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Prioritized Selection in Visual Search Through Onset Capture and Color Inhibition: Evidence From a Probe-Dot Detection Task

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Observers performed a preview search task in which, on some trials, they had to indicate the presence of a briefly presented probe-dot. Probes could be presented on locations corresponding to old or new elements and prior to or after the presentation of the new elements. After the presentation of the new elements, probes were generally detected faster on new than on old locations, indicating prioritized selection of new elements. Prior to the presentation of the new elements, probes were detected faster on new than on old locations only when old and new elements differed in color. These results suggest that prioritized selection of new elements is mediated not by visual marking but by onset capture. Additionally, observers may apply color-based inhibition.

When an observer views a natural scene, new objects are often more relevant than old objects that have been in the visual field longer. That is, new objects are unknown and might signal danger or otherwise important information. Accordingly, it would be useful for humans to be equipped with a mechanism enabling them to give priority to new objects over old objects in the visual field.

Evidence for the existence of such a mechanism has been found in studies using the *preview paradigm* (Watson & Humphreys, 1997). In this paradigm, observers perform a modified color–form conjunction search task in which two sets of elements are presented with different temporal onsets. The first set of elements—the *old* elements—is typically presented for about 1,000 ms before the second set of elements—the *new* elements—is added to the display. Participants have to search for the presence of a predefined target that can only appear among the new elements. The target (e.g., a blue *H*) differs from the old elements (e.g., green *H*s) along one feature dimension (i.e., color) and from the new elements (e.g., blue *A*s) along another feature dimension (i.e., form). Typically, search efficiency in this preview condition is much higher than that in a conjunction search baseline condition in which old and new elements are simultaneously presented (e.g., Watson & Humphreys, 1997, 2000). This difference in search efficiency between the preview condition and the conjunction search baseline condition is referred to as the *preview benefit*. In fact, search efficiency in the preview condition has generally been found to be equal to that in a feature search baseline condition in which only the new elements are presented. Apparently, the previewed elements do not compete with the new elements for attentional processing. Although these findings suggest that the brain is equipped with a mechanism that gives priority to new over old objects, the nature of this mechanism is still a matter of debate.

In their original article, Watson and Humphreys (1997) proposed that prioritized selection of new over old elements occurs because observers voluntarily deprioritize old elements during the preview period. According to this view, observers actively inhibit the locations of the old elements during the preview so as to prevent attentional redirection when the new elements appear (see also Humphreys, Jung Stalmann, & Olivers, 2004; Kunar, Humphreys, Smith, & Watson, 2003; Watson & Humphreys, 2000). The application of this top-down process, which Watson and Humphreys have termed *visual marking* (VM), thus facilitates the perception of new objects in advance of their appearance.

A completely different account has been put forward by Donk and Theeuwes (2001; see also Belopolsky, Theeuwes, & Kramer, 2005; Donk & Theeuwes, 2003; Donk & Verburg, 2004). Donk and Theeuwes (2001) claimed that the relative priority of new over old elements is directly attributable to the characteristics of the new elements. According to this view, referred to as the *onset capture (OC) account*, new elements are involuntarily prioritized over old ones because attention is automatically captured by the luminance onsets that accompany their appearance (e.g., Jonides & Yantis, 1988; Theeuwes, 1991, 1992, 1994; Yantis, 1993; Yantis & Jonides, 1984). As a result, new elements are prioritized in selection over old elements without any prior involvement of the observer during the preview.

Since Watson and Humphreys (1997) introduced the preview paradigm, many authors have been involved with the question of whether prioritized selection of new over old elements is mediated by VM or by OC (e.g., Atchley, Jones, & Hoffman, 2003; Belopolsky et al., 2005; Braithwaite, Humphreys, & Hodsoll, 2003; Donk & Theeuwes, 2001, 2003; Donk & Verburg, 2004; Humphreys et al., 2004; Humphreys, Watson, & Jolicœur, 2002; Kunar, Humphreys, & Smith, 2003; Kunar, Humphreys, Smith, & Hulleman, 2003; Olivers & Humphreys, 2002; Watson & Humphreys,

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2000).[1] Nevertheless, only a few studies have directly tested whether prioritized selection is related to inhibition of old elements or to facilitation of new elements (Humphreys et al., 2004; Olivers & Humphreys, 2002; Watson & Humphreys, 2000).

Initial evidence for the claim that the preview benefit is mediated by the inhibition of the locations of old elements comes from a study by Watson and Humphreys (2000), in which they combined the preview paradigm with a *probe-dot detection* paradigm. In this study, participants performed a classical preview search task in which a prespecified target letter had to be detected on the majority (76%) of trials. More important, however, were the less frequent (24% of the trials) *probe detection* trials. These were signaled by a brief tone accompanying the new elements, after which participants had to give a response with respect to the presence or absence of a small, dim white probe dot instead of the target letter. The probe could appear either on a location occupied by an old element or on a location occupied by a new element. Relative to a baseline condition in which all elements appeared simultaneously, probe detection accuracy in the preview condition was found to deteriorate when the probe was presented on an old location but not when the probe was presented on a new location. Watson and Humphreys (2000) concluded that, in line with their theory of VM, prioritized selection of new elements is mediated by active inhibition applied to the locations of old elements.

More recently, Olivers and Humphreys (2002, Experiment 3) also demonstrated that probe-dot detection performance was worse if probes were presented at old rather than new locations. Like Watson and Humphreys (2000), they presented a preview search task on the majority (80%) of trials and a probe-dot detection task on the remaining trials. Unlike Watson and Humphreys (2000), they measured probe detection reaction time (RT) instead of probe detection accuracy. The results showed that probe detection RT was longer if the probe appeared on a location occupied by an old element than if it appeared on a location occupied by a new element, which Olivers and Humphreys (2002) advanced as evidence for the active inhibition of the locations of the old elements.

Although the results of both Watson and Humphreys (2000) and Olivers and Humphreys (2002) are in agreement with the VM account, these results can also be explained by the OC account. It is possible that new elements were prioritized for selection over old ones because the new elements appeared with a luminance onset. As a result, attentional resources might have been redistributed over old and new locations, resulting in a cost at the old locations and a benefit at the new locations.[2] Thus, the results of Watson and Humphreys (2000) and Olivers and Humphreys (2002) do not speak with respect to whether prioritized selection is the result of VM or of OC.

