Vision Research 50 (2010) 346–356

Contents lists available at ScienceDirect

Vision Research

journal homepage: www.elsevier.com/locate/visres

Measuring the spread of spreading suppression: A time-course analysis of spreading suppression and its impact on attentional selection

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ARTICLE INFO

Article history:
Received 18 December 2008
Received in revised form 1 October 2009

Keywords:
Visual search
Selective attention
Inhibition
Awareness

ABSTRACT

We report three experiments investigating the time course of spreading suppression in visual search using preview conditions. A novel color-change procedure was employed in which a target letter changed into a new (singleton) color at various intervals after the onset of the search display. Performance when the singleton was unique across both preview and search displays was compared with that when the singleton carried the color of the preview display. Relative to the unique singleton baseline there were no costs to targets carrying the preview color when the singleton onset occurred shortly (80 ms) after the onset of the new, search display; however, costs emerged as the SOA increased before subsequently decreasing again. In addition, relative to when all the items appeared together (the full-set search baseline), there were benefits when the singleton replaced a target carrying the same color as the distractors in a search display, with the facilitation effect showing a marginal effect at an earlier time than the cost found when the change was to the preview color. The data suggest that there are contrasting time courses to attentional guidance to targets and the suppressive rejection of distractors in visual search.

1. Introduction

Current theories of visual search suggest that target detection is based on both the positive guidance of attention to a target and the biasing of attention away from distractors. For example, Guided Search Theory (GST: Wolfe, 1994, 1998) proposes that a top-down expectancy for the features of the target give the target a competitive advantage in the competition for selection. At the same time, lateral inhibition between distractors with common features will lead to these items being suppressed and weak competitors for selection. Attentional Engagement Theory (Duncan & Humphreys, 1989, 1992) similarly assumes that attentional resources are attracted to stimuli that match the template for the target, while distractors are subject to a process of spreading suppression through the features they share.

One procedure that allows these processes to be studied, by isolating aspects of distractor suppression from attentional guidance to a target, is preview search (Watson & Humphreys, 1997; see Watson, Humphreys, and Olivers (2003); for a review). Under preview search conditions one set of distractors is presented prior to the target and the other set of distractors. Provided the preview occurs over 400–500 ms or so prior to the second search display, the preview distractors can effectively be ignored. Search is then typically faster and more efficient under preview conditions than in a "full-set" baseline condition when all the distractors appear together, and search can be as efficient as in a "half-set" baseline when only the second set of stimuli is presented (Watson & Humphreys, 1997). This has become known as the *'preview benefit'* to search.

There is evidence that this 'preview benefit' reflects both positive expectancies to targets and the active inhibition of distractors. Evidence for the suppression of previewed distractors comes from studies showing that there is a reduced detection of probes presented on or near an old distractor relative to detection of probes on new distractors or even background regions (Braithwaite & Humphreys, 2007; Braithwaite, Humphreys, & Hulleman, 2005; Braithwaite, Humphreys, Hulleman, & Watson, 2007; Humphreys, Jung-Stalman, & Olivers, 2004; Olivers & Humphreys, 2003; Watson & Humphreys, 2000). In addition, recent studies have shown that it is difficult to detect new targets that carry a feature of the previewed items (i.e., color). One suggestion is that this "negative color carry-over effect" reflects a form of spreading suppression, following inhibition of the features of the preview stimuli (Braithwaite & Humphreys, 2003, 2007; Braithwaite, Humphreys, & Hodsoll, 2003, 2004; Braithwaite et al., 2007; Olivers & Humphreys, 2003). Importantly, this effect occurs when participants are 'set' to ignore irrelevant items and it is reduced when observers engage in a dual-task or are not set to ignore the preview display (Braithwaite & Humphreys, 2003, 2007; Braithwaite

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doi:10.1016/j.visres.2009.11.019

et al., 2003, 2007). There is also evidence indicating effects of a positive expectancy directed towards new stimuli. For example, the bias against stimuli carrying the features of old distractors can be reduced when participants hold an expectancy that the target will have a particular feature value (Braithwaite & Humphreys, 2003; Braithwaite et al., 2003, 2004).

Braithwaite et al. (2005) showed that the preview procedure could be used to isolate separate effects due to color grouping of distractors and effects of distractor suppression.

Braithwaite et al. (2005) had conditions where the color of the old preview items changed when the new stimuli were added to the display. Items in the preview display could be in one of two colors (red or green), – but these colors were not represented equally. For example, one color was carried by the majority of the stimuli (i.e., 66% of the items were red) and another color was carried by the minority of the items (33% green). When the second search display appeared, the previewed items were given new colors. Now, the majority group of items turned blue and the minority group turned yellow. Braithwaite et al. (2005) found that new targets carrying the same color as that held originally by the majority of the old distractors (red), still remained difficult to detect – even though these new targets could not group with the old distractors now on the basis of their color. This is the negative color carry-over effect. In addition, a luminance-based probe detection procedure was used to measure where attention was allocated in the search displays. Probes were difficult to detect if they fell on old items that carried the initial majority color (even though that color had changed when the new items appeared). This is consistent with inhibition of the old distractors based on these items grouping by color, with the same items remaining grouped even when their common feature changed. These data suggest that there is suppression of both the old groups of items and the color associated with those items.

Interestingly, although the term spreading suppression suggests a process that operates across time, there have been no published investigations into the time course of this process. This is an important omission given that the time course of processing can represent an important constraint on attempts to develop formal models of visual attention. The planned investigation here attempted to rectify this by using a novel probe procedure to examine the time course of suppression in search.

2. The present study

The aim of the present study was to examine the time course of spreading suppression in search. To do this, we introduced a new 'singleton' probe procedure, to measure the allocation of attention across time. In this procedure we used a preview search task in which the old items were presented in one homogeneous color (i.e., red letters) and the new distractors another (i.e., green letters). The target letter, appearing along with the new distractors, could be either red (carrying the color of the old items) or green (the same color as the new distractors). Previous studies have reported a negative color carry-over, where RTs are slowed to a target carrying the color of the preview display (i.e., slowed RTs to red rather than green targets: Braithwaite & Humphreys, 2003, 2007; Braithwaite et al., 2003, 2004, 2005, 2007; Olivers & Humphreys, 2003). In our new procedure, on a minority of trials the target could change into a new color at different time intervals, following the onset of the second display. This new color was always a singleton within the whole display (i.e., a blue item).[1]

We assessed whether the ease of detecting this new singleton probe varied according to whether it fell on a target initially carrying the color of the preview (red) or the color of the new stimuli (green). Performance with each kind of probe in the preview condition was also compared to that in a full-set baseline, when the search items all appeared together. Consider performance when the probe falls on a new, red target, which may be subject to spreading suppression following inhibition of the features of the preview, compared with when it falls on a green target which should not be subject to suppression. If the probe occurs prior to the target being suppressed, then the probe may be detected quickly efficiently when it appears on a red or green target. However, after there has been spreading suppression from the preview to the red target, then probes replacing a red target may be more difficult to detect than probes replacing a green target. There may thus be a temporal window where, in the preview condition, the detection of probes falling on red targets worsens compared with the detection of probes on green targets, as the interval increases from the onset of the search display to the onset of the probe (as there is more time for suppression to spread to the red target). This difference between probes on red and green targets should not occur in the full-set baseline, there should not then be differential suppression of one target compared with the other. Now any comparison between the detection of probes on red targets in the preview condition and red targets in the full-set baseline is difficult, since the suppression of previewed distractors will mean that attention is guided more easily to the target in the preview condition, and this may offset effects of spreading suppression to the target. The net result may be little difference between probe detection on red targets in the preview and full-set conditions. However, clearer predictions can be made for the comparison between the preview and the full-set conditions for green targets (which should not be subject to spreading suppression). Under preview conditions attention should be guided to green targets more efficiently than in the full-set baseline. .This enhanced guidance of attention to the target should make probes easy to detect when they then replace the target. Compared to when probes fall on the same targets in full-set search, performance should be facilitated. The variation in this facilitation effect, as a function of when the probe is presented, will provide information about when attentional guidance to the target is operating. A schematic illustration of the stimuli and method is given in Fig. 1.

