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Feature-blind attentional suppression of salient distractors

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Abstract

A recent paper has reported, for the first time, that people are capable of suppressing salient singleton distractors of unknown color if the search task requires them to search for the most prevalent of several shapes in the display. We identify here several potential limitations of the earlier findings. In particular, in the reported experiments, the likelihood of a salient distractor was higher than what is typically studied, the distractor object was similar in shape to the relevant objects, only two colors were studied, the distractor was consistently a fixed shape, and the distractor was always a unique shape different from the search targets. Each of these limitations leaves open some questions about the generality of the findings. We address each of the concerns here, and show, in five experiments, that the ability to suppress distractors of unknown color is a robust finding that is not compromised by the potential limitations identified. When searching for the most prevalent of several shapes in a display, people can indeed suppress capture by otherwise-salient color singleton distractors even when their color is not known in advance (i.e., in a feature-blind manner), facilitating efficient search. The experiments confirm the ability to suppress visual elements based on second-order (e.g., a unique color) or global salience information, and not merely based on first-order (e.g., a specific color) information.

Keywords Attentional capture · Suppression · Visual search · Visual attention

In order for people to efficiently process their visual worlds, it is necessary to bias processing in favor of the parts of a scene that are most important to them. One way in which this is accomplished is by suppressing elements that are known to be task irrelevant. For example, people can inhibit *locations* in a scene that are known to be less important, based either on explicit selection of relevant locations (e.g., Leber et al., 2016; Munneke et al., 2008), or on learned regularities in the scene (Huang et al., 2022; Wang & Theeuwes, 2018a, 2018b). Recently, it has also been found that people are able to suppress portions of a scene that contain *features* that are known to be irrelevant to the current task. For example, when a person is searching for one red shape among other red shapes, they are able to suppress attending to an otherwise-salient green shape in the scene (e.g., Chang & Egeth, 2021; Gaspelin et al., 2015, 2017; Stilwell et al., 2019, 2022; Stilwell & Gaspelin, 2021). Such feature-based suppression may enhance processing of scenes by allocating limited attentional resources to the elements that are most important.

Statement of significance
Efficient visual processing requires selection of the parts of a scene that are relevant to the observer's goal, and the avoidance of salient-but-irrelevant distractors in the scene. The ability to suppress attentional capture by otherwise-salient distractors has been believed to require that the distractor be a known color--until a recent paper demonstrated the possibility of suppressing color-unpredictable distractors. The present study extends that recent finding in five important ways by addressing, and dismissing, potential limitations in the previous experiments.

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There has been considerable interest in feature-based suppression in order to understand the conditions under which salient elements can be suppressed, as opposed to those under which salient elements will reflexively capture attention (Luck et al., 2020). Until recently, this research has suggested that a salient color singleton can be suppressed only if its defining feature (e.g., its color) is known in advance: If the irrelevant item in a display appears randomly in one of two colors, it cannot be suppressed (Gaspelin & Luck, 2018b; but see the following). This suggests that suppressive mechanisms operate on only a first-order, feature-based representation of the scene—that is, a specific color—and not on a higher-order, feature-blind representation, such as a unique color or a highly salient item.

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Ma and Abrams (2022) suggested, however, that the task typically used to study suppression may have prevented observation of the full range of suppressive capabilities. In particular, most previous studies of suppression used tasks in which participants searched for a prespecified target among an array of heterogeneous shapes (e.g., Gaspelin et al., 2015). Because the target itself was a unique single-instance item in those searches, suppressing any unique item, such as a color singleton distractor (i.e., a higher-order suppression) may have been counterproductive to the goals of the search task. As a result, the failure to find anything other than first-order suppression may have revealed a limitation of the search tasks used, and not a limitation of the attentional mechanisms. To test this idea, Ma and Abrams developed a new search task that did not suffer from that limitation—a *majority search* task. In their task, participants were asked to identify the most prevalent of several shapes with multiple instances in the display. Because the task goal did not require identification of a unique element, the task may have permitted suppression of any salient unique item in the display. Consistent with that analysis, Ma and Abrams found that people are capable of suppressing salient items that are of a unique color, even if their specific color is unknown. Those results revealed a previously unknown capability of the suppressive attentional mechanisms, and show that suppression can operate on a representation higher than simply a first-order feature. In particular, people are capable of suppressing portions of a scene containing a unique item (or a highly salient item) of unpredictable color.

The majority search task used by Ma and Abrams (2022) might be thought to be unusual in some ways because it departs from the tasks typically used to study suppression. However, quantity-guided, rather than specific-feature-guided, visual search may not be uncommon. For example, consider comparing boxed strawberries for the one containing the most fruit, or comparing stadium entrance lines for the one with the fewest people. Nevertheless, there are some limitations in the experiments reported by Ma and Abrams. In light of the novelty and importance of the findings, our goal here was to examine those limitations in order to assess the generality of the higher-order suppression that they reported. In each of the experiments that follow, we address one of five limitations identified in the earlier experiments. In each experiment here, the results reveal robust suppression of unknown-color singletons, confirming the earlier conclusions and extending the conditions under which higher-order suppression can be observed.