Recently, to enable discrimination between the VM account and the OC account, Humphreys et al. (2004) performed a study in which they compared probe detection performance between old and new locations prior to the presentation of new elements. In this study, observers were instructed to search for a red-outline vertical bar among new red horizontal bars and old green vertical bars, superimposed on a blue grid background. Apart from a speeded response with respect to the presence or absence of the target on 100% of the trials, participants had to indicate on 50% of the trials (*probe* trials) whether a probe was presented. The probe, which was presented on 50% of the probe trials, fell in the middle of the empty area between the squares making up either the background grid or the old or new elements. All of the contours present changed luminance in a random fashion around a level set to be roughly equiluminant across participants. Hence, luminance did not provide any contour information. Detection accuracy was higher for probes at new locations than for probes at old locations both before and after the presentation of the new elements. These results indeed suggest that old elements were deprioritized prior to the presentation of the new elements.

Even though the results of Humphreys et al. (2004) suggest that prioritized selection of new over old elements is mediated by a process of inhibition, it is unclear whether the application of active inhibition was really based on the "oldness" of the previewed elements, as suggested by the original VM account. Alternatively, old elements could have been deprioritized on the basis of their color (Brawn & Snowden, 1999; Egeth, Virzi, & Garbart, 1984; Kaptein, Theeuwes, & van der Heijden, 1995; Moore & Egeth, 1998). In fact, it is possible that new elements were prioritized through a process of active inhibition only because there was a color difference between old and new elements. Indeed, a study by Donk and Theeuwes (2001) in which old and new elements had the same color failed to provide evidence for the idea that new elements can be prioritized without luminance onset. It is possible that old elements can only be deprioritized prior to the presentation of new elements when there is a color difference between old and new elements.

To date, no studies have been performed to investigate whether old elements are inhibited prior to the presentation of new elements when both sets of elements have the same color. The present study aimed to determine whether, under such conditions, old elements are inhibited prior to the presentation of new ones.

Similar to Watson and Humphreys's (2000) Experiment 1, in the present Experiment 1, we used a probe-dot detection procedure in addition to a standard preview search procedure. On 76% of the trials, participants performed a letter search task, in which a target letter had to be searched for. On the remaining 24% of the trials,

[1] Another account was put forward by Jiang, Chun, and Marks (2002), according to which new elements are prioritized over old ones because new elements can be temporally segregated from old elements. Whether prioritized selection is related to inhibition of the old elements is not a central issue in this account.

[2] At this point, it should be noted that Watson and Humphreys (2000) provided additional support for their VM account in their Experiment 2, in which they found no difference between probe detection performance on old and new locations when all trials were probe trials. They concluded that new elements were not prioritized over old ones when there was no incentive to inhibit the old elements. The absence of an effect of probe location on probe detection performance when all trials were probe trials can, however, also be accounted for by the OC account (see Donk & Theeuwes, 2003). Participants probably did not prioritize the new elements when their only task was to detect a nonsalient probe near an irrelevant blue or green element. Gibson and Peterson (2001) showed that in search for a nonsalient target, participants tend to be engaged in a focused attentional state that prevents attentional capture by a singleton. In the absence of search trials, participants in Watson and Humphreys's (2000) Experiment 2 might have adopted a similar strategy. They might have limited their attentional window immediately after the appearance of the old elements so as to detect the dim probe dot. This might have prevented the abrupt luminance onsets accompanying the appearance of the irrelevant new elements from capturing attention.

participants performed a probe detection task in which a speeded response had to be made on probe detection. Unlike Watson and Humphreys's (2000) Experiment 1, old and new elements were presented in the same color instead of different colors. Furthermore, probes could be presented not only after but also before the presentation of the new elements. Finally, to avoid possible ceiling effects, instead of probe-dot detection accuracy, we chose probe-dot detection RT as the major dependent variable. According to the VM account, the inhibition of old locations is initiated prior to the presentation of new elements. This leads to the prediction that a difference in probe RT between old and new locations should be present prior to the presentation of the new elements. In fact, a VM account predicts that the difference in probe RT between old and new locations will increase as a function of preview interval. Alternatively, if new elements are prioritized over old elements through attentional capture of the new elements, it is predicted that a difference in probe RT between old and new locations will only be present after the presentation of these new elements.

Experiment 1

Method

Participants. Ten students, 4 women and 6 men (age range: 18–31 years), volunteered to participate in exchange for a €10 (U.S.$12.75) fee. The data from 2 participants, who had false alarm rates on the probe-dot detection task greater than 20%, were not included in the analyses, resulting in there being a total of 8 participants (2 women and 6 men). All participants had normal or corrected-to-normal vision and did not know the purpose of the experiment.

Materials. A Celeron 400-MHz/128-MB PC controlled the timing of events, the generation of the stimuli, and the recording of responses. Stimuli were presented on a 19-in. (48.26-cm) Multiscan color monitor (with an ATI Rage 4-MB card). The software package E-Prime (Schneider, Eschman, & Zuccolotto, 2002) was used for the layout and timing of the experimental trials. Participants were tested in a dimly lit room while seated approximately 85 cm in front of the monitor. Their left middle and index fingers rested on the left *control* and *alt* keys, respectively. The right index finger rested on the space bar.

