). This enables us to assess the effects of color relations within and between sets. On the basis of prior findings for search RTs, we may expect RTs to be longer to probes in the old majority color (red in our earlier example) than to probes in the old minority color (green). Interestingly, the opposite effect may arise when probes fall on new letters. If there is carryover of inhibition, probes will be more difficult to detect on the new minority distractors (red) than on the new majority distractors (green).

In Experiment 4, we repeated the color bias manipulation of Experiment 3 but crucially created a new condition in which the color of the old items changed on presentation of the new stimuli. By changing the color of the old items, we prevent possible color-based grouping between the old and the new items. We also render irrelevant any effects of feature map inhibition, originally applied to the color of the old distractors, on the detection of probes on old items in their new color (e.g., for old green distractors, inhibition of a green map should not affect a probe presented on the old distractors after they change color to, say, yellow). On the other hand, there may still be group-based inhibition of old distractors linked by their common color. This is what we find. However, we also find that probes remain difficult to detect on new letters carrying the color of the old distractors (e.g., new green letters in our example). Thus, we provide new evidence of both group-based inhibition (when probes fall on old distractors) and feature-based inhibition (when probes fall on new letters).

As well as being informative about the processes involved in rejecting distractors in search in general, the present results are also informative about how preview effects in particular arise. Although we have discussed



**Figure 1.** An illustration of a target search trial for the color-biased ratio manipulation used in Experiments 3 and 4. The top screen shows the initial preview display only, with a bias of 66% red items (illustrated by the dark black letters) and 33% green items (illustrated by the light gray letters). Below, the second set, with the opposite bias, is shown on its own. The final overall combined display on the right shows that at the time search was to be initiated there was no overall color bias. On any given trial, the color of the minority and majority sets were counterbalanced so the color or bias could not be used as a reliable cue for search. In this example trial, the target is the letter N (new minority group, second set). If the trial was a probe trial, then, with the arrival of the second search display, the luminance probe could fall on either group (minority or majority) in either set (new or old).

the role of inhibition in preview search, other authors have suggested that temporal grouping (Jiang et al., 2002a, 2002b) or attentional capture by new stimuli (Donk & Theeuwes, 2001) may be sufficient to generate the benefit. These accounts can be distinguished from an inhibitory account because they do not predict that probes on old items should be particularly difficult to detect (e.g., relative to when probes are presented in a baseline condition, when all the search letters appear together) and they do not predict any differences in detection on probes in the old minority or majority groups. The data contradict these accounts.

### EXPERIMENT 1 The Basic Effect

Experiment 1 provided a test of the basic effect of the preview condition on probe detection.

#### Method

**Participants.** Eleven participants (6 female, 1 left-handed) took part for course credit or a small payment. The ages of the participants ranged from 18 to 30 years, with a mean age of 21 years. All

were undergraduate or postgraduate students at the University of Birmingham. All had self-reported normal or corrected-to-normal vision (including normal color vision).

**Stimuli and Apparatus.** All the stimuli and conditions were generated by a series of computer programs written in Turbo Pascal. The programs were run on a Pentium PC fitted with a 15-in. Super VGA monitor. The programs recorded all relevant keypress responses and RTs. This setup was used in all the subsequent experiments. The stimuli consisted of colored (green) capital letters (6 × 5 mm) displayed on a plain black screen background. The colored letters were randomly assigned to an invisible circular matrix with 48 individual cells. This virtual matrix consisted of three concentric circular ring grids. The distance from central fixation to the middle of the cells of the first ring (containing 8 cells) measured approximately 19 mm, that of the second ring (containing 16 cells) measured 38 mm, and that of the third ring (containing 24 cells) measured 58 mm. Distractors consisted of the uppercase letters H, I, V, and X, and the target letter was either a Z or an N. Search displays were generated by randomly positioning each letter in the middle of individual matrix cells. Any distractor letter could repeatedly occur in multiple numbers in any presentation, with the restriction that at least 1 distractor letter of each type had to be presented. In the full-set baseline condition, these were 24 green letters. In the half-set baseline condition, they were 12 green letters. The preview conditions involved the presentation of half (12) of the distractor letters first (in the first preview display) followed by the presentation of

the remaining half (12) in the second, search display. The target was present on every target search trial, and was Z 50% of the time and N 50% of the time (at random). The RGB values for the stimuli were set here at 0/150/0. On probe trials, a single probed distractor had an increased RGB value of 0/230/0. Pilot baseline studies revealed this increment value to be sufficient for effective detection during standard search conditions.

**Design and Procedure.** A 3 (condition)  $\times$  2 (search type) within-subjects design was used. The three experimental conditions were as follows: (1) a *half-set baseline condition* (a single presentation of 12 green letters), (2) a *full-set baseline condition* (a single presentation of 24 green letters), and (3) a *preview condition* in which 12 green letters were presented in the first set, to which was added a search set of another 12 green letters, including the target (so the final display matched the full-set baseline; this is the *G + G preview condition*). There were also two types of search trial: (1) a standard target letter (Z/N) search and (2) a probe discrimination task in which the participants had to locate the brightest letter in the display and identify it. On probe trials, the target search letter did not appear. Each condition was run as a separate block of 288 trials, and a break was given halfway through each block. Of these trials, 33.3% were luminance probe trials; the remainder were standard Z/N search trials. Only one display size of 24 items was used. Trials within blocks were fully randomized, and block order was randomized across participants. A general block of practice trials for both preview and baseline conditions was completed at the beginning of the experiment. None of these practice trials was included in the analysis.

Standard search trials took the following form. Each trial began with the presentation of a plain white fixation cross, which remained visible until the end of the trial. For the baseline conditions, after 1,000 msec from fixation onset the search display was presented and remained visible until a response key was pressed or a time-out period of 10,000 msec had elapsed. This procedure was repeated for each trial for the duration of the experimental block. There was a 1,000-msec delay between presentations of individual trials in all conditions. For the preview conditions, the fixation cross was followed by the preview display for 1,000 msec and then by the target display. The distractors in the preview remained in the same positions when the target display appeared. For the preview presentations, the participants were instructed to remain fixated and not to initiate search until the arrival of the target display, since the target always appeared in the second display. For these preview conditions, RTs were measured from the onset of the target display.

Luminance probe trials followed a similar procedure and were signaled by a 20-msec auditory beep of 1000 Hz. For baseline conditions, this cue occurred 20 msec before the presentation of the whole search display. For the preview conditions, the cue occurred 20 msec before the presentation of the search set (i.e., 980 msec after the preview items had been presented). Up until this point, the participant would not know the nature of the search task for that particular trial. The participant was instructed that when the auditory cue occurred, the task was to locate the brightest letter on the screen as quickly and as accurately as possible. The probe letter could be any of the four distractor letters (chosen randomly and fully counterbalanced). For the preview condition, the probe fell equally often on either a new or an old letter (randomly determined). Initial responses to probes were made by pressing the space bar upon locating the probe letter (these RTs were recorded for analysis). When the participant located the probe and pressed the space bar, the display was immediately cleared of all items and the participant was presented with a new screen on which he or she saw the question, "What was the brightest letter?" and was given a reminder of the four possible options (H, I, V, and X). The participant then typed the identity of the probed letter from the four possible distractor letters, and accuracy was recorded. The experiment lasted approximately 50 min.

## Results

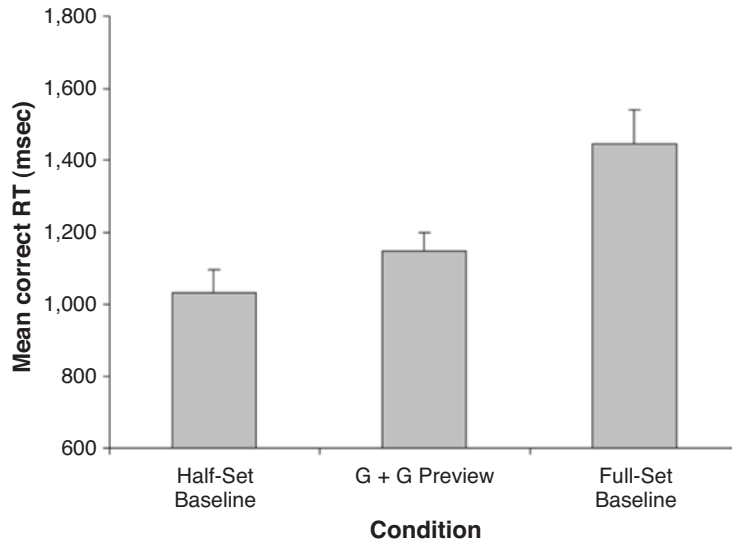
The RT data for both target and probe search trials were trimmed for outliers (deemed at  $\pm 2.5$  SDs and as any response faster than 200 msec) and incorrect responses. This procedure was used in all the subsequent experiments. The data for the search and probe trials were initially analyzed separately in one-way within-subjects analyses of variance (ANOVAs). These were further decomposed using a series of planned ANOVA comparisons. The planned comparisons were corrected using the Bonferroni procedure when necessary.<sup>2</sup>

**Search trials.** The search trial data for the three conditions (the half-set baseline, the full-set baseline, and the G + G preview conditions) were entered into a one-way ANOVA. The condition factor was significant [ $F(2,22) = 40.419$ ,  $MS_e = 15,958$ ,  $p < .001$ ;  $\eta^2 = .786$ ]. Separate planned comparisons showed that RTs in the G + G preview condition were longer (by 156 msec) relative to those in the half-set baseline condition [ $F(1,11) = 17.398$ ,  $MS_e = 8,347$ ,  $p < .01$ ;  $\eta^2 = .613$ ]. Nevertheless, RTs in the preview condition were greatly advantaged (301 msec) relative to those in the full-set baseline condition [ $F(1,11) = 22.230$ ,  $MS_e = 24,372$ ,  $p < .01$ ;  $\eta^2 = .669$ ]. Thus, the G + G preview condition did not produce optimal performance (e.g., equivalent to the half-set baseline), but there was a strong preview benefit in comparison with the full-set condition (see Figure 2).