3. Experiment 1

3.1. Methods

3.1.1. Participants

Twenty-one participants (16 female, 2 left-handed) took part for course credit or small payment. The age of participants ranged from 18 to 24 years with a mean age of, 21 years. All were undergraduate or postgraduate students at the University of Birmingham. All had self-reported normal (including normal color vision) or corrected-to-normal vision.

3.1.2. Stimuli and apparatus

All the stimuli and the conditions were generated by computer programs written in Turbo Pascal (v7) and were run on a Pentium PC fitted with a 17-in Samsung monitor. Viewing distance was not fixed but was approximately 60 cm. The stimuli consisted of colored red and green capital letters which were luminance-matched via a color flicker/fusion flicker test carried out on each participant. These were displayed on the plain black screen background. The singleton color (blue) was then matched to the green (RGB) color values provided from the previous flicker fusion test. Thus, all three

[1] This singleton-change manipulation acts as a kind of probe-event. For conciseness and clarity we merely refer to it as a 'probe' from this point forward – though it is important to be aware that the event itself does not involve the presentation of a new probe item – just a color-change taking place in the existing target item.

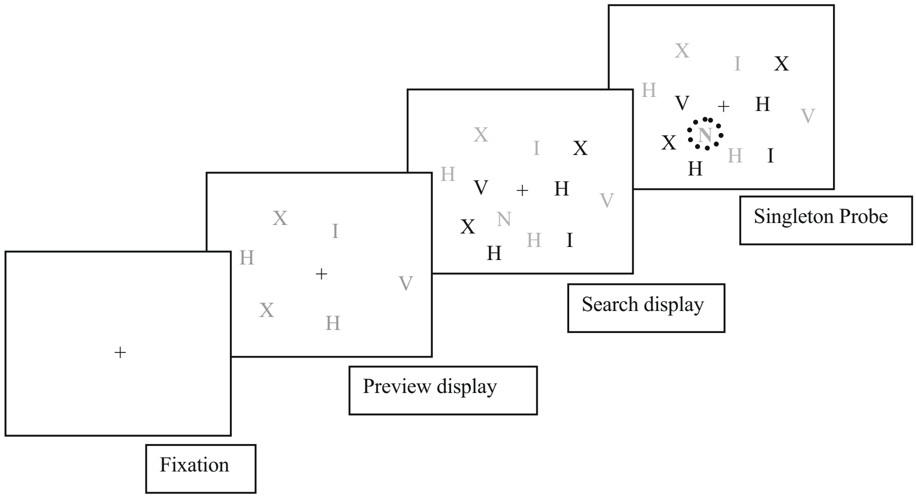

Fig. 1. A schematic illustration of the stimuli and protocol employed in the present study. A preview search condition is illustrated. A fixation cross is presented for 1000 ms. This is followed by the presentation of the red preview items (light-grey here). These items are irrelevant and must be ignored. After 1000 ms preview duration, the second search display is presented containing green distractor items (dark grey here) – and the target (a letter 'N' in this case). Note that here the target initially arrives in the same color as the preview items. Shortly after arriving, and at varying SOAs, this target can, on occasion, change color into a new singleton (blue) item. This is illustrated here by the dotted circle around the target letter (note – no circle was present in the actual display, it is for illustrative purposes only).

colors employed were calibrated to be isoluminant to each other for each participant. These letters were randomly assigned to an invisible 48 cell, circular matrix consisting of three concentric circular ring grids. The distance from central fixation to the middle of the cells of the first ring measured approximately 20 mm (containing 8 cells), the second ring 40 mm (containing 16 cells) and the third 60 mm (containing 24 cells). Distractor letters consisted of the upper case letters H, I, V, X. The target letters were either a Z or 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 display with the restriction that at least one distractor letter of each type was presented. Display size was fixed at 24 items. The preview conditions involved the presentation of half (12 items) of the distractor letters first (in the first preview display) followed by the remaining half (12 items) in the second, search display. The full-set baseline consisted of a single presentation of both displays combined (consisting of 24 items in total). The target letter could be initially presented in either red or green equally often.

3.1.3. Design and procedure

The experiment consisted of two main forms of trials. These were (i) display-change SOA trials where the target would change into a singleton color (as a kind of probe). These occurred infrequently 25% of the time. In addition there were (ii) standard search trials (no-probe event) where no items changed color. These occurred more frequently 75% of the time. In the standard (no singleton probe) trials, there were two factors. The first factor was condition: a trial was either a full-set baseline trial, where all 24 display items were presented simultaneously, or a preview trial where observers first saw half of the display (12 items) followed 1000 ms later by the remaining distractors and the target (12 items). The second factor was target color, where the target could be either red or green. For the display-change trials, a third factor was added to condition and target color. This factor was the display-change SOA. In every display-change trial, the target would change into a blue singleton. This could happen after either 80 ms or 200 ms after the target had been presented and occurred equally often for red targets and green targets. Full-set baseline and preview trials were run in separate blocks of 320 trials. So, each block contained 25% display-change trials and 75% standard trials, randomly intermixed.

Each trial began with the presentation of a plain white fixation cross presented on a plain black background. This fixation cross remained visible until the end of each trial. For the preview conditions, this was followed by the presentation of the preview display items, followed shortly afterwards by the search display. The preview items were all red in color. This was followed by the second search display consisting of green distractors and a target item which could be red (same color as the preview) or green (same color as the new items) equally often. When the target was red, it was a singleton in terms of the other green new items it arrived with. The full-set baseline consisted of presenting the preview and search display (described above) simultaneously with the preview duration removed.

In the preview condition, the red target was a singleton in the new search display but carried the color of the old distractors, In this condition we would expect a cost to performance (relative to when the target is green and matched its color with all the new items and none of the old). In all cases RTs were measured from the arrival of the search display. The experiment lasted approximately 55 min.

3.2. Results

All data were trimmed for response errors and outliers (± 2.5 standard deviations) and any responses faster than 200 ms (this procedure removed <2% of the data). This procedure was used in all subsequent experiments. The data were also explored for 'early detections' on singleton probe trials – where observers may have responded to the target before it had the opportunity to undergo its color change. There were no such instances. All the data were then analyzed via a series of within-subjects ANOVAs carried out on the remaining mean correct RTs.