Task and stimuli. Two different types of trials were randomly intermixed within blocks of trials (see Figure 1). On 76% of the trials, participants had to indicate the presence of the prespecified target letter, *A*. These trials are referred to as *letter search trials*. On the remaining 24% of the trials, participants had to indicate the presence of a white probe dot on one of the possible target locations. These trials are referred to as *probe detection trials*. All letter stimuli were presented in blue (Commission Internationale de l'Eclairage [CIE] *x*-, *y*-chromaticity coordinates of 0.177, 0.074, and 0.800 cd/m^2) against a black background. They were displayed in synchrony with the screen refresh, within an imaginary rectangle of 3.70° × 2.35° of visual angle. The target was always an *A* with right angles (*digital A*), whereas the distractors were *A*s in which the horizontal bars

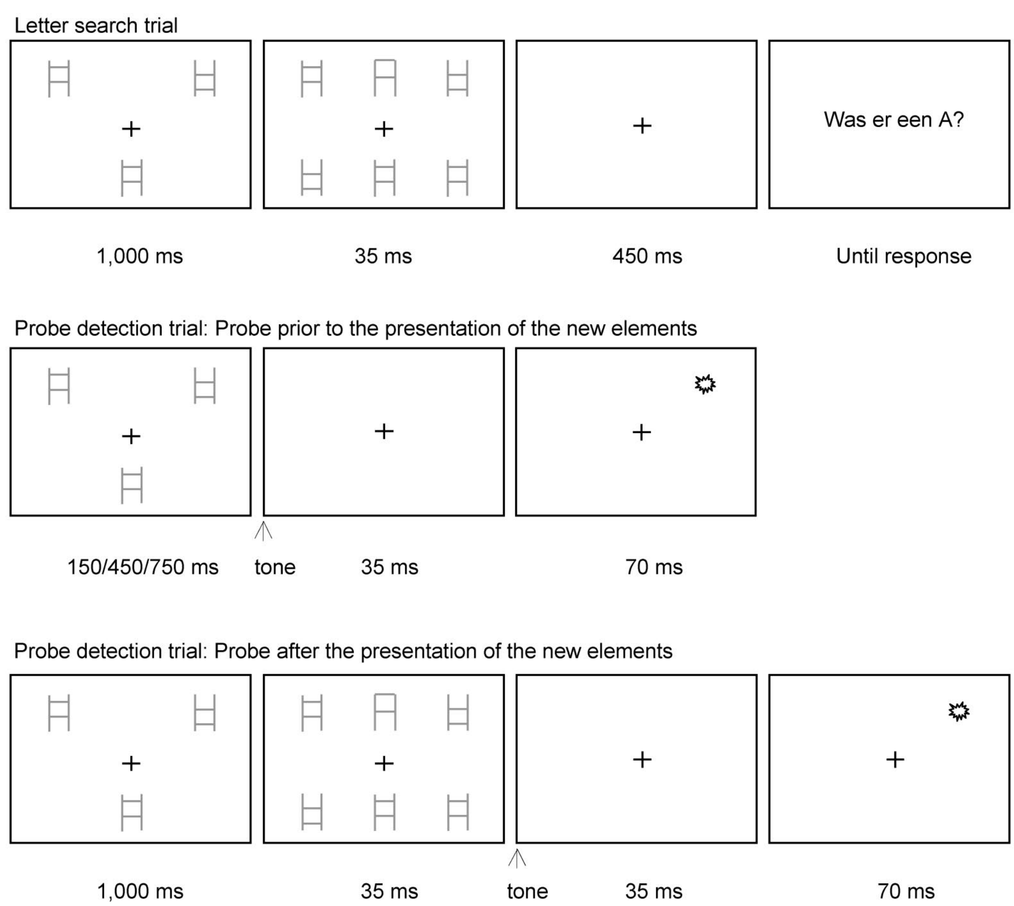

Figure 1. The sequence of displays in letter search and probe detection trials in Experiment 1.

were displaced 0.07° downward and inverted *A*s in which the horizontal bars were displaced 0.07° upward.

Letter search trials. Each trial began with a 500-ms black screen before a fixation cross (0.19° × 0.19° of visual angle) was presented on the middle of the screen for 500 ms. Then, three distractors (*old elements*), each subtending a visual angle of 0.47° × 0.37°, were presented in a 2 × 3 matrix. These elements were, similar to those in Watson and Humphreys (2000), arranged in a triangle such that they always occupied the center location of one row and the two outer locations of the other row. After 1,000 ms, three elements (*new elements*) were added to the display at the previously unoccupied locations. On half of the letter search trials, a target was presented among the new elements. On the other half of these trials, there was no target. After 35 ms, all elements disappeared, leaving a fixation cross. After another 450 ms, a question (*Was er een A?*) was displayed, probing participants to indicate whether the target had been presented. The question remained on the screen until the participant responded or until the maximum of 3,000 ms had elapsed. Participants had to make an unspeeded response by pressing either the left *control* key if the target was present or the left *alt* key if the target was absent.

Probe detection trials. Probe detection trials were identical to letter search trials until the presentation of a 1500-Hz tone for 35 ms. The tone was presented 150, 450, 750, or 1,050 ms after the presentation of the old elements. Concurrent with the presentation of the tone, all elements disappeared. After the tone, either a white probe dot (0.17° × 0.17° of visual angle) was presented at the center of an old or a new location (on 75% of the trials) or no probe was presented (on 25% of the trials). If presented, the probe-dot presentation duration was 70 ms. In the case of a *probe present* trial, participants had to press the space bar as quickly as possible after presentation of the probe. In case of a *probe absent* trial, no response had to be made. The next trial began on the response or after a fixed interval of 3,000 ms had elapsed since probe offset.

Participants were instructed to remain fixated on the fixation cross throughout a trial. Furthermore, they were told that in the letter search task, the target, if present, would be presented among the new elements. In both tasks, an incorrect response was immediately followed by the centrally presented word *fout!* (error) for 200 ms.

Design and procedure. The experiment consisted of five blocks of 250 trials each (190 search trials and 60 probe trials). The first block served as practice for the following four test blocks. Probe presence (present, absent), probe location (old, new), and stimulus onset asynchrony (SOA) between the presentation of the old elements and the presentation of the tone indicating a probe detection trial (150 ms, 450 ms, 750 ms, 1,050 ms) were randomly varied within blocks of trials.

Results

Figure 2 shows the mean correct probe RTs as a function of probe location and SOA. We conducted an analysis of variance (ANOVA) on the mean correct probe RTs with probe location (old, new) and SOA (150 ms, 450 ms, 750 ms, 1,050 ms) as repeated measures factors. There was a significant main effect of SOA, $F(3, 21) = 33.24$, $p < .01$. Mean RTs were longer for the 1,050-ms SOA than for all other SOAs. Furthermore, there was a significant Probe Location × SOA interaction, $F(3, 21) = 5.97$, $p < .01$, indicating that the effect of probe location varied as a function of SOA. There was no significant effect of probe location, although there was a trend, $F(1, 7) = 3.67$, $p < .10$. To investigate whether probe location differentially affected probe RTs before and after the presentation of the new elements, we performed separate analyses on the data obtained with the three shortest SOAs (150, 450, and 750 ms) and those obtained with the longest SOA (1,050 ms). Prior to the presentation of the new elements, there was neither an effect of probe location nor a Probe Location × SOA interaction (*F*s < 1). After the presentation of the new elements, probe location significantly affected probe RT, $t(7) = 2.97$, $p < .05$, indicating that observers were faster in detecting a probe dot if it was presented on a new location than they were if it was presented on an old location.