**Probe trials.** The data for probe detection from the full-set, half-set, and preview conditions were entered into a one-way ANOVA. The results for the preview condition were broken down according to whether the probe fell on an old or a new letter. The overall effect of condition was significant [ $F(3,33) = 35.086$ ,  $MS_e = 14,387$ ,  $p < .001$ ;  $\eta^2 = .761$ ]. Separate planned comparisons revealed that RTs to probes on new letters in preview search were 80 msec longer than RTs to probes in the half-set baseline, but this difference was not significant [ $F(1,11) = 6.044$ ,  $MS_e = 6,287$ ,  $p = .191$ ;  $\eta^2 = .355$ ]. However, RTs were reliably longer than in both the half-set [ $F(1,11) = 58.585$ ,  $MS_e = 22,256$ ,  $p < .001$ ;  $\eta^2 = .842$ ] and the full-set [ $F(1,11) = 26.574$ ,  $MS_e = 25,150$ ,  $p < .01$ ;  $\eta^2 = .707$ ] baselines if probes fell on old letters in the preview. These effects were quite substantial: a 466-msec difference relative to the half-set baseline and a 334-msec difference relative to the full-set baseline (see Figure 3).

**Old-probe versus new-probe comparison.** RTs to probes on old letters in the preview were compared directly with those on new probe letters. RTs to probes that fell on old letters were 387 msec longer than RTs to probes that fell on new letters; this difference was highly significant [ $F(1,11) = 38.496$ ,  $MS_e = 23,293$ ,  $p < .001$ ;  $\eta^2 = .778$ ; see Figure 3].

**Errors.** Error rates were very low in all conditions. Overall, the search trials produced 2.55% errors. Probe trials produced 1.22% errors averaged across all conditions. For the preview condition, there was a general trend toward increased errors to probes on old letters (1.74%) relative to probes on new letters (1.04%). However, this difference

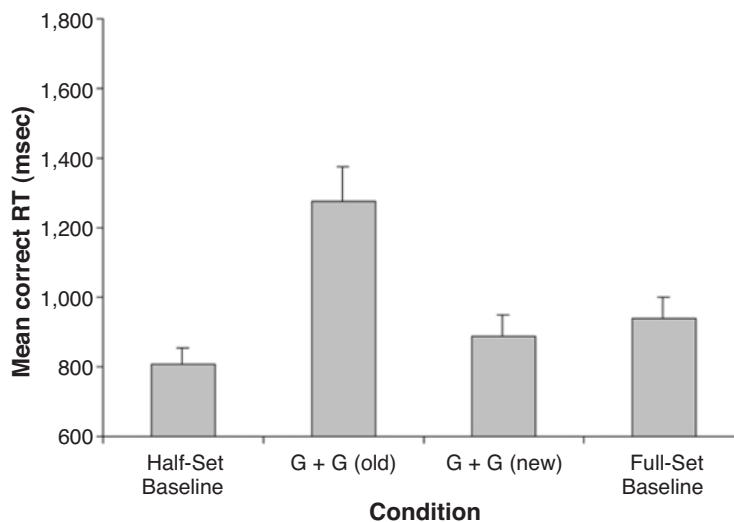


**Figure 2.** Mean correct reaction times (RTs, in milliseconds) for target search trials of Experiment 1.

was not significant [ $F(1,11) = 1.692$ ,  $MS_e = 0.394$ ,  $p = .220$ ;  $\eta^2 = .133$ ]. Errors for old and new items were pooled from the preview condition and entered, along with data from the other probe conditions and errors in the primary search task, into an overall 3 (condition)  $\times$  2 (search type) ANOVA. Only the main effect of search type was significant [ $F(1,11) = 80.817$ ,  $MS_e = 3.086$ ,  $p < .001$ ;  $\eta^2 = .880$ ]. There were more errors on search than on probe trials. The main effect of condition [ $F(2,22) = 1.245$ ,  $MS_e = 3.158$ ,  $p = .308$ ;  $\eta^2 = .102$ ] and the condition  $\times$  search type interaction [ $F(2,22) = 0.718$ ,  $MS_e = 1.991$ ,  $p = .499$ ;  $\eta^2 = .061$ ] were not significant. There was no evidence of a speed-accuracy tradeoff. The data are shown in Table 1.

### Discussion

We discuss the data for standard search trials before those for the probe trials. Although the preview condition did not produce optimal performance (e.g., RTs equivalent to those of the half-set baseline condition), there was a large and significant preview benefit relative to the full-set baseline condition. Providing the participants with a preview of half the distractors significantly improved search. This replicates the results of studies in which similar heterogeneous displays were used (Olivers et al., 1999; Theeuwes, Kramer, & Atchley, 1998). Since we used only one display size, we cannot assess here whether any cost to the preview condition



**Figure 3.** Mean correct reaction times (RTs, in milliseconds) for the probe trials of Experiment 1.

**Table 1**  
**Overall Error Percentages for Target Search and Probe**  
**Detection Trials in Experiment 1**

Condition	Target Search	Probe Detection
Half set	2.17	1.04
Full set	2.65	1.22
G + G	2.82	1.39

(relative to the half-set baseline condition) reflects an overall lengthening of RTs (an intercept effect) or a slowing of search. Previous studies have shown significant intercept effects in preview search relative to half-set baselines (e.g., Watson & Humphreys, 1997), which can be attributed to various factors, including inhibition of a response to the onset of a preview (Olivers, Braithwaite, & Humphreys, in press).

For probe detection for all conditions, RTs were considerably shorter (and error rates were reduced) in comparison with letter search (Z/N). This demonstrates that the luminance increment used here was more than sufficient for easy detection in all conditions. However, RTs to probes on new distractors in the preview condition were also longer than those to probes in the half-set baseline condition. This is consistent with the general lengthening of RTs in the search task in the preview relative to the half-set baseline condition. As was noted above, there may be slowing of the search itself or a general lengthening of RTs due to a factor such as response inhibition. More important, RTs to probes that fell on old distractors were even longer than RTs to probes in the full-set baseline condition. This pattern is consistent with other studies in which probe detection was used to measure attentional allocation in preview search (Olivers & Humphreys, 2002; Watson & Humphreys, 2000). The slowing of reactions to probes on old distractors is consistent with these items' being inhibited (relative to distractors in the full-set baseline condition).

However, several alternative accounts can be offered. For instance, the longer RTs to probes on old distractors may be due not to attentional factors but to earlier acting sensory factors, including forward visual masking and/or neural fatigue. In terms of a masking account, it could be argued that the luminance increment on old letters was masked by being presented against an already existing increment (the distractor relative to the background) in comparison with when the increment was in the form of a new item appearing against a dark background (a variation on Weber's law). Alternatively, probe detection at old locations could be poorer due to the neural fatigue associated with items that have been presented for some time. It is possible that activation of any stimuli at locations occupied for some period is weakened by this neural fatigue, making probes at these locations relatively difficult to detect.

In Experiment 2, we tested both of these possibilities. We introduced short previews lasting just 150 msec. Watson and Humphreys (1997) have shown that preview search is optimal only when previews appear for 500 msec

or longer. They attributed this to the time taken to inhibit the old items. Thus, with a reduced preview duration of 150 msec any inhibition of the old items should not be maximized. Detection of probes on old distractors should thus improve. However, a preview of 150 msec should be long enough to perceptually separate the old and the new items (see Yantis, 1996), so that any masking of probes by the perceptual representation of the old items should still take place. If forward masking is crucial, the probes on old distractors should be as hard to detect as when old items appear for 1,000 msec (as in Experiment 1). Note that in terms of neural fatigue, simply reducing the preview duration to 150 msec also removes the degree of possible fatigue that could be associated with the preview display. From a fatigue account, we would also expect improved detection of probes on 150-msec previews. To contrast the fatigue account with the inhibition account, we also created conditions in which participants only had to detect probes in a block of trials, whereas the temporal parameters of the displays remained matched to those used in Experiment 1 (e.g., with a 1,000-msec preview). When probe detection is the sole task, there is no need to prioritize search for targets in the new display. In terms of perceptual masking and neural fatigue, this should have no effect. In contrast, if previews are inhibited only when they have to be ignored in search, then the difficulty of detecting probes on old distractors should be removed here. This would replicate previous data on probe detection reported by Olivers and Humphreys (2002) and Watson and Humphreys (2000). Effects due to the attentional set adopted in search should occur only when probes are embedded into the search task (see Watson & Humphreys, 2000).

## EXPERIMENT 2

### Forward Masking and Neural Fatigue Effects

#### Method

**Participants.** Sixteen participants (9 female, 1 left-handed) took part for course credit or a small payment. The ages of the participants ranged from 20 to 31 years, with a mean age of 23.6 years. All were undergraduate or postgraduate students at the University of Birmingham. All had normal or corrected-to-normal vision (including normal color vision).

**Stimuli and Apparatus.** The stimuli were similar to those used in Experiment 1 except that the displays contained both red and green letters. For each participant, the red and green colors for the stimuli were set to be isoluminant on the basis of a flicker calibration test. For red stimuli, the probe value was then set to RGB maximum (255/0/0). The probe values for green were matched to this on the basis of a flicker calibration test. This enabled each given increase in luminance to be great enough to be perceived for each color, whereas the probes in the two colors did not differ in luminance relative to each other. In pilot studies, these values were sufficient for effective search and probe detection, and there was no evidence of an asymmetric bias in the color probe values used (i.e., probes on red letters detected faster than probes on green letters or vice versa).