Experiment 1

In order to study suppression of salient distractors, it is necessary to compare performance on trials in which a salient distractor is present in the search array to trials that do not contain a distractor. In most previous studies of suppression, the distractor has been present on 50% of the trials. The 50% distractor probability would presumably permit participants to adopt a search strategy that was not biased to expect a distractor (as suggested by Wöstmann et al., 2022). However, in the Ma and Abrams (2022) experiments, a distractor was present on two-thirds of the trials. This raises the possibility that participants used an atypical search strategy that was specifically tuned to the distractors, and the results might not reflect a more natural search in which a distractor appears relatively infrequently. Indeed, Geyer et al. (2008) and Won et al. (2019) have shown that salient distractors have a reduced effect when they appear on a greater proportion of trials. To examine that possibility, in the present experiment, we repeated Experiment 1 from Ma and Abrams with the only change being that we reduced the probability of a distractor from two-thirds to one-third of the trials. We assumed that here, with a distractor probability considerably less than 50%, any ability to suppress distractors of unpredictable color would more accurately reflect the consequences of the attentional control settings required for the majority search task, and not a strategy specifically tuned to frequently encountered distractors.

Method

Participants Twenty-four undergraduate students (eight males; 16 females) participated in the experiment. The same number of participants were recruited as in Ma and Abrams (2022). Based on an average effect size $d_z = .75$ from Experiments 1 and 2 in Ma and Abrams, the sample size is sufficient to detect a singleton presence benefit effect with a power of .97 using G*Power (Erdfelder et al., 1996). All participants reported normal or corrected-to-normal visual acuity, and normal color vision. Informed consent was obtained from individual participants.

Stimuli The experiment was programed in the PsychoPy software (Peirce et al., 2022). As shown in Fig. 1, the six-item search array was presented with the shapes centered on the circumference of an invisible circle ($r = 2°$), each separated by 60°. The array consisted of either three circles (1.4° × 1.4°) and two squares (1.2° × 1.2°), or two circles and three squares, plus a hexagon (1.5° × 1.5°). Items in the array were either all red or all green, except that on trials with a color singleton distractor the hexagon appeared in the alternate color. A fixation cross (0.7° in height) was displayed at the center of the screen. Stimuli were displayed against a black background.

Procedure Each trial began with a central fixation cross for 1,000 ms, which remained on the screen until the trial

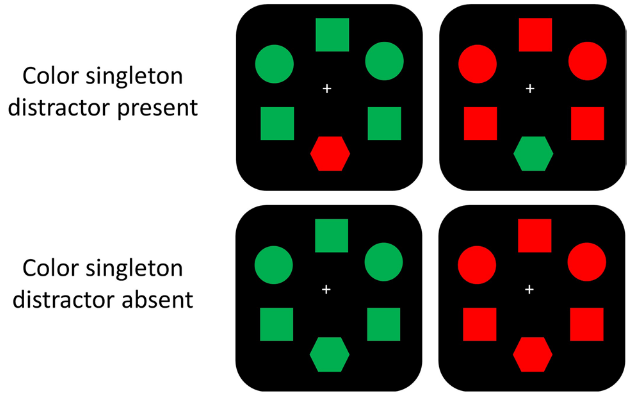


Fig. 1 Examples of search arrays used in Experiment 1. Participants indicated whether circles or squares were more prevalent in the array. The colors of the task-relevant items and the presence of a color-singleton distractor were unpredictable. See text for additional details. (Color figure online)

ended. Next, a six-item search array appeared. Participants were required to report the most prevalent shape in the display—either circles or squares—by pressing either the "Z" or "M" key as quickly and accurately as possible. The search array remained on the screen until response or after 2,500 ms had elapsed without responding. Performance feedback of "Incorrect!" or "Too slow!" was displayed for 1,000 ms unless a correct response was registered. The next trial began after a blank screen delay of 1,000 ms.

Design The circles and the squares appeared equally often as the most prevalent shapes, and they were all either red or green (equally often). On two-thirds of the trials, the hexagon distractor appeared in the same color as the relevant items (*color-singleton-absent* condition). On the other one-third of the trials, the hexagon appeared in the alternate color (*color-singleton-present* condition). Participants were instructed to ignore the unique color, as the most prevalent shapes would always be homogeneously colored. The most prevalent shape, array color, and color singleton distractor presence were manipulated to be fully crossed with each other, with the different types of trials presented in random order. The locations of the search array items were randomly selected on each trial. After a practice block of 24 trials, participants performed three blocks of 96 trials each, each consisting of 64 color-singleton-absent trials, and 32 color-singleton-present trials.