Figure 2. Mean correct probe reaction times as a function of probe location and stimulus onset asynchrony in Experiment 1.

Table 1 summarizes the error percentages in the probe detection trials as a function of SOA. An ANOVA on the mean error percentages with probe location (old, new) and SOA (150 ms, 450 ms, 750 ms, 1,050 ms) as repeated measures factors did not reveal any significant effects.

Detection accuracy in the letter search trials was high; there were 10.4% false alarms and 6.1% misses. Performance was unaffected by target presence, $t(7) = 1.452$, $p > .05$.

Discussion

When probes were presented after the appearance of the new elements, they were detected faster on a location previously occupied by a new element than they were on a location previously occupied by an old element. This finding, which is similar to the result obtained by Watson and Humphreys (2000), suggests that new elements were prioritized over old elements. To distinguish between the VM account and the OC account, the critical conditions were those in which probes were presented prior to the presentation of the new elements. The corresponding data show that prior to the presentation of the new elements, probe RT was unaffected by probe location.

The results of Experiment 1 are difficult to reconcile with the VM account. According to this account, prioritized selection of new over old elements is the result of the application of inhibition to the locations of the old elements during the preview. However, the present results indicate that prior to the presentation of the new elements, there is no difference in probe RT between old and new locations. This strongly suggests that observers were not actively involved in an inhibitory process prior to the appearance of the new elements. Instead, prioritized selection of new elements was most probably induced by those elements' abrupt onsets.

The present results are different from those of Humphreys et al. (2004), who found an RT difference between probes at old and new locations prior to the presentation of new elements. As men-

Table 1
Mean Percentages of Misses (for Old and New Probe Locations) and False Alarms in the Probe Detection Trials of Experiments 1–3

Variable	Misses: Old	Misses: New	False alarms
Experiment 1			
150-ms SOA	3.5	1.5	8.4
450-ms SOA	1.0	1.5	8.4
750-ms SOA	1.5	1.0	6.1
1,050-ms SOA	3.5	1.0	15.4
Experiment 2			
150-ms SOA	2.0	0.5	7.6
450-ms SOA	2.0	1.5	4.5
750-ms SOA	0.5	0.5	4.6
1,050-ms SOA	3.1	2.5	21.6
Experiment 3			
Color difference	2.0	1.5	5.0
No color difference	2.0	2.5	4.0

Note. SOA = stimulus onset asynchrony.

tioned in the introduction, participants in the Humphreys et al. (2004) study might have prioritized the new elements not by a mechanism of OC or of VM but by the active inhibition of the target-irrelevant color. In Experiment 2, we tested whether a probe-RT difference between old and new locations would be present during the preview interval if old and new elements were presented in different colors.

Experiment 2

Experiment 2 was identical to Experiment 1, with the exception that the old elements were presented in a different color (green) than the new elements (blue).

Method

Participants. Eleven students, 7 women and 4 men (age range: 20–31 years), volunteered to participate in exchange for a €10 (U.S.$12.75) fee. The data from 3 participants, who had false alarm rates on the probe-dot detection task greater than 20%, were not included in the analyses, resulting in there being a total of 8 participants (4 women and 4 men). All participants had normal or corrected-to-normal vision and did not know the purpose of the experiment. One of the participants had taken part in Experiment 1.

Materials. A Hewlett-Packard/Compac 2.6-GHz/512-MB PC controlled the timing of events, the generation of the stimuli, and the recording of responses. Stimuli were presented on a 19-in. (48.26-cm) CRT color monitor. The rest of the materials were the same as in Experiment 1.

Task and stimuli. The stimuli were identical to those in Experiment 1 in all aspects but one. In this experiment, the old elements were green (CIE *x*-, *y*-chromaticity coordinates: 0.381, 0.469, and 1.65 cd/m^2) instead of blue. Green and blue elements were equiluminant, as determined by a flicker fusion test (Ives, 1912).

Design and procedure. These were identical to those of Experiment 1.

Results

Figure 3 shows mean correct probe RTs as a function of probe location and SOA. An ANOVA was conducted on the mean correct probe RTs with probe location (old, new) and SOA (150 ms, 450 ms, 750 ms, 1,050 ms) as repeated measures factors. There were significant main effects of probe location, $F(1, 7) = 15.23$, $p < .01$, and SOA, $F(3, 21) = 38.12$, $p < .01$. Probes were detected faster on new locations than on old locations. Mean RTs were longer for the 1,050-ms SOA than for all other SOAs. There was no Probe Location × SOA interaction ($F < 1$). An ANOVA on the mean correct probe RTs for trials with SOAs shorter than 1,000 ms with probe location (old, new) and SOA (150 ms, 450 ms, 750 ms) as repeated measures factors revealed that probe location affected RT prior to the presentation of the new elements, $F(1, 7) = 15.11$, $p < .01$. Probes were detected faster on new than on old locations. There was no effect of SOA, $F(3, 21) = 1.32$, $p > .05$, nor was there a significant Probe Location × SOA interaction ($F < 1$). The effect of probe location on RT after presentation of the new elements (SOA = 1,050 ms) was also significant, $t(7) = 6.80$, $p < .01$.

Table 1 summarizes the error percentages in the probe detection trials as a function of SOA. An ANOVA on the mean error percentages with probe location (old, new) and SOA (150 ms, 450 ms, 750 ms, 1,050 ms) as repeated measures factors did not reveal any significant effects.

Detection accuracy in the letter search trials was high; there were 12% false alarms and 8% misses. Performance was affected by target presence, $t(7) = 2.986$, $p < .05$. Response accuracy was higher when the target was present than it was when the target was absent.