3.2.1. Standard search trials (no singleton probe)

Search performance from the standard (i.e., no singleton probe events occurring) full-set baseline and preview conditions was assessed via a 2×2 (Condition $\times$ Target color) ANOVA. There were significant main effects of Condition, $F(1, 20) = 5.99$, $p < .05$, and Target color, $F(1, 20) = 68.17$, $p < .001$, along with a reliable Condition $\times$ Target color interaction, $F(1, 20) = 53.108$, $p < .001$. With green targets, RTs were slower in the full-set baseline than the preview condition, $F(1, 20) = 117.58$, $p < 001$. For red targets there was

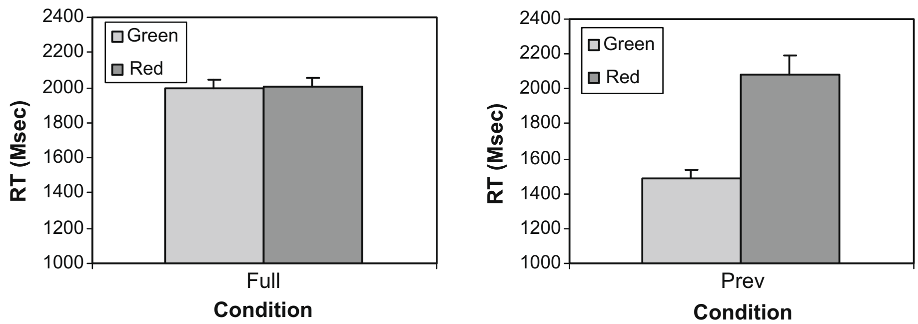

Fig. 2. Mean correct RTs for standard (no singleton probe) visual search trials from both the full-set baseline (left) and the preview search (right) conditions from Experiment 1.

no difference between the full-set and preview conditions, $F(1, 20) = 2.90$, $p = .104$ (see Fig. 2).

3.2.2. Display-change singleton probe trials

RTs on singleton probe trials were considerably faster than on the standard search trials (i.e., there was an advantage even relative to the detection of green targets under preview conditions). Thus, there was evidence that the novel colored probe could draw attention efficiently. The singleton probe trials from the full-set and preview conditions were compared using a three-way (Condition $\times$ SOA $\times$ Target color) within-subjects ANOVA. The main effect of Condition was not significant, $F(1, 20) = .028$, $p = .868$, though there were reliable mains effect of SOA, $F(1, 20) = 8.05$, $p < .02$, and Target color, $F(1, 20) = 18.859$, $p < .001$. There were significant interactions between Condition and Target color, $F(1, 20) = 11.145$, $p < .01$, SOA and Target color, $F(1, 20) = 24.131$, $p < .001$, and Condition $\times$ SOA $\times$ Target color, $F(1, 20) = 4.54$, $p < .05$ (see Fig. 3).

RTs for singleton probe trials were analyzed separately for each SOA to test for differences between the preview and full-set baseline conditions for red and green targets. With an 80 ms SOA there were no significant effects (all $Fs < 1$, all $ps > .400$). However, with a 200 ms SOA both the main effect of Target color and the Condition $\times$ Target color interaction were significant, $F(1, 20) = 43.657$, $p < .001$; and $F(1, 20) = 10.620$, $p < .01$, respectively. The main effect of Condition was not significant, $F(1, 20) = .50$, $p = .829$. A paired *t*-test revealed that, in the 200 ms SOA preview condition, probes on red targets were detected more slowly than probes on green targets $t(20) = 5.5$, $p < .001$. In contrast, there was no difference in the detection of probes replacing red and green targets in the full-set baseline ($t < 1.0$). Relative to probes on green and red targets in the full-set baseline condition, probes on green targets were easier to detect in the preview condition $t(20) = 26.3$, $p < .001$, while probes on red targets were harder to detect $t(20) = 23.5$, $p < .001$.

3.2.3. Errors

The overall level of errors for the Experiment was low at 3.25%. There were no indications of a speed-accuracy trade-off. Probe detection accuracy was explored in the same manner as the probe RT data (described above). There were no significant main effects or interactions. (all $Fs < .730$, $ps > .404$; see Table 1 for the full-set of means).

3.3. Discussion

In the full-set baseline condition, there were no effects of color on either standard search trials (differences between red and green targets in search RTs) or singleton probe trials (no differences between RTs to probes replacing red and green targets). This suggests that there were no inherent discontinuities in the color values employed in the present study, making either red targets or blue probes replacing on red targets particularly difficult to detect. In contrast, significant effects of color emerged in the preview condition. For standard search trials, RTs to green targets were facilitated in the preview condition compared with the full-set baseline. This is the *preview* benefit in search. In contrast, there was no facilitation for red targets in the preview condition compared with the full-set baseline and, in the preview condition, RTs to red targets

Table 1
Mean percentage error (%) for Experiment 1, for the singleton probe trials broken down across condition, SOA, and the target color it replaced.

Condition	80 ms (SOA)	200 ms (SOA)
Full (green)	3.57	4.05
Full (red)	3.81	3.82
Preview (green)	4.52	4.05
Preview (red)	3.57	5.1

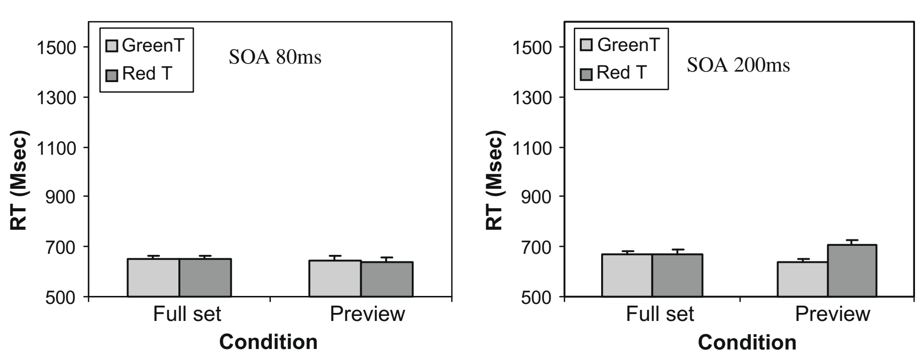

Fig. 3. Mean correct RTs from the singleton probe trials, plotted for the target color the probe replaced and condition for SOA 80 ms (left) and SOA 200 ms (right) from Experiment 1.

were slowed relative to those to green targets. This replicates the *color-based carry-over effect* reported previously (Braithwaite & Humphreys, 2003, 2007; Braithwaite et al., 2003, 2004, 2005, 2007; Olivers & Humphreys, 2003). The result is consistent with there being a suppressive bias against the color of the old items. Interestingly, the difference between red and green targets in preview search here is somewhat larger than the effects reported in previous studies at similar display sizes (cf. Braithwaite & Humphreys, 2003, 2007; Braithwaite et al., 2003, 2007). We suggest that the negative carry-over effect was particularly effective here because the red target was a singleton in the new search display. In prior studies the target has often been one of a minority set of new items carrying the color of the old items. In this case, the larger sub-set of new stimuli may be better able to withstand any spreading suppression from the old distractors, based on their common color. The size of the effect is striking given that the singleton red target should be highly salient, if attention is captured by the new search items (cf. Donk & Theeuwes, 2001, 2003). We return to consider this point in Section 6.