**Design and Procedure.** A 4 (condition)  $\times$  2 (time period) within-subjects design was employed. In all the conditions, a preview procedure was used, consisting of an equal number of red and green items in both the preview and the search displays. There were two

search/probe conditions and two new probe-only conditions. The two experimental conditions were as follows: (1) a standard 1,000-msec preview with only probe detection, and (2) a 150-msec preview with only probe detection. In the search tasks, probes were presented on 33% of the trials (as in Experiment 1). In the probe-only tasks, probes appeared on every trial. In all the conditions, half of the letters in the preview were red and half were green, and the same held for the letters in the search displays.

Standard search trials were similar to those in Experiment 1. The search target (Z/N) always appeared in the second search display, and it was red or green equally often (randomly determined). Hence, color was irrelevant to the search task. Luminance probe trials followed a similar procedure and were signaled by an auditory beep of 1000 Hz that occurred 20 msec before the onset of the second search display. For probe-only conditions, the beep occurred on every trial.

For both the probe-in-search and probe-only conditions, the probe (when present) occurred equally often on new and on old distractors. For the probe-in-search conditions, the participants were instructed that the probe occurred rarely in relation to the search task. Thus, they were asked to prioritize the search task. For the probe-only trials, the participants were told that the probe could occur on old items and new items equally often and that there was no advantage to ignoring the old items. The experiment lasted approximately 60 min.

## Results

The data from the standard search conditions were compared in a one-way within-subjects ANOVA. Search RTs were, on average, 216 msec shorter for the 1,000-msec than for the 150-msec preview. This difference was significant [ $F(1,15) = 12.010$ ,  $MS_e = 31,186$ ,  $p < .01$ ;  $\eta^2 = .445$ ]. This improvement at the longer preview duration is indicative of a preview benefit (see Figure 4).

**Comparing probe RTs.** Probe RTs for all conditions were analyzed in a three-way 2 (search: yes vs. no)  $\times$  2 (time: 150 vs. 1,000 msec)  $\times$  2 (set: old vs. new) within-

subjects ANOVA. This revealed significant main effects of search [ $F(1,15) = 20.757$ ,  $MS_e = 23,193$ ,  $p < .001$ ;  $\eta^2 = .580$ ] and set [ $F(1,15) = 118.909$ ,  $MS_e = 11,723$ ,  $p < .001$ ;  $\eta^2 = .888$ ]. The main effect of time was not significant [ $F(1,15) = 1.028$ ,  $MS_e = 36,260$ ,  $p = .327$ ;  $\eta^2 = .064$ ]. The search  $\times$  time interaction was not significant [ $F(1,15) = .769$ ,  $MS_e = 22,487$ ,  $p = .394$ ;  $\eta^2 = .049$ ], but the search  $\times$  set and time  $\times$  set interactions were significant [ $F(1,15) = 7.147$ ,  $MS_e = 3,644$ ,  $p < .05$  ( $\eta^2 = .323$ ) and  $F(1,15) = 17.667$ ,  $MS_e = 5,743$ ,  $p < .01$  ( $\eta^2 = .541$ ), respectively]. The search  $\times$  time  $\times$  set interaction was also significant [ $F(1,15) = 11.122$ ,  $MS_e = 5,045$ ,  $p < .01$ ;  $\eta^2 = .426$ ]. Figure 5 shows these data.

To assess which condition led to the largest RT effects, the differences in RTs to probes on old and new stimuli were calculated for each condition to produce an overall difference score ( $dRT$ ). These overall difference scores were then entered into a one-way ANOVA, which revealed a significant difference between the conditions [ $F(3,45) = 12.723$ ,  $MS_e = 9,622$ ,  $p < .001$ ;  $\eta^2 = .459$ ]. The difference in RTs to probes on new items was 141 msec larger in the 1,000-msec preview search condition relative to the 1,000-msec probe-only condition [ $F(1,15) = 11.629$ ,  $MS_e = 13,640$ ,  $p < .01$ ;  $\eta^2 = .437$ ]. Indeed, the  $dRT$ s for probes embedded in search after a 1,000-msec preview were significantly different from the  $dRT$ s in all the other conditions.

**Errors.** Error rates for the mixed color displays used here were slightly increased relative to those of Experiment 1. Search trials produced an overall error rate of 3.48%, in comparison with 1.09% of errors on probe trials. The error data were entered into a 2 (search: yes vs. no)  $\times$  2 (time: 150 vs. 1,000 msec)  $\times$  2 (set: old vs. new) within-subjects ANOVA. This revealed a significant

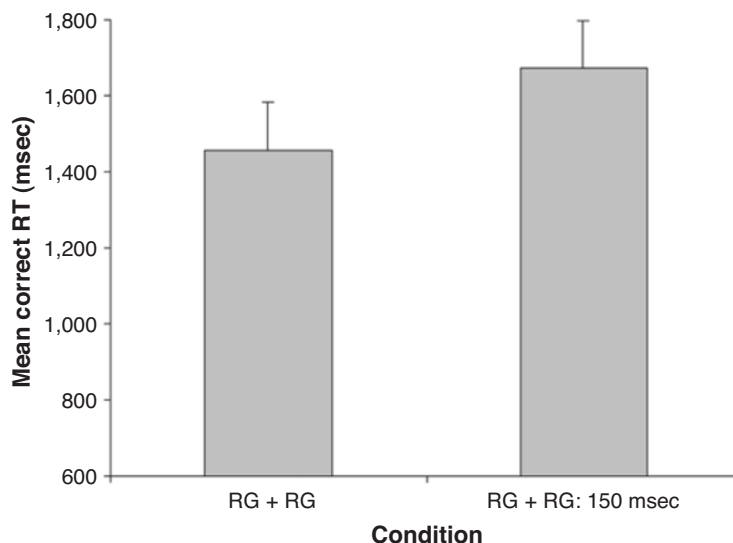


Figure 4. Search reaction times (RTs, in milliseconds) for the search/probe embedded conditions of Experiment 2.



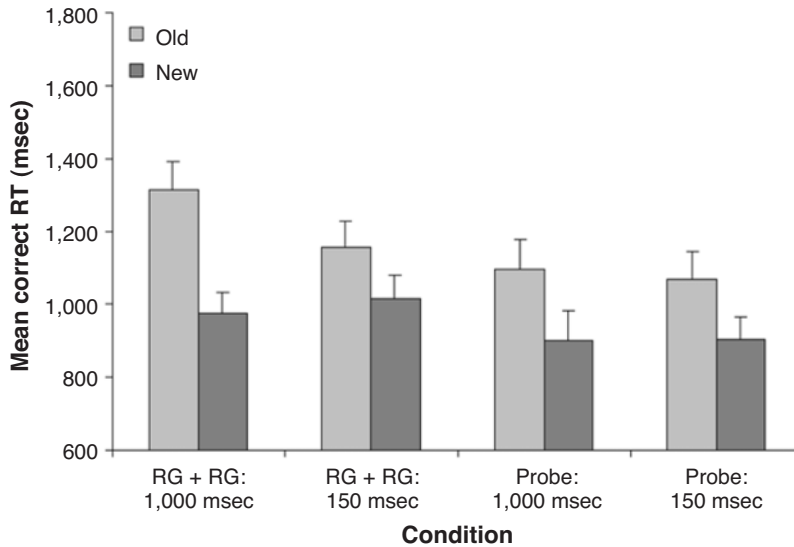


Figure 5. Mean correct reaction times (RTs, in milliseconds) for probes that came in the old and new sets for each condition in Experiment 2.

main effect of search only [ $F(1,15) = 5.787$ ,  $MS_e = 1.058$ ,  $p < .05$ ;  $\eta^2 = .278$ ], and there were more errors in the search task than in the probe task (for all other main effects and interactions,  $F_s < 1$ ; see Table 2 for the overall errors).

## Discussion

The results of Experiment 2 are clear. The search data replicated prior results, which have shown that reducing the duration of the preview leads to increased search RTs. This finding is consistent with the notion that the preview benefit takes time to reach its maximum level (see, e.g., Watson & Humphreys, 1997). Now consider the probe detection results. As with Experiment 1, probe detection was faster than search for the new letter target for both the long (1,000-msec) and short (150-msec) preview conditions. There was also a general trend for probe RTs to be shorter when only probes had to be detected than when probes were embedded in the search task, suggesting some effect of dual-task load.

The main purpose of Experiment 2 was to assess the differential impact of preview duration and attentional set on RTs to probes. For probe-only trials, RTs were 28 msec longer for long relative to short previews; this difference was not significant. In contrast, when probes

were embedded in the search task there was an RT cost of 197 msec to probes on old items following a long rather than a short preview. This was due primarily to a lengthening of RTs to probes on old items at the longer preview duration; there was no effect of preview duration on RTs to probes on new stimuli. Thus, although there may have been a small (and nonsignificant) effect of increasing the preview duration on probe RTs, this effect was greatly enhanced when probes fell on old items within the context of a search task. Thus, performance was affected by the attentional set adopted by the participants. The effect of attentional set matched the results previously reported by Olivers and Humphreys (2002) and Watson and Humphreys (2000), where costs to probes on old items were exaggerated when probes appeared within the context of a search task.