Finally, we conducted an across-experiment ANOVA with Experiment (1, 2), SOA (150 ms, 450 ms, 750 ms), and probe location (old, new) as repeated measures factors. There was a significant Experiment × Probe Location interaction, $F(1, 7) = 17.42$, $p < .01$, indicating that probe location differentially affected RT prior to the presentation of new elements in Experiments 1 and 2. After the presentation of the new elements (SOA = 1,050 ms), there was no Experiment × Probe Location interaction ($F < 1$).

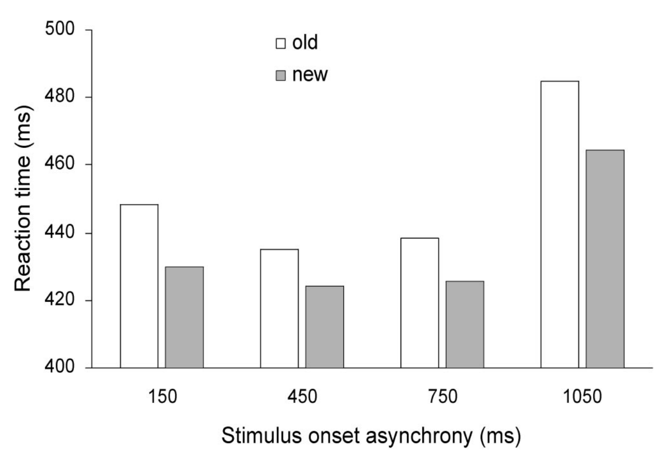

Figure 3. Mean correct probe reaction times as a function of probe location and stimulus onset asynchrony in Experiment 2.

Discussion

In Experiment 2, probes were detected faster when they were presented on locations corresponding to new elements than when they were presented on locations corresponding to old elements. This difference in probe RT was consistently present before and after the appearance of the new elements. These results suggest that if old and new elements are presented in different colors, old elements can be deprioritized prior to the appearance of the new elements. The results of Experiment 2 are consistent with the VM account originally proposed by Watson and Humphreys (1997).

One point worth mentioning in this respect is that the difference in probe RT between old and new locations was equal irrespective of SOA. According to Watson and Humphreys (1997), prioritized selection of new over old elements occurs by a time-consuming process of active inhibition. On the basis of their Experiments 3a and 3b, Watson and Humphreys (1997) inferred that the complete inhibition of old elements takes about 400 ms. The results of Experiment 2 suggest differently: The difference in probe RT between old and new locations was already maximal at 150 ms. These results suggest that old elements can be fully inhibited after about 150 ms (instead of 400 ms). A possible explanation for the discrepancy between the present results and those obtained earlier by Watson and Humphreys is that there were three old elements in the present experiment and eight in the study of Watson and Humphreys (1997). The time required for inhibition to build up may be dependent on the number of old elements. If a relatively small number of old elements is presented, as was the case in the present experiment, inhibition may require less time to build up than it does if the number of old elements is large.

The findings of Experiment 2 are different from those of Experiment 1. In Experiment 2, in which old and new elements differed in color, the results suggest that inhibition was applied to the old elements prior to the presentation of the new ones. By contrast, we failed to find evidence for inhibition prior to the presentation of the new elements in Experiment 1, in which old and new elements were presented in the same color. This failure to find evidence for inhibition in Experiment 1 might have been related to observers not being involved in the prioritization of new elements. That is, the small number of elements might have made observers more inclined to passively wait for the stimuli instead of actively applying inhibition. We investigated this issue in Experiment 3.

Experiment 3

The aim of Experiment 3 was to investigate whether new elements were prioritized over old ones in the paradigm used in Experiments 1 and 2. Furthermore, we wanted to replicate the findings of Experiments 1 and 2 with regard to probe detection and extend them to larger display sizes. Experiment 3 consisted of two conditions: one condition in which old and new elements were presented in the same color (as they were in Experiment 1) and a second condition in which they differed in color (as they did in Experiment 2). In both conditions, the number of old elements and the number of new elements were orthogonally varied. This manipulation allowed us to evaluate whether the new elements were prioritized in the present experiment. If new elements are prioritized over old ones, performance should be independent of the number of old elements, whereas it should deteriorate with the number of new elements (Theeuwes, Kramer, & Atchley, 1998).

Unlike in Experiments 1 and 2, the major dependent variable on the search trials was RT (instead of accuracy). RT is a more sensitive measure by which to determine whether new elements were prioritized over old ones. Moreover, RT allows one to dismiss the possibility of ceiling effects. As in Experiments 1 and 2, the majority of trials consisted of search trials, and a minority consisted of probe detection trials. On probe detection trials, the SOA between the presentation of the old elements and the presentation of the tone indicating a probe detection trial was held constant at 750 ms.

Method

Participants. Sixteen students, 9 women and 7 men (age range: 17–31 years), volunteered to participate in exchange for a €6 (U.S.$7.65) fee. All participants had normal or corrected-to-normal vision and did not know the purpose of the experiment. Two participants had taken part in Experiment 1 or Experiment 2.

Materials. The materials were identical to those in Experiment 2.

Task and stimuli. The stimuli were identical to those in Experiments 1 and 2. Old and new elements had identical colors in one half of the experiment and different colors in the other half. Participants were presented with a letter search task on 75% of the trials, whereas the remaining 25% of the trials were probe detection trials. The number of old elements (three or six) and the number of new elements (three or six) were orthogonally manipulated and presented in a 4 × 3 matrix within an imaginary rectangle of 3.70° × 4.70° of visual angle.

Letter search trials. Letter search trials were identical to those in Experiments 1 and 2 until the presentation of the old elements. Then, three or six distractors (old elements) were presented. These elements were arranged diagonally such that the center locations of one or more rows were occupied as well as the two outer locations of their adjacent row or rows (see Figure 4). When there were three old elements, these were placed in the two middle rows, as in Experiments 1 and 2. When there were six old elements, these were placed in all four rows. After 1,000 ms, three or six new elements were added to the display at previously unoccupied locations. New elements were placed in the two middle rows (three new elements) or in all four rows (six new elements).

The target was present on 50% of the trials. All elements remained visible until a participant responded or a maximum of 3,000 ms had elapsed. Half of the participants had to make a speeded response by pressing either the left *control* key if the target was present or the left *alt* key if the target was absent. For the other half of the participants, the stimulus–response mapping was reversed.