Not surprisingly, RTs were faster on trials where the target changed into a novel singleton probe, consistent with this item attracting attention. However, the data also demonstrate that the detection of the singleton probe was affected by the color relation between the preview and the target. At the longer of the two singleton probe SOAs (200 ms) there was an effect of whether the probe replaced a red or a green target in the preview condition. RTs were slowed when the probe replaced a red target compared with when it replaced a green target. This is consistent with color-based suppression spreading from the previewed distractors to the target, when the target carries the same (red) color. The emergence of this apparent inhibitory effect at the longer probe SOA suggests that the color-based suppression from the old to the new stimuli takes time, and is not effective at the onset of the search display. Compared with the full-set baseline, the preview condition produced small benefits for the detection of probes on green targets and small costs for the detection of probes on red targets. The results indicate there was enhanced guidance of search to the green target in the preview condition along with some costs to selecting the red target; the costs occurred even though the selection of new stimuli should benefit from distractor suppression in the preview condition.

Although there was a significant cost at 200 ms to red targets in the preview condition, this cost was small. The small magnitude of the effect may be because the color-change singleton was so salient that it produced bottom-up guidance of attention in all conditions, minimizing any preview effects. Another possibility, however, is that the SOA was not long enough to generate maximal spreading suppression. As a consequence, one prediction is that the effect will grow with an increasing SOA. If the cost is based on a slower acting top-down bias against the irrelevant items, then the magnitude of the spreading suppression may increase with a more prolonged SOA duration. If true, then it would become important to plot the progression of this effect and its time course (i.e., its build up and dissipation). Experiment 2 and Experiment 3 investigated this by employing a similar design to that of Experiment 1, but with longer SOAs: 350 ms and 500 ms (Experiment 2) and 750 ms and 1000 ms (Experiment 3), respectively.

4. Experiment 2

4.1. Methods

4.1.1. Participants

Fifteen participants (10 female, all right-handed) took part for course credit or small payment. The age of participants ranged from 18 to 32 years with a mean age of, 23 years. All were undergraduate or postgraduate students at the University of Birmingham. All had self-reported normal (including normal color vision) or corrected-to-normal vision.

4.1.2. Stimuli and apparatus

The stimuli were similar to those employed for Experiment 1 except that now different SOAs were assessed.

4.1.3. Design and procedure

The design and procedure matched that of Experiment 1. The crucial difference for Experiment 2 was that two new singleton probe SOAs (350 ms and 500 ms) were employed to assess attentional allocation.

4.2. Results

The data were made fit for analysis in the same manner as that described previously. In addition, there were no instances of 'early detections' on the increased SOAs employed in the singleton probe trials.

4.2.1. Standard search trials (no singleton probe)

Search performance from the full-set baseline and preview conditions was assessed via a 2 × 2 (Condition × Target color) ANOVA. Both the main effects of Condition and Target color were significant, $F(1, 14) = 5.54$, $p < .05$, and, $F(1, 14) = 48.70$, $p < .001$, respectively. The Condition × Target color interaction was also significant, $F(1, 14) = 56.99$, $p < .001$ (see Fig. 4). Search for green targets in the preview condition was facilitated relative to search for the same targets in the full-set baseline, $F(1, 14) = 28.29$, $p < .001$ (a benefit of 459 ms). For red targets, there was a non-significant trend for RTs to be slowed in the preview condition compared with the full-set baseline (an effect of 124 ms), $F(1, 14) = 2.69$, $p = .123$. Thus there were opposite effects of the preview on red and green targets. There

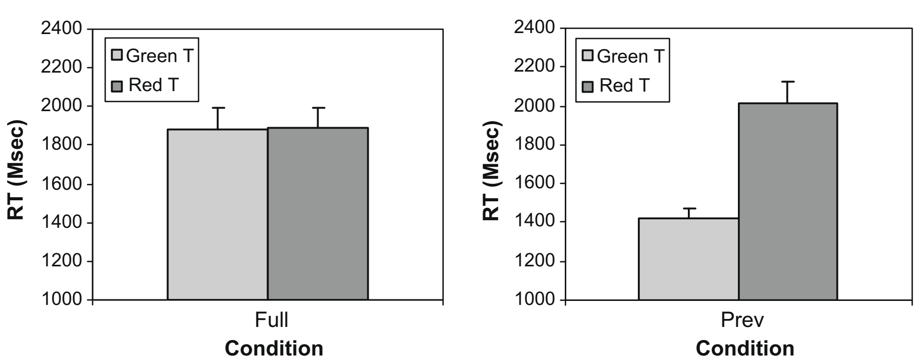

Fig. 4. Mean correct RTs for standard (no singleton probe) visual search trials from both the full-set baseline (left) and the preview search (right) conditions from Experiment 2.

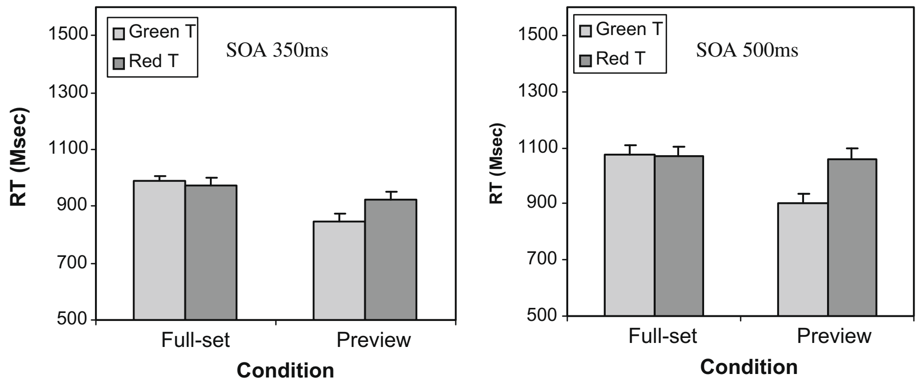

Fig. 5. Mean correct RTs from the singleton probe trials, plotted for the target color the probe replaced and condition for SOA 350 ms (left) and SOA 500 ms (right) from Experiment 2.

was no effect of target color in full-set search, $F(1, 14) = .042$, $p = .840$.

4.2.2. Display-change singleton probe trials

As in Experiment 1, RTs to singleton probe targets were faster than to targets in the search task. RTs on probe trials with full-set and preview displays were compared via a three-way (Condition × SOA × Target color) within-subjects ANOVA. There were significant main effects of Condition, $F(1, 14) = 16.741$, $p < .01$, of SOA, $F(1, 14) = 24.70$, $p < .001$, and of Target color, $F(1, 14) = 39.57$, $p < .001$. The Condition × SOA interaction was not significant, $F(1, 14) = .001$, $p = .971$. The Condition × Target color and SOA × Target color interactions were significant, $F(1, 14) = 19.32$, $p < .01$, and $F(1, 14) = 6.81$, $p < .02$, as was the three-way Condition × SOA × Target color interaction, $F(1, 14) = 6.78$, $p < .03$ (see Fig. 5).