These data provide evidence against two main alternative sensory accounts of the results on probe detection in preview search: visual masking and neural fatigue. If masking were crucial, then we would expect any difference between RTs to probes on new and old items to be equivalent for the 1,000-msec and 150-msec preview conditions. It was not: The disadvantage for the probes on old previews was much greater for the 1,000-msec preview condition. Furthermore, the masking account holds that performance should be unaffected by manipulation of the attentional set of the participants. On the contrary, the attentional set had a substantial effect. The negative effects of the preview duration here are consistent with a neural fatigue account, since activation in the representation of old distractors may decrease for long duration previews. This could in turn make probes at these locations relatively difficult to detect. However, like the proposal for visual masking, the neural fatigue account predicts that probe detection should not alter as

Table 2  
Overall Error Percentages for Target Search and Probe Detection Trials in Experiment 2

Condition	Target Search	Probe Detection
RG + RG, 1,000 msec	3.84	1.17
RG + RG, 150 msec	3.13	1.17
Probe only, 1,000 msec	—	1.23
Probe only, 150 msec	—	0.78

a function of whether probes are embedded in a search task (provided the stimulus durations are held constant). The results of Experiment 2 go against this, since the disadvantage for probes on old stimuli was exacerbated when probe detection was embedded in search. The pattern of probe RTs cannot be explained simply in terms of sensory-based neural fatigue.

Nevertheless, it is important to note that even with 150-msec previews RTs were longer when probes fell on old relative to new stimuli. This difference may reflect the contribution to performance of factors other than distractor inhibition, including some degree of forward masking, some neural fatigue, and even attentional capture by the new stimuli (Donk & Theeuwes, 2001). There may also be suboptimal inhibition of the old items (Humphreys et al., 2004). All of these factors may combine to make probes on new distractors generally more salient than probes on old distractors. We do not claim (and indeed have never claimed) that inhibitory marking of old items is the only factor that contributes to preview search. Even so, the data provide clear evidence of the occurrence of marking. The disadvantage for probes on old items increased both with the preview duration and when observers were set to search for a new target letter. Neither of these effects is predicted by the alternative accounts of performance (e.g., forward masking, neural fatigue, onset capture) or by some general notion of a saliency difference (since this difference should be the same across the conditions and should not be influenced by our manipulations).

### EXPERIMENT 3

#### Grouping, Inhibition, and Negative Color Carryover Effects

Having established that not all of the probe effects can be explained in terms of forward masking, neural fatigue, and onset capture, in Experiment 3 we used the procedure to address the nature of color carryover effects in preview search. In this experiment, we used displays with letters of different colors (some red and some green). The ratios of red to green letters were varied across the preview and new (search) displays. For example, if in the preview display there was an uneven ratio with a red bias (66% red, 33% green), then this was balanced by an opposite bias in the new search display (33% red, 66% green).<sup>3</sup> Hence, overall there was an equal number of red and green items in the final display. Using these conditions, Braithwaite et al. (2003) found that the color ratio of the distractors greatly affected search in the preview condition but not in the baseline conditions. In particular, search was slowed for targets in the majority color of the preview display (the minority color in the new set) in comparison with search for targets that were in the minority color of the preview display (the majority color of the new set; e.g., red targets in a condition such as 66R/33G + 33R/66G). This result is highly informative for understanding preview search, since it goes in exactly the opposite direction of any prediction based on the new

items' capturing attention. In terms of onset capture, we would expect search to benefit for targets carrying the minority color in the search display (Bacon & Egeth, 1997; Egeth et al., 1984; Kaptein et al., 1995; Moore & Egeth, 1998; Poisson & Wilkinson, 1992). On the contrary, these targets were particularly difficult to detect. To account for these data, Braithwaite et al. (2003) proposed that old distractors were inhibited and that this inhibition carried over to new stimuli sharing features with old distractors. If inhibition was applied primarily to the majority set in the preview, then the carryover would be strongest for the properties of this set. Such differential inhibition might take place if suppression spreads between like stimuli (Duncan & Humphreys, 1989, 1992): There is a greater level of spreading suppression when more like distractors are present. Also, any inhibitory carryover may be particularly strong if the new items, which share this feature, are few in number so that their onset does not overcome any inhibition that has accrued (see Watson & Humphreys, 1998, for evidence). The net effect would be that targets are most difficult to find when they are in a new minority set that shares properties with a prior majority set.

One difficulty with the argument mounted by Braithwaite et al. (2003) is that no direct measures of inhibition were taken; inhibition was assumed from the costs to search for targets carrying the old majority/new minority color. In Experiment 3, we sought to remedy this problem by combining search with a probe detection task designed to measure attentional allocation in the displays. There were three search conditions: a full-set baseline and two preview conditions. In the full-set baseline condition, an equal number of red and green items (50R/50G) was used. In the two preview conditions, the full-set baseline was broken up in two ways. In the 50/50 + 50/50 condition, there was an equal number of red and green items in the preview display and an equal number of red and green items in the second search display. In the 66/33 + 33/66 preview condition, 66% of the letters had one color and 33% had the other, whereas the search display was also biased but in the opposite direction. The colors of the minority and majority groups were counterbalanced and varied randomly on a trial-by-trial basis within a block of trials. For all the conditions, the targets appeared equally often in each color, as did the probe (when present). In the preview conditions, probes were carried by old and new items an equal number of times. In the 66/33 + 33/66 preview condition, the probe appeared equally often in the old majority, the old minority, the new majority, and the new minority color sets. Here, for the first time, we provide a direct test of whether or not greater inhibition is applied to old letters in the majority color relative to old letters in the minority color. This manipulation gives us a more refined test of inhibitory modulation directed to the old items than that provided by other studies in which probe detection was used in preview search (e.g., Olivers & Humphreys, 2002; Watson & Humphreys, 2000).

## Method

Unless otherwise mentioned, the method was the same as in the previous studies.

**Participants.** Twenty participants (9 female, 1 left-handed) took part for course credit or a small payment. The ages of the participants ranged from 18 to 34 years, with a mean age of 22.3 years. All were undergraduate or postgraduate students at the University of Birmingham. All had normal or corrected-to-normal vision (including normal color vision).

**Design and Procedure.** A 3 (condition)  $\times$  2 (search type) within-subjects design was used. The three experimental conditions were (1) a full-set baseline condition (a single presentation of 24 items, 12 red and 12 green), (2) a 50/50 + 50/50 condition (a preview condition with an equal number of red and green items in both the preview and the second search displays), and (3) a 66/33 + 33/66 preview condition (a preview condition in which the initial display and the second display were color biased in opposite directions, so that overall the ratio was equal after both presentations). Each condition was run as a separate block of 288 trials. A break was given halfway through each block. Thirty-three percent of the trials in each condition contained a luminance probe, and 66% were standard search trials. For target search trials, there was an equal number of trials for new minority and for new majority targets. Similarly, the total number of probe trials was divided equally across the four possible distractor groups (old majority, old minority, new majority, and new minority) and were generated on a random basis. Trial types (target search and probe detection) within each condition were fully randomized within blocks, and block order was randomized across participants. A general block of practice trials for both the preview and the full-set baseline conditions was completed at the beginning of the experiment. None of these practice trials was included in the analysis.

## Results

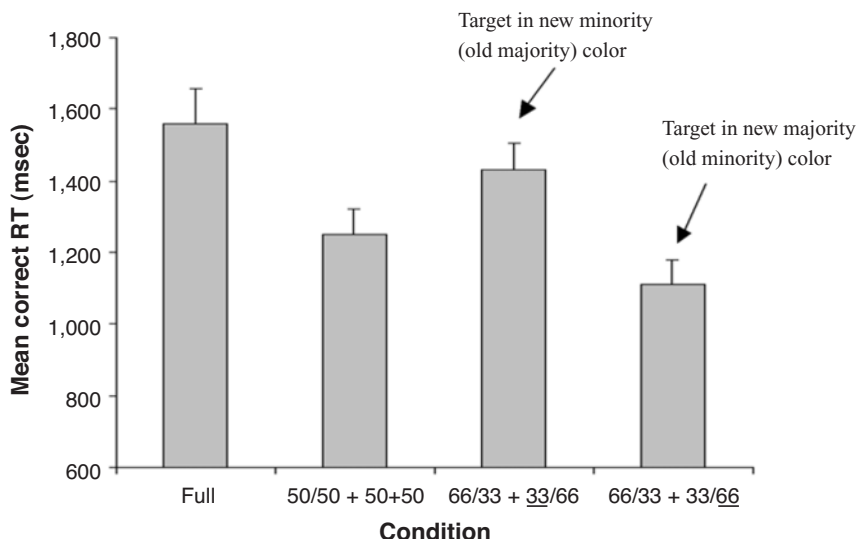
The results were analyzed in a manner similar to that used for the results of the previous experiments.

**Analysis of search trials.** There was a significant effect of search condition [ $F(2,38) = 18.821$ ,  $MS_e = 30,031$ ,

$p < .001$ ;  $\eta^2 = .498$ ]. Search RTs in both the 50/50 + 50/50 and the 66/33 + 33/66 preview conditions were shorter than in the full-set baseline [effects of 307 and 272 msec, respectively;  $F(1,19) = 30.339$ ,  $MS_e = 31,146$  ( $\eta^2 = .615$ ) and  $F(1,19) = 23.583$ ,  $MS_e = 31,290$  ( $\eta^2 = .554$ ), both  $ps < .01$ ]. Search in the 66/33 + 33/66 condition was broken down as a function of whether the target was in the new majority or the new minority color. In comparison with the 50/50 + 50/50 preview, targets in the new minority group were responded to more slowly [an effect of 178 msec;  $F(1,19) = 9.110$ ,  $MS_e = 34,778$ ,  $p < .01$ ;  $\eta^2 = .324$ ]. In contrast, RTs to targets in the new majority color were shorter [an effect of 141 msec relative to the 50/50 + 50/50 preview;  $F(1,19) = 8.359$ ,  $MS_e = 23,649$ ,  $p < .01$ ;  $\eta^2 = .306$ ]. The mean correct RTs are shown in Figure 6. Search RTs from the 66/33 + 33/66 condition were then directly compared according to whether the target was in the new minority or the new majority group. New minority targets were responded to 319 msec more slowly than new majority targets [ $F(1,19) = 142.844$ ,  $MS_e = 7,106$ ,  $p < .001$ ;  $\eta^2 = .883$ ].