Probe detection trials. Probe detection trials were identical to probe detection trials in Experiments 1 and 2 except for two changes. First, the tone was always presented 750 ms after the presentation of the old elements. Again, the probe, if present, appeared on offset of the tone. Second, the number of old elements was varied between three and six. Probes could be presented on all locations.

Design and procedure. The experiment was divided in two sessions. In one session, old and new elements were presented in the same color, as they were in Experiment 1. In another session, old and new elements differed in color, as they had in Experiment 2. Both sessions consisted of two experimental blocks of 128 trials each. These were preceded by one or more practice blocks of 64 trials each. Participants practiced until detection accuracy was over 85% in both types of trials, which was obtained after between one and three practice blocks prior to the first session. Prior to the second session, 85% accuracy was always obtained after one practice block. Session order was counterbalanced across participants. Within a

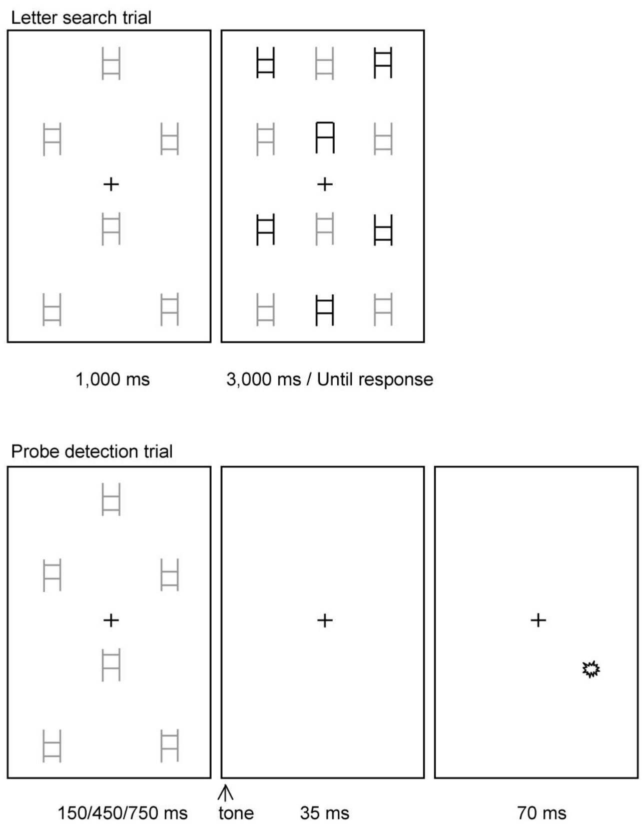

Figure 4. The sequence of displays in letter search and probe detection trials in Experiment 3. In this example letter search trial, old and new elements have different colors.

block, participants were presented with a letter search task on 75% of the trials, whereas the remaining 25% of the trials were probe detection trials. Number of old elements (three, six), number of new elements (three, six), probe presence (present, absent), and probe location (old, new) were randomly varied within blocks of trials.

Results

Figure 5 shows mean correct search RTs as a function of condition, number of old elements, number of new elements, and target presence. An ANOVA was conducted on the mean correct search RTs with condition (color difference, no color difference), number of old elements (three, six), number of new elements (three, six), and target presence (present, absent) as repeated measures factors. There was a significant main effect of number of new elements, $F(1, 15) = 74.28$, $p < .01$, indicating that RTs increased with the number of new elements. Furthermore, there was an effect of target presence, $F(1, 15) = 41.94$, $p < .01$. Generally, RTs were longer when the target was absent than they were when it was present. The Target Presence × Number of New Elements interaction was significant, $F(1, 15) = 15.01$, $p < .01$, indicating that the effect of number of new elements was stronger on target-absent trials than on target-present trials. There were neither effects of condition nor of number of old elements (Fs < 1). These findings show that regardless of whether old and new elements have different colors, participants are able to restrict their search to new items. Whether this restriction is accomplished by marking of the old items or by onset capture of the new ones can be established by the probe data, to which we turn below. An ANOVA on the detection accuracy in the letter search trials did not reveal any significant effects.

Figure 6 shows the mean correct probe RTs as a function of condition and probe location. We conducted an ANOVA on the mean correct probe RTs with condition (color difference, no color difference) and probe location (old, new) as repeated measures factors. There was a significant Condition × Probe Location interaction, $F(1, 15) = 5.07$, $p < .05$, indicating that the effect of probe location varied as a function of condition. There was no significant effect of probe location when old and new elements had the same color ($t < 1$). In contrast, when old and new elements were presented in different colors, probes were detected faster on new than on old locations, $t(15) = 3.50$, $p < .01$. The error percentages in the probe detection trials as a function of condition are summarized in Table 1. An ANOVA on the mean error

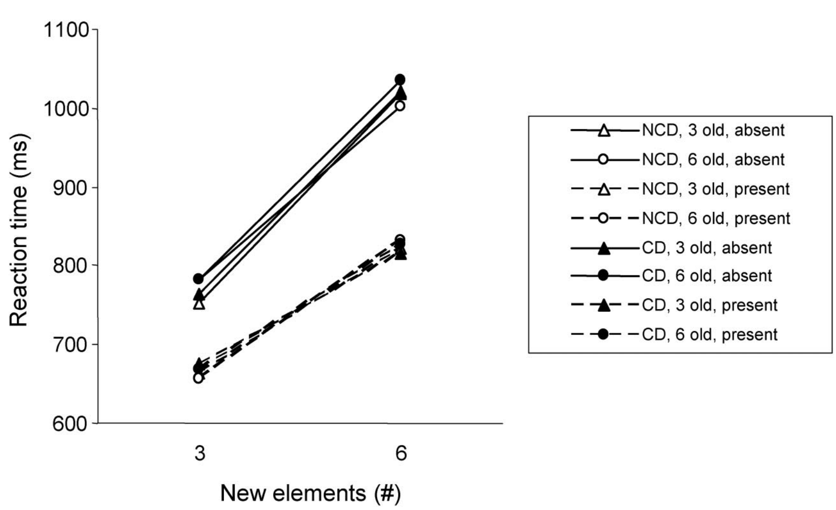

Figure 5. Mean correct search reaction times as a function of condition, target presence, number of old elements, and number of new elements in Experiment 3. NCD = no color difference; CD = color difference.