RTs for singleton probe trials were analyzed separately for each SOA in two 2 × 2 (Condition × Target color) within-subjects ANOVA's. Most critically, the Condition × Target color interaction was significant both at the 350 ms SOA, $F(1, 14) = 7.082$, $p < .02$, and at the 500 ms SOA, $F(1, 14) = 29.744$, $p < .001$.

With a 350 ms SOA, probe detection in the preview condition was 75 ms faster when the probe replaced a green target than when it replaced a red target $t(14) = 4.33$, $p < .001$. There was no effect of the color of the target on RTs to probes in the full-set baseline ($t < 1.0$). Moreover, probe detection times for green targets were reliably faster (by 139 ms) in the preview condition than in the full-set condition, $t(14) = 5.90$, $p < .001$. There was no difference in RTs to probes replacing red targets in the preview and full-set conditions ($t < 1.0$).

With a 500 ms SOA similar results were found. There were faster RTs when probes replaced green rather than red targets in the preview condition, $t(14) = 5.87$, $p < .001$ (158 ms). RTs to probes on green targets were also faster in the preview condition than the full-set baseline, $t(14) = 6.66$, $p < .001$ (176 ms). Probes on red targets were slower in the preview than the full-set condition ($t < 1.0$).

Although the pattern of data across the SOAs was similar, the three-way interaction arose because the selective effects of color in the preview condition were greater at the longer SOA of 500 ms (e.g., the difference in RTs to probes falling on red compared with green targets under preview conditions was 75 ms with an SOA of 350 ms and 158 ms with a 500 ms SOA; this contrast was reliable, with $t(14) = 3.43$, $p < .005$; for green targets across SOA and $t(14) = 4.95$, $p < .001$; for red targets.

4.2.3. Errors

Total error percentage was again low at 3.86%. Probe data were explored in the same manner as the RT data (described above). There was a significant effect of Target color {$F(1, 14) = 5.526$, $p < .05$} and a significant Condition × Target color interaction {$F(1, 14) = 6.463$, $p < .05$}. All other effects were not significant (all Fs < 1.5 ps > .235 see Table 2). An inspection of the mean error rates in Table 2 shows that were more errors for probes falling on red targets relative to probes falling on green ones in the preview condition, at both SOAs. There were no signs of a speed-accuracy trade-off.

4.3. Discussion

As with Experiment 1, there were no effects of color in the full-set baseline condition, either for standard search performance or for probe detection. In contrast, there were significant effects of color on standard preview search, with RTs being slowed for new red targets compared with new green targets, and only RTs to green targets showing a preview benefit compared with the full-set baseline. This replicates our previous findings here and elsewhere (Braithwaite & Humphreys, 2007; Braithwaite et al., 2003, 2005, 2007; Olivers & Humphreys, 2003).

However, unlike Experiment 1, in the present experiment there was a significant advantage for probes on green compared with red targets in the preview condition – with this advantage increasing at the longer SOA. The results indicate that the relatively small effects of target color in Experiment 1 were not only due to attentional capture by the singleton probe, but also due to the relatively short SOAs explored in that experiment. The present result indicates that the probes on red targets became relatively more difficult to detect when the search display had been presented for some period (after 500 ms). This is consistent with the operation of a relatively slow spreading suppression process, so that targets carrying the color of the preview are subject to stronger suppression after that they been in the field for some period. When comparisons were made between probes in the preview and full-set conditions, there was evidence not only for the suppression of red targets but also for the guidance of attention to green targets in preview search. RTs to probes on red targets became slower in the preview compared with the full-set condition

Table 2
Mean percentage error (%) for Experiment 2, for the singleton probe trials broken down across condition, SOA, and the target color it replaced.

Condition	350 ms (SOA)	500 ms (SOA)
Full (green)	3.1	4.0
Full (red)	3.34	3.34
Preview (green)	2.32	1.87
Preview (red)	4.33	5.0

at the longer SOA. In addition, the advantage for probes on green targets in the preview condition compared with the full-set baseline increased as the SOA lengthened. This last result suggests that attention was being guided more accurately to the green target in the preview condition compared with the full-set condition, facilitating detection when the probe then replaced the target.

Experiment 3 examined performance with longer SOAs again (750 ms and 1000 ms respectively). With the shorter SOAs in Experiments 1 and 2, there were no responses prior to the onset of the novel singleton. However, with these larger SOAs this was less likely to be the case. This could have the effect of diluting any attentional capture by the novel singleton, if "early response" trials were included. To avoid this, we discarded trials where responses occurred prior to the onset of the singleton. However, with the long SOAs in Experiment 3 this could also lead to a reduced number of trials per condition. To remedy this, the number of trials was increased by 33% to allow for some early detections without there being a serious impact on the reliability of the data. Please note, we did not expect the detection rate to be excessive based primarily on the fact that absolutely no early detections occurred at all in Experiment 2 even for the most prolonged SOA of 500 ms.

5. Experiment 3

5.1. Methods

5.1.1. Participants

Fourteen participants (10 female, all right-handed) took part for course credit or small payment. The age of participants ranged from 18 to 35 years with a mean age of, 24 years. All were undergraduate or postgraduate students at the University of Birmingham. All had self-reported normal (including normal color vision) or corrected-to-normal vision.

5.1.2. Stimuli and apparatus

The stimuli were similar to those employed in previous experiments.

5.1.3. Design and procedure

The design and procedure generally matched that of previous experiments. However, there were two crucial differences for Experiment 3 in relation to the previous experiments. Firstly, two new singleton probe SOAs (750 ms and 1000 ms) were employed. Secondly, due to the extended duration in time for these singleton probes to occur – there is an increased chance of 'early-target detections' where the observer may locate the target before it has had the chance to change into the color singleton. In this sense, these instances would be equivalent to the standard search trials. Depending on the degree of these early detections – this may have the potential to reduce the number of trials contributing to the mean RTs for those cells and thus could compromise the data. To address this we increased the total block size from 320 trials to 480 trials (an increase of 33%). The block still maintained the same division between the trial types as in previous experiments (with singleton probe trials occurring rarely – 25% of the time). This translated into there being 40 more singleton probe trials in the present experiment than in the previous ones.

5.2. Results

The data were made fit for analysis in the same manner as that described previously. In addition, the data were explored for instances of 'early detections' on the increased SOAs. Due to the increased SOAs employed in the present study there were some instances of these (which are discussed below). These were removed from the mean correct RT analysis for singleton probe trials.

5.2.1. Early detections for singleton probe trials

Overall there was a 16% rate of early detections. There were 12.7% early detections in the full-set baseline and 19.5% in the preview condition – this is expected, given that search is facilitated in the preview condition. For the full-set baseline there were 9.3% early detections at 750 ms SOA with this increasing to 16.2% at 1000 ms SOA. For the preview condition there was 14.9% at 750 ms SOA and 24.1% at 1000 ms SOA. In addition, for the preview condition only there were more early detections for green targets (25%) relative to red targets (14.1%). These early-detection trials were removed from the analysis and not considered further (see Table 3 for a breakdown).