**Analysis of probe trials.** Relative to RTs to the full-set baseline, those to probes that appeared on old distractors were longer. For the 50/50 + 50/50 preview, there was a cost of 280 msec [ $F(1,19) = 63.108$ ,  $MS_e = 12,454$ ,  $p < .001$ ;  $\eta^2 = .769$ ]. For the 66/33 + 33/66 preview, there was a cost of 319 msec [ $F(1,19) = 36.254$ ,  $MS_e = 28,007$ ,  $p < .001$ ;  $\eta^2 = .656$ ]. In the preview conditions, there was no difference between RTs to probes in the full-set baseline and those to probes in the new set (all  $F_s < 2$ ).

To assess the relations between probe RTs as a function of whether the new and old items had minority or majority colors, we assessed probe performance in a 2



**Figure 6.** Mean correct target search reaction times (RTs, in milliseconds) from Experiment 3. Underscores denote the groups within which targets occurred.

(set: old vs. new)  $\times$  2 (group: minority vs. majority) within-subjects ANOVA. This revealed a significant main effect of set [ $F(1,19) = 34.000$ ,  $MS_e = 56,291$ ,  $p < .001$ ;  $\eta^2 = .642$ ]. The main effect of group was not significant [ $F(1,19) = 1.682$ ,  $MS_e = 24,992$ ,  $p = .210$ ;  $\eta^2 = .081$ ], but the set  $\times$  group interaction was significant [ $F(1,19) = 44.721$ ,  $MS_e = 13,153$ ,  $p < .001$ ;  $\eta^2 = .702$ ; see Figure 7]. RTs to probes were generally longer if they fell on old rather than new distractors. However, performance differed according to whether the probe was an item in the minority or the majority color group, and whether it was on the old or on the new stimuli. When the probe was on an old item, RTs were longer (by 207 msec) when it was in the majority relative to when it was in the minority color group [ $F(1,19) = 22.837$ ,  $MS_e = 18,736$ ,  $p < .001$ ;  $\eta^2 = .546$ ]. When the probe was on a new item, RTs were longer (by 136 msec) when it was in the new minority (old majority) group in comparison with when it was in the new majority (old minority) group [ $F(1,19) = 19.976$ ,  $MS_e = 9,279$ ,  $p < .001$ ;  $\eta^2 = .513$ ; see Figure 7].

**Errors.** Error rates were very low in all the conditions. Overall, target search trials produced 2.75% errors. Probe search trials produced 1.29% errors averaged across conditions. Errors were averaged over old and new locations and entered into an overall 3 (condition)  $\times$  2 (search type) ANOVA. This revealed a significant main effect of search type only [ $F(2,38) = 69.038$ ,  $MS_e = 7.128$ ,  $p < .001$ ;  $\eta^2 = .784$ ]. There were more errors on search than on probe trials. Neither the main effect of condition [ $F(1,19) = 1.226$ ,  $MS_e = 3.757$ ,  $p = .305$ ;  $\eta^2 = .061$ ], nor the condition  $\times$  search type interaction [ $F(2,38) = .313$ ,  $MS_e = 2.951$ ,  $p = .733$ ;  $\eta^2 = .016$ ] was significant. Like probe RTs, probe errors were also analyzed as

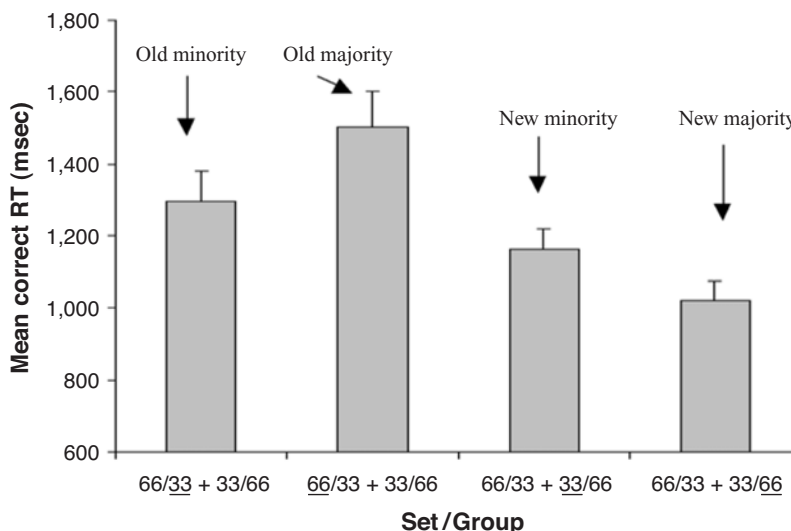
**Table 3**  
Overall Error Percentages for Target Search and Probe Detection Trials in Experiment 3

Condition	Target Search	Probe Detection
Full set	2.47	1.09
50/50 + 50/50	2.97	1.51
66/33 + 33/66	2.81	1.25

a function of set (old vs. new) and group (minority vs. majority). Although there was a trend toward slightly more errors to probes in the new minority group, this was not significant. No other effects or interactions approached significance (all  $F$ s  $< 4$ ; see Table 3).

### Discussion

**Preview search.** Relative to the full-set baseline, there was a preview advantage for both the 50/50 + 50/50 and the 66/33 + 33/66 preview conditions. Nevertheless, search RTs to targets that were in the new minority group were much longer in the 66/33 + 33/66 condition relative to RTs for the 50/50 + 50/50 preview condition. In contrast, RTs for targets in the new majority group were shorter relative to RTs for the 50/50 + 50/50 preview condition. Clearly, performance was influenced by the color relations between the displays. It is difficult to explain this result in terms of attentional capture by the new stimuli. For instance, if there is capture by new onsets, then the color of the old items should be irrelevant (see Donk & Theeuwes, 2001). Also, we would expect search to be directed to the smaller of the two new color groups (Bacon & Egeth, 1997; Egeth et al., 1984; Kaptein et al., 1995; Moore & Egeth, 1998; Poisson & Wilkinson, 1992). As in Braithwaite et al. (2003), the data went in the opposite



**Figure 7.** Mean correct probe reaction times (RTs, in milliseconds) for the 66/33 + 33/66 preview condition of Experiment 3. Underscores denote the groups within which targets occurred.

direction (see also Braithwaite et al., 2004, for similar effects on singleton targets). The data are also relevant to at least one other explanation of preview search—the “feature-blind” inhibition account (Watson & Humphreys, 1997). Watson and Humphreys (1997) proposed that preview search is efficient because inhibition is applied to the locations of old items. For this account, the color relations between the old and the new items should not matter. This fails to explain the present data.

To account for the results, several alternative accounts of search must be considered. Some of these accounts attribute the effects to particular inhibitory mechanisms, but other noninhibitory accounts are also viable. One possibility is that there is color-based inhibition of old items, which is carried over from the preview to the new display, lengthening search times for targets carrying the inhibited color (Braithwaite & Humphreys, 2003; Braithwaite et al., 2003). The differential effects on items in the old majority color would occur if there is inhibition of a color map corresponding to the color of the majority of a set of distractors (see Treisman & Sato, 1990). An alternative inhibitory account holds that there is group-based inhibition, which is stronger for larger distractor groups (Duncan, 1995; Duncan & Humphreys, 1989, 1992). However, there may also be grouping effects not linked to distractor inhibition. For example, on the basis of their common color, new targets may be grouped with old preview items. When the number of old distractors is greater than the number of new letters carrying the color, the new letters may be assimilated into the old group. This may make it difficult to detect a new target in that color. A similar, noninhibitory account of preview search based on the formation of separate temporal groups by old and new items has been offered by Jiang et al. (2002b).

One argument against an inhibitory account might be to point out that the color bias in the preview set (66/33) is actually confounded with the color bias in the search set (33/66), so that the final display has equal colors (50/50). This might make it problematic to say to what degree the effects come from the bias in the preview or from the bias in the search set. Note that this point refers only to the color carryover effects and does not bear on long RTs to probes in the old set, in which the color of the old items clearly has an effect (even when changed on presentation of the new items; see below). Furthermore, this point has been addressed in detail elsewhere. For instance, Braithwaite et al. (2003) orthogonally decomposed the color bias by creating conditions in which the preview set had a color bias (66/33) but the search set did not (50/50), for comparison with a condition in which the preview had an equal number of red and green items (50/50) and the search set was biased (66/33). In the latter case, there was no majority group in the preview set. The findings showed that it was the relationship between the sets that was crucial: As long as the new items in a particular color did not outnumber their same-colored counterparts in the preview, a negative carryover occurred. Therefore, color carryover effects depend on the rela-

tionship between the old and the new sets. Furthermore, the carryover effects to new targets were greatly reduced when the preview duration was reduced to 150 msec. This shows clearly that it is not just the color of the items in the preview that influences performance, and that the result is instead consistent with an account in terms of inhibition from the preview. This inhibition takes time to accrue and become optimal.

It is also possible to offer a modified account of attentional capture by new objects. For example, the new majority color could capture attention because it produces a larger change signal (cuing attention to the new stimuli) relative to the new minority color. Here, color change is critical to cuing attention to new objects. An additional possibility is that observers use the old minority color to predict the likely color of the target in the new majority (although in fact the target was more likely to be one of the new minority set than one of the new majority, when we take into account the probability that any one item was the target). Although these differing accounts can be put forward to explain the search data, they can be distinguished by the probe data, which we consider below.