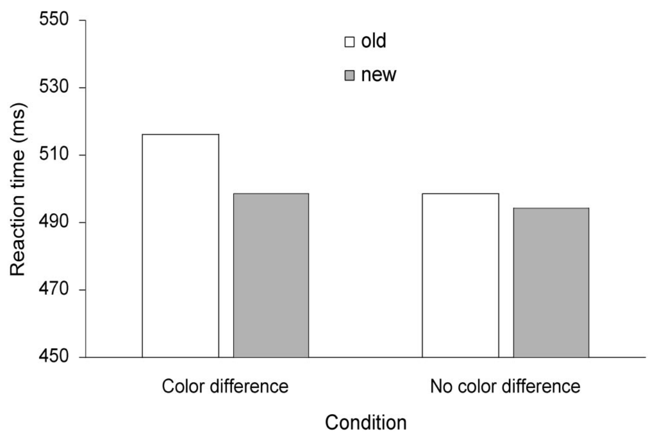

Figure 6. Mean correct probe reaction times as a function of probe location and condition in Experiment 3.

percentages with condition (color difference, no color difference) and probe location (old, new) as repeated measures factors did not reveal any significant effects.

Discussion

Experiment 3 was designed to test whether new elements receive prioritized selection over old ones. The results show that RT was independent of the number of old elements, whereas it increased with the number of new elements. Apparently, the old elements did not compete for attention during the search process. New elements were prioritized over old ones. A second aim of Experiment 3 was to generalize the findings of Experiments 1 and 2 to larger display sizes. When old and new elements were presented in the same color, probe RT was independent of probe location. When old and new elements were presented in different colors, probes were detected faster on a location corresponding to a new element than they were on a location corresponding to an old element. These findings suggest that inhibition prior to the presentation of the new elements only occurs when there is a color difference between old and new elements. Nevertheless, observers always prioritize new over old elements, irrespective of the presence of a color difference between old and new elements. This latter finding suggests that the mechanism responsible for prioritized selection of new over old elements does not necessarily operate prior to the presentation of new elements.

General Discussion

The present study investigated the role of element color in preview search. In Experiment 1, old and new elements were presented in the same color. Probes were detected equally quickly on new and on old locations prior to the presentation of new elements. Probes presented after the appearance of the new elements were detected faster on new than on old locations. These findings are not in line with the original VM account (Watson & Humphreys, 1997). According to this account, observers are assumed to be actively involved in inhibiting the locations of old elements prior to the presentation of new elements. Consequently, old locations should have been inhibited prior to presentation of the new elements. The results of Experiment 1 indicate that this was not the case. Instead, probes were detected faster on new than on old locations only after presentation of the new elements. This suggests that if old and new elements have the same color, prioritized selection is most likely mediated by the abrupt onsets accompanying the appearance of the new elements (Donk & Theeuwes, 2001).

The results obtained in Experiment 1 were fundamentally different from those obtained earlier by Humphreys et al. (2004), who found that probes were detected faster on new than on old locations prior to the presentation of new elements. In their study, however, element color was perfectly correlated with oldness–newness of elements. We hypothesized that the RT difference found by Humphreys et al. (2004) might have been mediated by a color-based inhibition process (for a similar argument, see Theeuwes et al., 1998). We tested this idea in Experiment 2. Experiment 2 was identical to Experiment 1 except that old and new elements differed in color. The results of Experiment 2 demonstrated that when old and new elements differed in color, probes were detected faster on new than on old locations, both before and after the presentation of new elements. These findings were replicated and extended in Experiment 3, in which we orthogonally varied the number of old and new elements between three and six. The findings indeed suggest that old elements can be deprioritized prior to the appearance of new elements. However, contrary to what is predicted by the original VM account, the application of this inhibition was critically dependent on the presence of a color difference between old and new elements. The new elements' advantage was only present prior to presentation of the new elements when old and new elements differed in color.

Many authors have suggested that observers can adopt a subset-selective search mode that is based on the presence of a color difference (Brawn & Snowden, 1999; Egeth et al., 1984; Kaptein et al., 1995; Moore & Egeth, 1998). For instance, Kaptein et al. (1995) demonstrated that when observers searched for a red vertical bar among a variable number of red tilted bars and green vertical bars, RT was independent of the number of green bars. Kaptein et al. (1995) argued that observers probably prioritize one subset of elements sharing the relevant color over another subset of elements lacking the target color. The results of the present study provide positive support for this idea, with the addition that the mechanism responsible for color-based subset-selective search is possibly related to the application of inhibition. It is possible that if two subsets of elements differ in color, observers may voluntarily deprioritize the selection of the irrelevant subset by actively inhibiting the locations of the elements of that irrelevant subset.

Whether the application of such a color-based inhibition mechanism contributes to better performance in the preview paradigm is, however, questionable. It has repeatedly been demonstrated (Donk & Theeuwes, 2001, 2003; the present Experiment 3) that when new elements are presented with luminance onset, the preview benefit is perfect, leaving no room for improvement. Moreover, the present study demonstrated that performance in the letter search task was strikingly similar across conditions. Thus, performance was similar irrespective of whether old and new elements were differently colored. This again suggests that the presence of a color difference does not really contribute to a better ability to prioritize the selection of new over old elements in the preview paradigm.

The results obtained by Braithwaite and Humphreys (2003; see also Braithwaite et al., 2003) were quite different, however. They examined, among other things, the effects of color mixing on preview search across old and new elements. They found that color mixing had a profound effect on search efficiency. That is, performance was worse when the target shared its color with the majority of the old elements relative to when it shared its color with a minority of the old elements.

A possible reason for the discrepancy between the present results and those obtained by Braithwaite and Humphreys (2003) is that color perfectly correlated with oldness–newness in the present study, whereas this was not the case in the study of Braithwaite and Humphreys. In our Experiment 2, all old elements were in one color, and all new elements were in another color. In Braithwaite and Humphreys (2003), color and oldness–newness were partly orthogonally manipulated. As a result, color-based inhibition allowed observers to further limit their search process above and beyond subset selection on the basis of oldness–newness. It is clear that if observers can further limit the size of the relevant subset, color may affect search efficiency. When, however, as in the present study, color is redundant with oldness–newness, it may not contribute to the ability to prioritize the selection of new over old elements.