5.2.2. Standard search trials (no singleton probe)

The Full-set baseline and Preview conditions were compared in a 2×2 (Condition $\times$ Target color) within-subjects ANOVA. This revealed significant main effects of Condition, $F(1, 13) = 5.253$, $p < .05$ and of Target color, $F(1, 13) = 70.89$, $p < .001$. The Condition $\times$ Target color interaction was also significant, $F(1, 13) = 81.97$, $p < .001$ (see Fig. 6). Search performance for green targets in the preview condition was significantly benefited relative to green targets in the full-set baseline, $F(1, 13) = 48.800$, $p < .001$. For red targets, there was a non-significant trend between the full-set and preview conditions, with red targets in the preview condition tending to be slower (by 124 ms), $F(1, 13) = 2.62$, $p = .129$. Thus there were opposite effects of the preview on red and green targets. There was no effect of target color in full-set search, $F(1, 13) = .232$, $p = .638$.

5.2.3. Singleton probe trials

RTs to singleton probes in the full-set and preview conditions were compared in a three-way (Condition $\times$ SOA $\times$ Target color) within-subjects ANOVA. The main effect of Condition was not significant, $F(1, 13) = .239$, $p = .633$, but there were reliable main effects of SOA, $F(1, 13) = 55.31$, $p < .001$, and Target color, $F(1, 13) = 27.78$, $p < .001$. There was a reliable two-way interaction between Condition and Target color, $F(1, 13) = 53.32$, $p < .001$. The Condition $\times$ SOA $\times$ Target color interaction approached significance, $F(1, 13) = 3.37$, $p = .09$ (see Fig. 7).

RTs for singleton probe trials were analyzed separately for each SOA in two 2×2 (Condition $\times$ Target color) within-subjects ANOVA's. Critically, the Condition $\times$ Target color interaction was significant at both SOAs; SOA 750 ms, $F(1, 13) = 31.070$, $p < .001$; and SOA 1000 ms, $F(1, 13) = 5.996$, $p < .03$.

At an SOA of 750 ms there was a difference between RTs to probes on red and green targets in the preview condition, with RTs being faster (by 258 ms) to probes replacing a green target, $t(13) = 5.14$, $p < .001$. There was no effect of target color in the full-set baseline ($t < 1.0$). Probe RTs faster in the preview condition than in full-set baseline when a green target was replaced (130 ms), $t(13) = 3.07$, $p < .01$, but they were slower in the preview condition (by 151 ms) when a red target was replaced, $t(13) = 3.30$, $p < .007$.

Table 3
Mean percentage error (%) for Experiment 3, for the singleton probe trials broken down across condition, SOA, and the target color it replaced.

Condition	750 ms (SOA)	1000 ms (SOA)
Full (green)	4.64	3.93
Full (red)	4.28	3.21
Preview (green)	3.93	4.64
Preview (red)	5.1	5.36

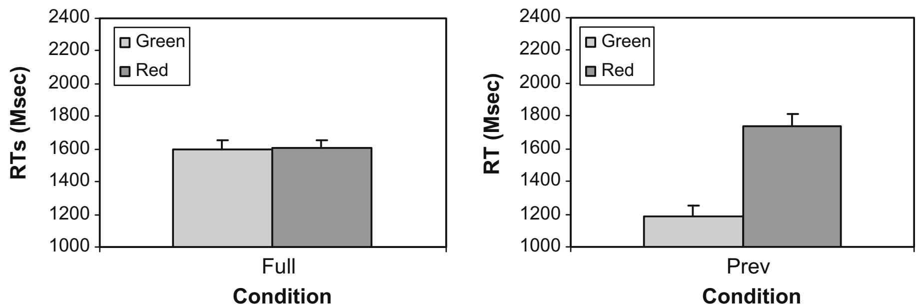

Fig. 6. Mean correct RTs for standard (no singleton probe) visual search trials from both the full-set baseline (left) and the preview search (right) conditions from Experiment 3.

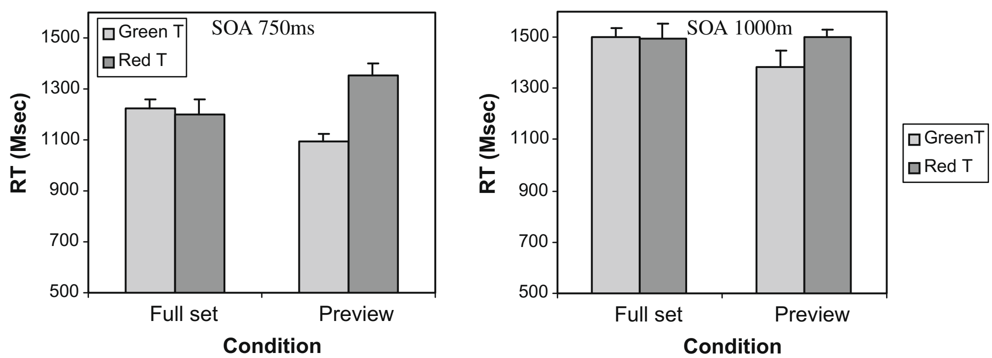

Fig. 7. Mean correct RTs from the singleton probe trials, plotted for the target color the probe replaced and condition for SOA 750 ms (left) and SOA 1000 ms (right) from Experiment 3.

At an SOA of 1000 ms, RTs in the preview condition were faster when probes replaced a green target than when probes replaced a red target (effect size 114 ms, $t(13) = 2.22$, $p < .05$). RTs to probes falling on green targets were faster in preview search than in the full-set baseline (effect size 109 ms, $t(13) = 2.37$, $p < .04$); RTs to probes falling on red targets did not differ across the preview and full-set conditions ($t < 1.0$).

5.2.4. Errors

Total error percentage was low at 2.95%. There was no evidence of a speed-accuracy trade-off (see Table 5). An exploration of the probe data revealed no significant main effects or interactions (all $Fs < .121$, $ps > .378$, see Table 5).

5.2.5. Development of facilitation and suppression over time

To trace the time course of probe detection, data from the singleton probe trials from all three experiments were assessed. Fig. 8 indicates the benefit for detection probes on green targets in the preview condition compared with the full-set baseline (the preview advantage in probe detection), along with the cost for detecting a probe replacing a red target compared with a green target in the preview condition (the color suppression effect). Fig. 8 suggests that color suppression spreads more slowly, and peaks later than the preview advantage for green targets. This pattern was explored via a 3 × 2 two-way between subject ANOVA with SOA (80, 350 and 750) and RT-effect (advantage/suppression) as factors. There was no effect of RT-effect $F(1, 94) = 0.66$, $p < .42$, but there was an effect of SOA $F(2, 94) = 27.9$, $p < .001$. Moreover, there was also an interaction between the RT-effect and SOA $F(2, 94) = 6.0$, $p < .005$. The color suppression effect increased across SOAs 350 ms and SOA 750 ms, $t(27) = 3.5$, $p < .002$. In contrast, the preview advantage had reached plateau by this time (no difference in preview advantage at SOA 350 ms and SOA 750 ms, $t(27) = 0.18$, $p < .86$). The time courses were further explored using both paired and independent t-tests (forced by the nature of the experimental designs). Table 4 shows that the reaction time benefits for singleton probes falling on green targets emerge early (>200 ms) but peak by 350 ms. There are no further beneficial impacts on performance after this time period. In contrast, the cost for probes falling on new red targets did not fully emerge until around 500 ms and it still had an impact on performance at 750 ms.