**Probe detection search.** RTs were significantly longer for probes on old distractors relative to probes that fell on new distractors and probes in the full-set baseline. This is consistent with active inhibition of the old items in preview search (Olivers & Humphreys, 2002; Watson & Humphreys, 2000). Note that if there were new object capture, we would expect RTs to be facilitated to probes falling on new distractors in the preview in comparison with probe RTs in the full-set baseline condition (see also Experiment 1). This was not the case. In addition to this, probe RTs varied as a function of the color relations within the old and new displays. When probes fell on old distractors, RTs were longer when the distractors had the majority color in the preview. However, when probes fell on new distractors, RTs were longer when the distractors had the minority color in the search display. The latter result is quite inconsistent with the idea of new object capture, according to which we might expect attention to be attracted to the new minority (see Bacon & Egeth, 1997; Egeth et al., 1984; Kaptein et al., 1995; Moore & Egeth, 1998; Poisson & Wilkinson, 1992). In addition, performance should be equal irrespective of whether probes fall on old distractors carrying the majority color or on those carrying the minority color in the preview display. Even if there were attentional capture by majority distractors, in the new set RTs to probes on old items would not be expected to vary. This is countered by the data.

The other noninhibitory accounts of preview search also fail to predict that probe detection should vary on old items in the majority and minority colors. For example, all old items are part of a single temporal group, so probe detection should not vary within this set (cf. Jiang et al., 2002b). Similarly, a color change signal (drawing attention to the new majority color) should render all old letters unattended. Noninhibitory grouping between the

old and the new items could explain the data if old letters in the minority color were assimilated into the new majority color group and old letters in the majority color were assimilated into the new minority set. But the difficulty then lies in explaining why RTs were in all cases longer to probes on old items, including those in the old minority color. Probes on these letters were not equivalent to probes on new items in the majority color, yet these items should be grouped together. Finally, detection should not vary across old letters if sensory factors such as masking or neural fatigue were crucial. For instance, all the preview items were displayed for the same period of time (1,000 msec) and, hence, all should have received equivalent influences of fatigue and masking irrespective of whether they were in the majority or the minority color. Clearly, this was not the case. Experiment 3 suggests that inhibitory processes may be needed to explain the data.

There remains one potential counterexplanation for the observed difference in target and probe detection as a function of the group to which they belong. This counterargument is that performance is affected by the relative "change signal" generated by the color relations between the preview display and the search display. For instance, consider a trial that consisted of a preview set with a minority red display (and thus a majority green display). Here, when the second search set was presented, there would be a greater relative change signal for the new majority group (the red items) than for the new minority group (the green items). It is possible that the change signal from minority to majority color is particularly potent for capturing and guiding attention, which is then drawn to the new majority color set. That is, attention may well be captured not by the properties of the new set per se but by the relative change signal between the old set and the new display. However, it is unlikely that such a mechanism is crucial here. Braithwaite et al. (2003) tested this suggestion using the same color-biased manipulation as we used here, but with a reduced preview duration (150 msec). In terms of capture by change signal, performance should be equivalent for long and short preview durations. However, an account of visual marking claims that such inhibitory processes take time to become optimal, and as such would be weaker with 150-msec previews (Watson & Humphreys, 1997, 1998). In consistency with the inhibitory account, Braithwaite et al. (2003) found that the negative color carryover was greatly reduced with a preview duration of 150 msec relative to carryover with a preview duration of 1,000 msec. Apparently, any differences in the color change signal were not sufficient to generate the pattern of data. If this were crucial, then there should still have been an effect of uneven groups at 150 msec; there was not.

In Experiment 4, we further examined the nature of any inhibitory effects. Unlike prior studies of preview search, here we changed the colors of the old distractors at the onset of the new search displays. New targets could still be in the same color as either the majority or the mi-

nority of items in the preview display, but the preview was actually a different color when the target appeared. The color change should prevent the grouping of old and new stimuli on the basis of their colors. It should also limit effects when probes fall on old items but not when they fall on new items. In contrast, group-based inhibition should remain on old stimuli. Since our interest in Experiment 4 was focused on performance in the preview conditions, we did not include baseline search conditions (matched to either the new search items or the final combined search display). It is highly unlikely that the effects we have previously obtained (i.e., that search is slowed to targets in the new minority color) are due to RTs' always being long to minority targets. As we have noted, prior studies show that RTs tend to be shorter to targets carrying the minority color when all the search items appear together (Bacon & Egeth, 1997; Egeth et al., 1984; Kaptein et al., 1995; Moore & Egeth, 1998; Poisson & Wilkinson, 1992). Also, Braithwaite et al. (2003) conducted several studies with baselines on which there were uneven proportions of distractors in different colors. In all cases, RTs tended to be shorter to targets in the minority color—the opposite result to that found in the 66/33 + 33/66 preview condition.

## EXPERIMENT 4 Inhibition Versus Grouping

### Method

**Participants.** Fifteen participants (9 female, 2 left-handed) took part voluntarily, for course credit or a small payment. The ages of the participants ranged from 18 to 31 years, with a mean age of 23.4 years. All were undergraduate or postgraduate students at the University of Birmingham. All had normal or corrected-to-normal vision (including normal color vision).

**Stimuli and Apparatus.** The stimuli were similar to those used in Experiments 1–3. However, here two new colors (blue and yellow) were used for the letters for certain conditions. Like the colors used in Experiment 2, these new colors were calibrated for near isoluminance through a flicker calibration test. Pilot studies using a preview search condition with equal numbers of items in each color showed that RTs varied little when probes appeared on yellow or blue letters relative to red or green letters.

**Design and Procedure.** A 2 (condition)  $\times$  2 (search type) within-subjects design was used. The two experimental conditions were as follows: (1) a 66/33 + 33/66 preview condition (in which the initial display and the second display were color biased in opposite directions, as in Experiment 3) and (2) a 66/33 + 33/66-cc preview condition (in which the initial display and the second display were color biased in opposite directions, but here a color change [cc] occurred in the first items when the second search set appeared).

The preview conditions were run according to the procedure outlined for Experiments 1–3. For the new 66/33 + 33/66-cc condition, the procedure was the same as that of the other preview condition except that for both search and probe trials the old (red and green) items changed in color to blue and yellow when the second search set appeared. The color change was fully counterbalanced so that the colors blue and yellow replaced the colors red and green in the minority and majority groups, equally often. There was no predictive link between the majority/minority colors in the preview and the colors to which they changed.

## Results

The results were analyzed in a manner similar to those for Experiment 3.

**Analysis of search trials.** Search was analyzed by separating performance for targets in the new minority and the new majority colors, with target color (new minority vs. majority) and condition (color change vs. no color change) as factors. RTs to targets in the new minority color were longer [ $F(1,15) = 35.113$ ,  $MS_e = 10,536$ ,  $p < .001$ ;  $\eta^2 = .701$ ]. There was no effect of color change [ $F(1,15) = .819$ ,  $MS_e = 29,825$ ,  $p = .380$ ;  $\eta^2 = .052$ ] and no interaction [ $F(1,15) = 2.419$ ,  $MS_e = 4,237$ ,  $p = .141$ ;  $\eta^2 = .139$ ; see Figure 8].

**Analysis of probe trials.** Probe RTs were compared in the two preview conditions. There was a significant main effect of condition [ $F(1,15) = 6.555$ ,  $MS_e = 110,921$ ,  $p < .05$ ;  $\eta^2 = .304$ ] and a significant effect of whether the probe was on an old or on a new distractor [ $F(1,15) = 24.112$ ,  $MS_e = 69,718$ ,  $p < .001$ ;  $\eta^2 = .616$ ]. The main effect of whether the probe was in the majority or in the minority group was not significant [ $F(1,15) = 0.052$ ,  $MS_e = 21,805$ ,  $p = .823$ ;  $\eta^2 = .003$ ]. There was one significant interaction, between whether the probe was on an old or on a new distractor and whether it was in the minority or in the majority color group [ $F(1,15) = 38.977$ ,  $MS_e = 14,676$ ,  $p < .001$ ;  $\eta^2 = .722$ ]. This interaction is depicted in Figure 9. When probes were on old distractors, RTs were longer if the distractor had the (original) majority color. When probes were on new distractors, RTs were longer if the distractor was now in the new minority color (e.g., if it carried the original majority color). This interaction was not affected by whether the old distractors maintained or changed their color.

**Errors.** Errors were low across all conditions. Search trials produced an overall error rate of 3.42%, and probe trials an error rate of 2.37%. An overall 2 (condition)  $\times$

2 (search type) ANOVA revealed only a main effect of search type [ $F(1,15) = 35.025$ ,  $MS_e = 2.124$ ,  $p < .001$ ;  $\eta^2 = .700$ ]. There were more errors on the search task than on the probe task. No other factors approached significance. These data are summarized in Table 4.

## Discussion

**Preview search.** The results demonstrate that changing the color of the old distractors had little effect on search. This is consistent with the results of other studies in which effects of color change in old items in preview search were examined (e.g., Watson & Humphreys, 2002). Furthermore, the effects of whether the target carried the old majority color or the old minority color were unaltered by the change of the color of the preview. This result counters an account of the color ratio effects in terms of noninhibitory color grouping between the old and new displays. In the color change condition, any such grouping should be disrupted. Despite this, RTs were longer to targets in the new minority color, which was also carried by the old distractors when they were initially present. The result, however, is consistent with an explanation in terms of color-based inhibition of old items (Treisman & Sato, 1990). This inhibition is carried across to new stimuli, lengthening RTs to targets in the inhibited color even if the color of the old distractors then changes (Braithwaite et al., 2004).