In conclusion, our results support the idea that if old and new elements have the same color, prioritized selection is based on onset capture, not on visual marking. If old and new elements differ in color, observers may additionally use a color-based inhibition mechanism. Whether the application of this mechanism contributes to the search efficiency seems to depend on the extent to which color enables the observer to limit the search process above and beyond the limitations imposed by the preview task.

References

Atchley, P., Jones, S. E., & Hoffman, L. (2003). Visual marking: A convergence of goal- and stimulus-driven processes during visual search. *Perception & Psychophysics, 65,* 667–677.

Belopolsky, A. V., Theeuwes, J., & Kramer, A. F. (2005). Prioritization by transients in visual search. *Psychonomic Bulletin & Review, 12,* 93–99.

Braithwaite, J. J., & Humphreys, G. W. (2003). Inhibition and anticipation in visual search: Evidence from effects of color foreknowledge on preview search. *Perception & Psychophysics, 65,* 213–237.

Braithwaite, J. J., Humphreys, G. W., & Hodsoll, J. (2003). Color grouping in space and time: Evidence from negative color-based carryover effects in preview search. *Journal of Experimental Psychology: Human Perception and Performance, 29,* 758–778.

Brawn, P., & Snowden, R. J. (1999). Can one pay attention to a particular color? *Perception & Psychophysics, 61,* 860–873.

Donk, M., & Theeuwes, J. (2001). Visual marking beside the mark: Prioritizing selection by abrupt onsets. *Perception & Psychophysics, 63,* 891–900.

Donk, M., & Theeuwes, J. (2003). Prioritizing selection of new elements: Bottom-up versus top-down control. *Perception & Psychophysics, 65,* 1231–1242.

Donk, M., & Verburg, R. C. (2004). Prioritizing new elements with a brief preview period: Evidence against visual marking. *Psychonomic Bulletin & Review, 11,* 282–288.

Egeth, H. E., Virzi, R. A., & Garbart, H. (1984). Searching for conjunctively defined targets. *Journal of Experimental Psychology: Human Perception and Performance, 10,* 32–39.

Gibson, B. S., & Peterson, M. A. (2001). Inattentional blindness and attentional capture: Evidence for attention-based theories of visual salience. In C. L. Folk & B. S. Gibson (Eds.), *Attraction, distraction and action: Multiple perspectives on attentional capture* (pp. 51–76). Oxford, England: Elsevier Science.

Humphreys, G. W., Jung Stalmann, B., & Olivers, C. (2004). An analysis of the time course of attention in preview search. *Perception & Psychophysics, 66,* 713–730.

Humphreys, G. W., Watson, D. G., & Jolicœur, P. (2002). Fractioning the preview benefit in search: Dual-task decomposition of visual marking by timing and modality. *Journal of Experimental Psychology: Human Perception and Performance, 28,* 640–660.

Ives, H. E. (1912). Studies of the photometry of different colours: I. Spectral luminosity curves obtained by equality of brightness photometer and the flicker photometer under similar conditions. *Philosophical Magazine, 24,* 149–188.

Jiang, Y., Chun, M. M., & Marks, L. E. (2002). Visual marking: Dissociating effects of new and old set size. *Journal of Experimental Psychology: Human Perception and Performance, 28,* 717–730.

Jonides, J., & Yantis, S. (1988). Uniqueness of abrupt visual onset in capturing attention. *Perception & Psychophysics, 43,* 346–354.

Kaptein, N. A., Theeuwes, J., & Van der Heijden, A. H. C. (1995). Search for a conjunctively defined target can be selectively limited to a color-defined subset of elements. *Journal of Experimental Psychology: Human Perception and Performance, 21,* 1053–1069.

Kunar, M. A., Humphreys, G. W., & Smith, K. J. (2003). Visual change with moving displays: More evidence for color feature map inhibition during preview search. *Journal of Experimental Psychology: Human Perception and Performance, 29,* 779–792.

Kunar, M. A., Humphreys, G. W., Smith, K. J., & Hulleman, J. (2003). What is "marked" in visual marking? Evidence for effects of configuration in preview search. *Perception & Psychophysics, 65,* 982–996.

Kunar, M. A., Humphreys, G. W., Smith, K. J., & Watson, D. G. (2003). When a reappearance is old news: Visual marking survives occlusion. *Journal of Experimental Psychology: Human Perception and Performance, 29,* 185–198.

Moore, C. M., & Egeth, H. (1998). How does feature-based attention affect visual processing? *Journal of Experimental Psychology: Human Perception and Performance, 24,* 1296–1310.

Olivers, C. N. L., & Humphreys, G. W. (2002). When visual marking meets the attentional blink: More evidence for top-down, limited-capacity inhibition. *Journal of Experimental Psychology: Human Perception and Performance, 28,* 22–42.

Schneider, W., Eschman, A., & Zuccolotto, A. (2002). *E-prime user's guide.* Pittsburgh, PA: Psychology Software Tools.

Theeuwes, J. (1991). Cross-dimensional perceptual selectivity. *Perception & Psychophysics, 50,* 184–193.

Theeuwes, J. (1992). Perceptual selectivity for color and shape. *Perception & Psychophysics, 51,* 599–606.

Theeuwes, J. (1994). Stimulus-driven capture and attentional set: Selective search for color and visual abrupt onsets. *Journal of Experimental Psychology: Human Perception and Performance, 20,* 799–806.

Theeuwes, J., Kramer, A. F., & Atchley, P. (1998). Visual marking of old objects. *Psychonomic Bulletin & Review, 5,* 130–134.

Watson, D. G., & Humphreys, G. W. (1997). Visual marking: Prioritizing selection for new objects by top-down attentional inhibition of old objects. *Psychological Review, 104,* 90–122.

Watson, D. G., & Humphreys, G. W. (2000). Visual marking: Evidence for inhibition using a probe-dot detection paradigm. *Perception & Psychophysics, 62,* 471–481.

Yantis, S. (1993). Stimulus-driven attentional capture. *Current Directions in Psychological Science, 2,* 156–161.

Yantis, S., & Jonides, J. (1984). Abrupt visual onsets and selective attention: Evidence from visual search. *Journal of Experimental Psychology: Human Perception and Performance, 10,* 601–621.

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