Table 4
Individual paired (SOA within-condition) and independent t-tests (between condition) comparing the different SOA for both red and green targets as computed for Fig. 8. The '*' denotes significance after correction (explained in the text).

Green targets	Red targets	t-Test	t-Value	p
200 vs. 350	–	Independent	3.96	$p < .001$*
350 vs. 500	–	Paired	1.71	$p = .109$
350 vs. 750	–	Independent	.18	$p = .860$
–	200 vs. 350	Independent	.251	$p = .803$
–	350 vs. 500	Paired	3.54	$p < .005$*
–	500 vs. 750	Independent	1.78	$p = .08$
–	750 vs. 1000	Paired	1.71	$p = .111$
–	350 vs. 750	Independent	3.54	$p < .002$*

Table 5
Mean percentage of early detections (%) for Experiment 3, for the singleton probe trials broken down across condition, SOA, and target color.

Condition	750 ms (SOA)	1000 ms (SOA)
Full (green)	8.6	16.7
Full (red)	10	15.7
Preview (green)	20	28
Preview (red)	9.8	18.3

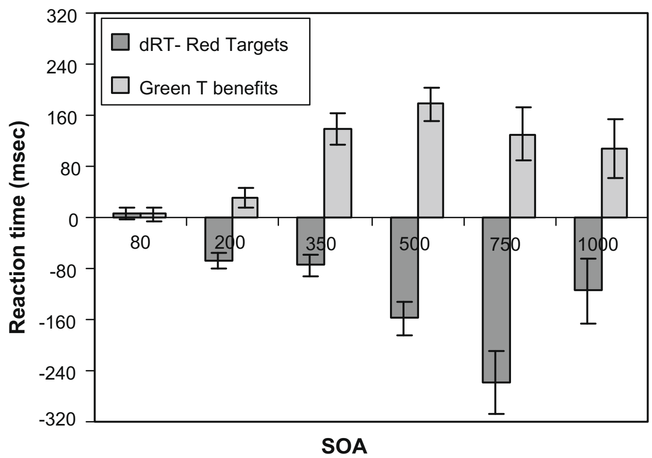

Fig. 8. Combined performance across all experiments at the singleton probe trials, plotted across SOA and the target color it replaced. dRT – red targets: cost of suppression (preview singleton red–preview singleton green). Green T benefits: preview advantage (full-set green – preview green). To emphasize the suppression, dRT has been plotted in negative values.

5.3. Discussion

As with previous experiments, significant effects of color only emerged in the preview condition – there was a strong benefit for green targets in the preview condition compared with the full-set baseline, while RTs to probes replacing red targets were slowed relative to probes replacing green targets in the preview condition. Target color had minimal impact in the full-set baseline.

The new result here is that the effects of color on preview search appeared to decrease at the longest SOA. Also, comparisons across experiments suggested that there were different time courses to the apparent suppression of red targets, and the attentional guidance to green targets (Fig. 8). The apparent suppression of red targets, carrying the color of ignored previews, was maximum with an SOA of 750 ms. In contrast, the facilitated guidance of attention to the green target was maximal at the 500 ms SOA The present findings suggest that there were no further costs to selection beyond 750 ms and indeed, there was a suggestion that the cost to carry-over targets was dissipating by 1000 ms (a difference of 114 ms between singleton probes falling on red and green targets at 1000 ms).

6. General discussion

We have reported data on a novel procedure for measuring the allocation of attention in visual search over time. Here a salient new color singleton probe was added to the search target to enable it to be detected efficiently. By varying the time when the singleton probe appeared after the search display, we assessed when the processes of (i) attentional guidance to a target, and (ii) the suppression of distractors operated under preview conditions. The basic search conditions (with red and green targets) replicated prior studies: there was a strong benefit for preview search when the target's color differed from the old distractors (new green targets), and there was a cost selective to preview search when the target carried the color of the old distractors (new red targets; cf. Braithwaite & Humphreys, 2003, 2007; Braithwaite et al., 2003, 2004, 2005, 2007; Olivers & Humphreys, 2003). The new result was that these costs and benefits could be traced over time by measuring RTs to a new singleton probe presented at various intervals after the onset of the search display. Relative to when the probe fell on a green target in a full-set display, RTs were facilitated when it fell on a new green target in a preview display. This benefit was maximal with a display-probe SOA of around 350–500 ms. Relative to when the probe fell on a green target in preview search, RTs were slowed when it fell on a new red target. This cost was maximal with a display-probe SOA of 750 ms, and decreased when the SOA was 1000 ms.

We propose that the costs and benefits in responding to the probe reflect the time course of attentional guidance to targets and attentional suppression of distractors. When the probe replaced a green target; RTs benefitted in preview search. We suggest that this was due to attention being guided to the target more easily in preview search than in the full-set baseline. The closer participants were to the probe at the time of its onset, the faster probe detection and target identification. The RT benefit in preview search would arise due to attention being drawn to the target prior to the onset of the probe. It appears that this process of guiding attention to the previewed target took around 350–500 ms, generating the maximal benefit to probe detection at that display-probe SOA. In contrast, when the probe replaced a red target, there was a cost to RTs in preview search. We propose that this cost is due to the spread of inhibition from the old items to a new item carrying the same color. This spread of inhibition could affect performance in either of two-ways. One possibility is that attention is directed away from areas of the display where items are suppressed. A second possibility is that there is inhibition not only of the target's color but also of its form. Due to suppression of the target's form, the target takes longer to identify. In either case, RTs are slowed when participants have to identify the item where the probe falls.

The apparent guidance and suppression processes showed different time courses with guidance peaking at display-probe SOA of 350–500 ms and suppression being maximal at the later SOA of 750 ms. It is interesting to note that this long time course for suppression of the new target is reminiscent of the long time course of the preview benefit itself. Several studies have shown the previews need to be exposed for relatively long time periods (400 ms or even longer) in order for the maximum benefit to emerge relative to full-set baseline conditions (e.g., Humphreys et al., 2004; Watson & Humphreys, 1997). This would be expected if it takes time to suppress the previewed stimuli. The present results indicate that the carry-over of suppression from the initial previewed distractors to the new target is also a relatively slow acting process – accordingly there is little cost when the novel singleton followed shortly after the onset of the search display. In contrast, guidance to the vicinity of the target operated earlier. On trials where the target carried the color of the preview display, though, any guidance based on the target's shape may have been delayed by the beginning of the suppression. Consequently, there would not necessarily be time to shift attention to the vicinity of the target prior to suppression being maximal. A final point to stress is that the present evidence for suppression arose even though (i) the red target was a singleton in the new search display, and (ii) the probe had a novel singleton color. The fact that the red target was difficult to detect (on non-probe trials), while the ease of detecting the novel probe also decreased when it fell on a red target, contradicts some accounts of preview search. In particular it has been argued that the preview benefit reflects the capture of attention by the new onsets created by the search display (Donk & Theeuwes, 2001, 2003). This account predicts that red target singletons should be easy to detect, while the ease of detecting the novel singleton probe should not differ between singleton and full-set display conditions (indeed the detection of the singleton probe should be easiest when it falls on a red target in preview search, since attention should be attracted to that item amongst the new onsets). On the other hand, these results do fit the argument that the preview benefit involves both the suppression of the old items and the positive guidance of attention to the new target (Braithwaite & Humphreys, 2003, 2007; Braithwaite et al., 2003, 2004, 2007; Watson & Humphreys, 1997). The present results provide the first evidence that these processes have different time courses.