**Probe trials.** As with the previous experiments, RTs were shorter on probe trials than on search trials, indicating that probes could be detected quite efficiently. Nevertheless, probe detection was influenced by the relations between the old and new items. The results replicated the pattern in Experiment 3. In essence, probes were difficult to detect if they fell on stimuli that carried the original majority color in the preview; this resulted in longer RTs to probes in the old majority color, and also

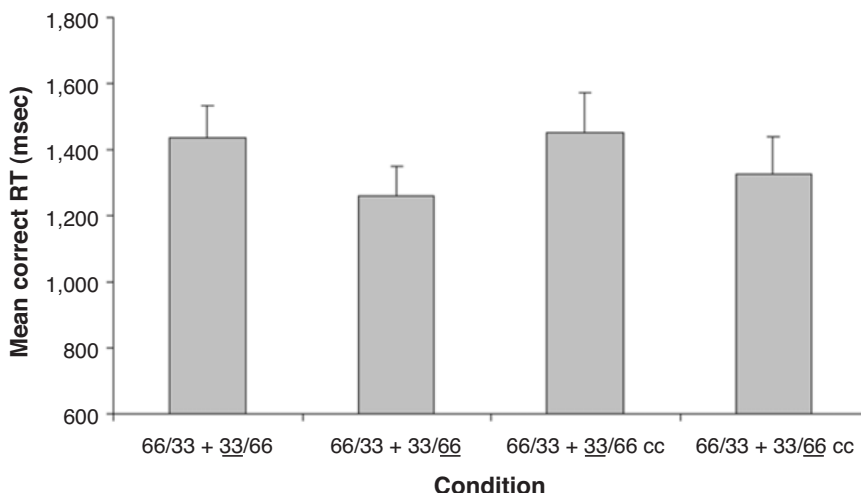
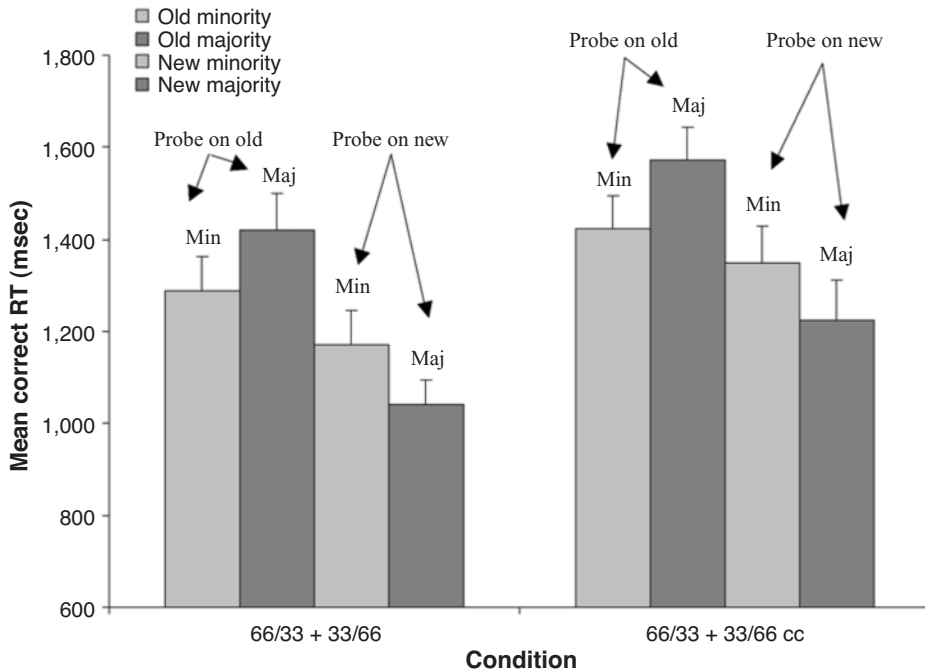


Figure 8. Mean correct reaction times (RTs, in milliseconds) for target search trials from Experiment 4. Underscores denote the groups within which targets occurred.



**Figure 9.** Mean correct probe reaction times (RTs, in milliseconds) for both the 66/33 + 33/66 and the 66/33 + 33/66-cc preview conditions from Experiment 4. RTs are shown here as a function of set (old vs. new) and group (minority vs. majority).

in longer RTs to probes in the new minority group (which shared its color with the old majority). The crucial new finding is that this occurred even though the color of the old items had changed. Two important conclusions follow from this. The first concerns the lengthening of RTs to probes falling on new distractors in the minority color in search displays. These distractors no longer shared their color with the old distractors (which changed color at the onset of the search display). Hence, they should not be assimilated into the old color group. We suggest instead that this effect, on new distractors, is caused by inhibitory carryover from properties shared by the majority of suppressed old stimuli (cf. Treisman & Sato, 1990). Inhibition of the properties of the old majority biases attention away from new stimuli carrying the same features. The second conclusion concerns the lengthening of RTs to probes falling on old majority distractors. The interesting thing here is that, in the color change condition, these old distractors were shown in a new color when the probe appeared. Thus, the long RTs to these stimuli cannot reflect color inhibition alone, since their (new) colors should

not be inhibited. Rather, there seems to be lingering suppression based on these items' being originally grouped by the old majority color. That is, Experiment 4 provides new evidence for both color-based inhibition and inhibition of the old majority group (even when the preview items change color).

An alternative account of the data in the color change condition is that they reflect slow perception of color itself. For example, if coding of the new (changed) color is slow, then the old color might be carried over when the new display is processed. However, the random letter search task used throughout this study was in fact relatively difficult, with search RTs being on average about 1,400 msec in the color change condition in Experiment 4. Probe RTs were on the order of 1,500 msec. At these long latencies, it is almost certain that the color change would be coded before the target is selected. Nevertheless, attention remained biased away from items that were in the majority color in the preview. This account seems unlikely.

Finally, one other point to note is that RTs to probes were longer overall in the color change relative to the no-change condition. This is not particularly surprising since generally more "change" took place in the former condition, against which probes had to be detected. These effects were additive with whether probes were on new or on old items, or whether or not they carried the original majority color. This suggests that the variations of interest here (i.e., whether probes were on old or on new items,

**Table 4**  
Overall Error Percentages for Target Search and Probe Detection Trials in Experiment 4

Condition	Target Search	Probe Detection
66/33 + 33/66	3.84	1.95
66/33 + 33/66 cc	3.00	2.78



and whether or not the probed items carried the original majority color) were independent of effects reflecting the overall amount of change taking place when probes appeared.

## GENERAL DISCUSSION

In four experiments, a luminance-probe technique was used to examine attentional allocation in preview search. These experiments have provided evidence, for the first time, of both inhibitory coding of old groups and inhibition based on the feature properties of old groups (i.e., their color). We summarize the major findings below before discussing implications for current models of attentional selection. Collectively, Experiments 1–4 demonstrated the following: (1) A preview advantage in search performance was modulated by the color relations between the old and the new items (Experiments 3 and 4). (2) Detection of probes that fell on old relative to new items was poor. This effect could not be attributed to low-level sensory changes (e.g., masking, neural fatigue). The effect was also not caused by automatic attentional capture by new stimuli, since it did not occur unless the participants were set to search for a new target (Experiment 2). (3) Differences in probe detection emerged as a function of whether the probes fell into the minority or the majority group of old distractors. This provides new, direct evidence of differential inhibition according to the strength of the distractor group. In both cases, however, probe detection remained worse on old than on new distractors. Finally, (4) both target search and probe detection were influenced by the color of the preview set even when these items changed color when the search display appeared. We suggest that the drop in probe detection on old items reflects group-based inhibition. The drop in detection on new items carrying the old color is attributed to feature-contingent carryover of inhibition.

The data provide direct evidence of several sources of inhibition involved in rejecting old distractors in preview search. We now discuss (and reject) alternative accounts for the effects reported before going on to consider a general framework for the results.

### Alternative Accounts of Preview Search

**Onset capture.** Donk and Theeuwes (2001) proposed that the preview benefit in search was due entirely to automatic attentional capture by new onsets (in the search display). Our data counter this account in several ways. For instance, in Experiment 1 RTs were significantly longer for probes on old distractors not only relative to probes that fell on new distractors but also relative to probes in the full-set baseline. The differences between probes on old and on new distractors may be due to new onset capture; however, the drop in probe detection on old distractors in comparison with probe detection in the full-set baseline is less easy to attribute to new object

capture. Moreover, the results of Experiment 2 showed that search RTs were influenced by the preview duration, even though the preview and search displays could always be temporally segmented. Search was speeded when the preview's duration increased. This long time course of performance should not arise if search is determined only by new onset capture. Experiment 2 also showed clear effects of the observers' attentional set on the probe detection effects, undermining the idea of automatic onset capture.

In addition to the above, the onset capture account fails to explain the effects of color similarity and grouping that were evident in the search and probe detection data in Experiments 3 and 4. In fact, some results are in completely the opposite direction to that expected from any straightforward onset capture effect. For instance, in standard search displays (with all the items presented together), RTs tend to be shorter to targets that appear in the minority group (see Bacon & Egeth, 1997; Egeth et al., 1984; Kaptein et al., 1995; Moore & Egeth, 1998; Poisson & Wilkinson, 1992). However, we demonstrated that search and probe RTs are lengthened to stimuli in the new minority group, if it is preceded by a matching but larger group of old distractors (see also Braithwaite, 2002; Braithwaite et al., 2003). These results strongly indicate that preview search is influenced by the old distractors as well as by the new stimuli.

There are other variants of the onset capture account, but these too have difficulty explaining our results. One variant is that attention is captured not just by the onsets of the search items but by a color change signal generated when the new items appear. If the color change signal is larger when the change is from an old minority to a new majority color, then attention could be captured by the new majority color. This, in turn, would lengthen RTs to targets in the new minority group, as we observed. However, this proposal fails to predict the differences in probe detection that we observed when probes fell on old distractors that were either in the majority or in the minority color (in Experiment 3). Since both types of distractor are in the old set, neither should be attended. However, we found that the cost to probe RTs was greater for the old majority set (see also Braithwaite et al., 2003, for further evidence against "capture-by-change-signal" accounts).