6.1. Alternative accounts: are the effects due to low-level grouping factors alone?

The increased cost for carry-over targets seen at increased SOAs cannot be explained merely by low-level grouping factors. A low-level grouping account would argue that the new red singleton target (i.e., the carry-over target) passively 'sinks' into the background provided by the preview items. However, there were a number of findings which suggests that such grouping factors were not crucial. For example, grouping accounts fail to explain why this 'sinking' effect did not impact on performance with an 80 ms SOA in the preview condition. Effects from low-level grouping factors should have been maximal at the very earliest SOA and dissipate with time. Instead – we observed the complete opposite pattern – where the cost to carry-over targets only emerged after more prolonged SOAs (>200 ms). Indeed the carry-over was maximal at around 750 ms which is too slow for current estimates of grouping processes (see Wolfe (1998); for a review). A further argument might be that at short SOAs the occurrence of the singleton probe itself might be masked to some degree by the arrival of the second search display. On this view, if the two temporal events occur in very close succession, then the guiding properties of the color singleton may well be reduced. However, even if this were the case it cannot explain the systematic effects of color where there were differing impacts of SOA as a function of whether the target carried the color of the old items or not (i.e., for red and green targets). Therefore, we suggest that the most parsimonious account for the effects reported on carry-over targets is one based on a top-down inhibitory mechanism that is directed towards filtering the old and irrelevant distractors. This mechanism is sensitive to the featural attributes in the visual field.

6.2. Spreading suppression and failures of awareness

The present findings are consistent with the notion that inhibitory processes contribute to preview benefits in search. In addition, the present results show that feature-based spreading suppression is not immediate or automatic. The present findings show that spreading suppression can (i) take time to accrue and impact on selection and (ii) display a different temporal profile to that of facilitatory effects directed towards other color values.

The cost seen for singleton probes falling on new red items is consistent with spreading suppression propagating towards new information on the basis of featural similarity to that which is currently being ignored. One account of how new items might be inhibited, if they share the color of previewed stimuli, is that there is inhibition of a color map corresponding to the color of the items in the initial display. Treisman and Sato (1990) proposed that visual search under simultaneous presentation conditions could operate more efficiently if observers inhibited whole 'feature-maps' that were activated selectively by specific distractors. Here all activations coded within a particular feature dimension (i.e., a specific color) could be inhibited en-masse, thus making selection more efficient for a target carrying a different feature (see Fig. 9), but difficult for a target carrying the inhibited feature. However, a simple account in terms of inhibition of a color map would not expect inhibition to spread across items over time, given that the whole map is inhibited. However, it is possible that the initial activation of the target in its color map could be boosted by its new onset. If the map is inhibited then this activation might then decay away over time, leading to poor detection of the probe replacing an item of the inhibited color. These ideas are captured in the framework presented in Fig. 9.

A final point is whether there is any relation between the present results (and related studies of the negative color carry-over effect) and phenomena such as sustained inattentional-blindness. Studies of sustained inattentional-blindness (Most & Astur, 2007; Most, Scholl, Clifford, & Simons, 2005; Most et al., 2001; Simons & Chabris, 1999) have shown that participants may ignore stimuli based on the suppression of a common feature. Under some condi-

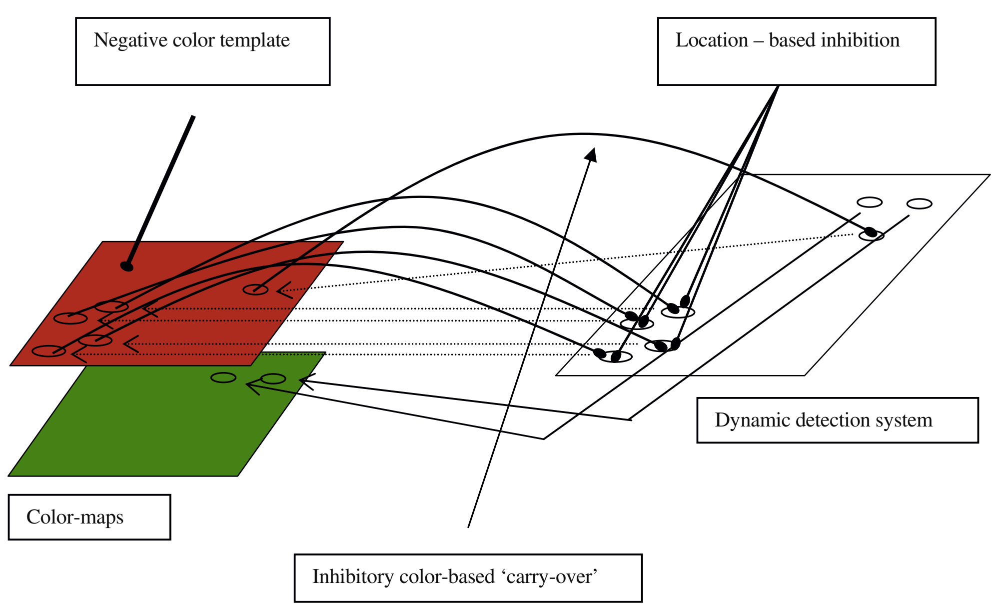

Fig. 9. An illustration of the feature-map inhibition account extended to preview search. Here activations associated with the preview items are registered in a dynamic detection system and in the associated color map. Soon after this, top-down inhibition is directed towards a whole feature-map de-prioritizing the activations coded within in it. When new items are presented. (two green items and one red item, in our example) – a target carrying the color of the previewed stimuli will be inhibited. The inhibition may take to apply, however, if the target's representation initially benefits from a boost in activation due to the target's new onset.

tions (e.g., with limited exposures of stimuli), this can lead to participants not being aware of certain stimuli. The present study used prolonged stimulus exposures which meant that participants were eventually able to identify the target, even when it appeared to be suppressed (e.g., red targets in the preview condition) – though this is likely due to the fact that the displays were left visible for up to 10,000 ms. However, the vastly prolonged detection times and increased search inefficiency for carry-over targets suggests that we could confidently expect that there would be a selective loss of awareness for the inhibited items were the experiment run using shorter exposure durations for stimuli. Such a result would point to there being common inhibitory mechanisms involved in selectively ignoring irrelevant stimuli and resulting failures of awareness of new information carrying critical attributes of the information currently being ignored. The present data further suggest that these inhibitory mechanisms take time to build, and can be sustained for some period of time.

Acknowledgments

We would like to thank Marisa Carrasco and two anonymous reviewers for helpful comments on earlier versions of this paper. This research was supported by a Roberts Research Fellowship (RCUK) awarded to the first author, an ESRC 3+1 PhD studentship awarded to the third author and an MRC Grant to the fourth author.

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