**Inhibition or strategy?** A somewhat different account of the preview effects is that they are due to participants' use of color differences between the old and new displays to direct a strategic bias through the new stimuli. For example, if the majority of old items are red, it might be that participants predict that the target will be in a different color; in Experiment 3 this would benefit search for targets in the new majority, as we observed. There are several problems with this account. One is that the targets were actually *less* likely to be in the new majority color than in the new minority color when unequal colors were used in the preview and search displays. Consider a trial in which the initial set consisted of 66%

red letters and 33% green letters, to which a target display of 33% red and 66% green letters was added. Within the new set, the target was two times less likely to be any particular green letter than any particular red letter. If the participants adopted a strategic bias in search, they ought to favor new letters in the minority color and not those in the majority color (see also Braithwaite & Humphreys, 2003, and Braithwaite et al., 2003, for detailed assessments and rejections of this account). The data from Experiments 3 and 4 arose not because of but in spite of the probability that the color of the letters in the new display would predict the target. The data on differential detection of probes on old distractors are also contrary to this account. Any prediction about the new stimuli should not impact differentially on old letters in the majority or minority color. Despite this, we observed just these differences.

**Temporal grouping.** As well as helping to counter some accounts of preview search, the present results point to a factor that has not previously been highlighted: the grouping of old distractors by color. Two findings are important here. One is the variation in probe detection as a function of whether probes fell on majority or minority distractors (Experiment 3). This suggests that old items are segmented into majority and minority groups. The second finding is that, in Experiment 4, probes were difficult to detect on old majority distractors even when the distractors changed color at the onset of the search display. Here, the old items seem to retain their status as a group despite the change in their actual featural properties. This continued status influenced probe detection. The effects of color grouping, evident on probe detection within the old set, indicates that temporal grouping cannot be the only factor determining preview search. Jiang et al. (2002a, 2002b) proposed that temporal segmentation between the old and the new displays could be sufficient to generate a preview benefit based on selective search of new items. However, were that sufficient, then the evidence for color grouping should not have occurred. For instance, both majority and minority items should be coded as being in the old group; despite this, we found differential probe detection performance.

The temporal grouping account also fails to explain the data on attentional set (Experiment 2). We failed to find a difference in probe detection when the participants were not set for search, yet the temporal differences between the displays were constant. Temporal differences alone are not sufficient. Indeed, the evidence of color carryover to new items (Experiment 4) also points to the importance of additional factors.

**Location-based inhibition.** The original account of preview search advanced by Watson and Humphreys (1997) was that old items were deprioritized for selection by “feature-blind” location-based inhibition. In this account, the underlying assumption was that the inhibitory strength at all old locations should be the same. Indeed, probe data provided by Watson and Humphreys (2000) indicated that inhibition was equivalent at all the old lo-

cations. Like the idea of temporal grouping, the location-based inhibition account is not sufficient to explain our data. This account (like the others considered above) fails to explain why probe detection differed on old majority and minority stimuli (although all should be inhibited equally). It also fails to explain the effects of color carryover. We conclude that, in addition to any effects of temporal grouping and location-based inhibition, both color grouping and color inhibition have effects on performance. Current accounts of preview search must be expanded to explain these results.

### **A Functional Account of the Findings: Multiple Inhibitory Codes?**

**Direct feature-based inhibition.** Treisman and Sato (1990) proposed that visual search could operate efficiently if participants could inhibit a whole “feature map” that was activated selectively by distractors. Such feature map inhibition would help to prevent irrelevant distractors from being selected. The same idea could be applied here, but extended to the notion of inhibition across time as well as space. For instance, inhibition of the dominant color in the preview may be useful for deprioritizing preview letters from search. The cost of this becomes clear when new items appear in the same color as the old stimuli. Here, the consequence of successful inhibition of the old items would be an inhibitory feature-based carryover to new items. Watson and Humphreys (1998) argued that new items could reset inhibition in a color map if they outnumbered the old inhibited items. In these situations, the occurrence of a large change signal within the color map representing the old items would disrupt the feature-based inhibitory coding directed toward those items. This resetting idea is consistent with our data, showing that there is stronger carryover onto new minority distractors bearing the color of the old majority.

**Group-based inhibition.** In addition to our evidence for color-based carryover effects, our probe detection data indicate effects of color grouping on performance (Experiment 4). To explain the latter effects, we propose that (in addition to any feature map inhibition) there is also grouping and suppression of like distractors, according to their common color. The group-based account assumes that color helps to determine the degree of inhibition allocated to locations in space, whereas color itself is not directly inhibited. In this sense, inhibition is “feature guided” to the appropriate locations in space. This evidence of effects of color grouping complements other evidence of the influence of distractor grouping in preview search. For example, Watson (2002) demonstrated effects of motion-based grouping. Kunar, Humphreys, Smith, and Hulleman (2003) have also presented evidence that there is configural coding of old distractors. They showed that search is disrupted when old items change their configuration but not when there is movement without configural change. It appears that several forms of grouping can aid the segmentation of old and

new stimuli, helping to prevent old items from being selected. It may even be that effects of color on grouping are separable from effects of color map inhibition. Consider studies in which the properties of the previews change on presentation of the search display. Watson and Humphreys (2002) examined effects of isoluminant color changes and found that they did not have any impact on search. Since the map for the changed color should not be inhibited, such color changes should make the old distractors compete again for selection. This was not the case. A complementary argument can be made from Experiment 4 here. We changed the color of the old distractors but found that probe detection remained impaired to the majority relative to the minority old items. This cannot be based on color map inhibition. Instead, we suggest that items group through color similarity and that grouping coordinates inhibition applied to the old distractors. Duncan and Humphreys (1989) suggested that grouping in search could operate through a process of spreading suppression. If inhibition spreads in a multiplicative fashion, then there will be greater inhibition of the old majority in comparison with the old minority group. However, although the grouping argument accounts for our data on probe detection, it does not explain the effects on detecting probes on new distractors. Here, we found that detection was disadvantaged on new items carrying the old majority color, even though the color of the old items changed (Experiment 4). This disadvantage cannot be due to grouping of new items with the old majority on the basis of their common color. We conclude that both color map inhibition and color grouping need to be considered to explain the full pattern of the results.

**Multiple inhibitory codes.** The data from the present study indicate that there may be several contributions to the preview benefit in visual search, at least two of which are inhibitory in nature. From the results, we can also begin to ask about the relations between the different inhibition effects. The data from Experiment 4 are most relevant here. These data suggest that old items are grouped using common color in addition to any other grouping cues (such as their common onset; cf. Jiang et al., 2002a, 2002b). This old group is inhibited to facilitate its segmentation from the new stimuli. On top of this, there is also inhibition of a feature map representing at least the dominant group. However, when the color of the dominant group changes, there is still a cost to a probe that falls there. Thus, group-based suppression seems to be independent of feature map inhibition, since any feature map inhibition should not impact probes presented on an old distractor in a new color.

The notion of independent group-based and feature map inhibition fits with other findings on preview search. For example, several studies have demonstrated that color differences between old and new items are not necessary for the preview benefit (Olivers et al., 1999; Theeuwes

et al., 1998), so that feature map inhibition is not a necessary process. This is also shown by evidence that color changes within the old set are not disruptive to search (our Experiment 4; Watson & Humphreys, 2002). On the other hand, color carryover effects have been reported (Braithwaite, 2002; Braithwaite & Humphreys, 2003; Braithwaite et al., 2003, 2004; Olivers & Humphreys, 2002, 2003), demonstrating that relations between old and new items can contribute to performance. Similarly, data showing effects of configural change are consistent with additional object-based representations playing an important role in preview search performance (Kunar et al., 2003; Watson, 2002).

Although we have discussed color map inhibition and object-based suppression within the context of preview search, it is likely that these processes are also involved in “standard” search tasks (when all the items appear together) to some degree. As we have noted, theorists have previously posited a process of within-group spreading suppression to explain how distractors are rejected in search (Duncan & Humphreys, 1989). We have provided direct evidence of this in the form of differentially impaired probe detection on old distractors in majority and minority colors (Experiment 3). Likewise, Treisman and Sato (1990) first proposed that feature map inhibition would provide a mechanism of efficient distractor rejection, and we have found evidence of this from carryover effects on new stimuli. Previously, these two ideas of how distractors are rejected in search have been contrasted against each other (see Duncan & Humphreys, 1992). Our data, though, suggest that both processes may hold under the present circumstances.

One clear difference between preview and “standard” search, though, is the temporal difference between old and new distractors in preview search. This may enable some inhibitory processes of distractor rejection to be set up prior to the appearance of search displays. It may also facilitate grouping between one set of distractors without competition of grouping from the second search set. The consequence is that probe detection on this distractor set is impaired.

In sum, by combining visual search with probe detection we have provided important new evidence on the process leading to the efficient selection of new targets. This probe technique has fractionated group-based and feature-based inhibition, which have not been separated by prior carryover effects in target search alone. These processes may also operate in “standard” search tasks, but they are enhanced by the temporal difference between the stimuli under preview conditions. The data show that, in certain circumstances, there are negative consequences for successful distractor rejection; there is some degree of attentional blindness for new stimuli that are similar to old rejected distractors. Collectively, the findings presented here suggest that current accounts of preview search require substantial revision.

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## NOTES

1. This luminance singleton version of the probe procedure was used for several reasons. One was the nature of our random letter displays. Since we used heterogeneous letter distractors, it was impossible to present a probe in the same relative location within the shape across all distractors. Presenting probes in different positions relative to distractors could generate unwanted noise in the study. Furthermore, by brightening one of the letters that would have been present anyway, we kept probe displays as similar as possible to the actual search displays.

2. Note that the comparisons we conducted were all planned comparisons. It has been suggested that if the comparisons are planned there is little reason for correction (Clark-Carter, 1997). However, nearly all of the relevant significant effects in our analysis were significant at the  $p < .01$  and  $p < .001$  levels and thus did not disappear following correction.

3. The majority color in the preview (minority color in the new display) was fully counterbalanced and was presented randomly on each trial.

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