Results and discussion

Trials with reaction times (RTs) more than two standard deviations from each individual participant's mean (separately for the color-singleton-absent, red-color-singleton-present, and green-color-singleton-present conditions; 4.4%), and trials with an incorrect response (5.3%) were not included in the RT analysis. All 24 participants met an 80% or greater overall accuracy criterion to be included in the analysis.

Primary analysis Reaction times and accuracies are shown in Fig. 2. Data analysis in all experiments was performed in R (R Core Team, 2020). The *t* tests were conducted using the R base function t.test. The effect size d_z was calculated using the lsr package and the cohensD function (Navarro, 2015). A paired-samples *t* test showed that participants were significantly faster to report the majority search target in the

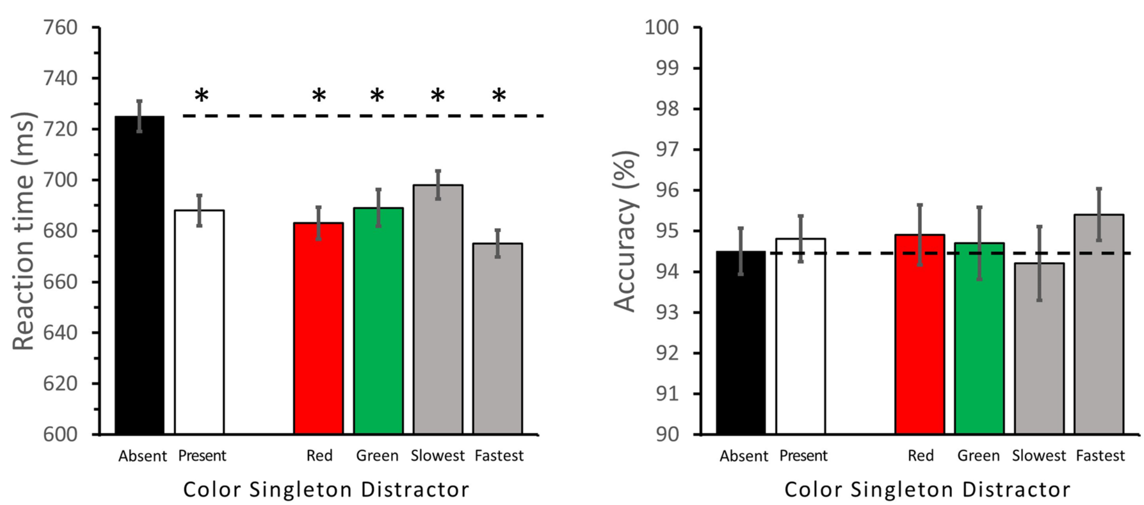


Fig. 2 Reaction time (left) and accuracy (right) from Experiment 1. Asterisks indicate conditions that significantly differed from the color singleton distractor-absent condition (all *ps* < .001). Error bars represent within-subject standard errors, calculated using the superb package in R (Cousineau et al., 2021). (Color figure online)

color-singleton-present condition (688 ms) compared with the color-singleton-absent condition (725 ms), $t(23) = 6.21$, $p < .001$, $d_z = 1.27$. This singleton presence benefit indicates effective suppression of the unpredictable-color distractor. The same analysis on accuracy did not reveal a significant difference between the color-singleton-present (94.8%) and color-singleton-absent (94.5%) conditions, $t(23) = .50$, $p = .622$, $d_z = .10$.

Additional analyses The comparison of the overall RT showed that the presence of a color singleton distractor speeded performance, which is consistent with effective suppression of the color-unpredictable singleton distractor. However, it is possible that the overall performance benefit was mainly driven by suppression of one particular singleton color, rather than both colors. To test that possibility, we separately examined the RTs on trials with a red color singleton distractor and trials with a green color singleton distractor. Both the presence of a red color singleton distractor (683 ms) and a green color singleton distractor (689 ms) led to significantly faster RT compared with the color-singleton-absent trials (725 ms), for red: $t(23) = 6.23$, $p < .001$, $d_z = .43$; for green: $t(23) = 4.72$, $p < .001$, $d_z = .38$. This indicates that both the red and green colors were suppressed across participants. Furthermore, to take into account individual differences in the ability (or choice) to suppress different colors, we identified each individual's *most suppressed* color, as indexed by faster RTs in the presence of a singleton distractor of that color ("Fastest" in Fig. 2), and each individual's *least suppressed* color, as indexed by slower RTs in the presence of a singleton distractor of that color ("Slowest" in Fig. 2). It was found that the presence of a singleton distractor in both the fastest (i.e., most suppressed; 675 ms) and the slowest (i.e., least suppressed; 698 ms) color led to significantly faster RT than the color-singleton-absent condition, for fastest color: $t(23) = 7.56$, $p < .001$, $d_z = .53$; for slowest color: $t(23) = 3.96$, $p < .001$, $d_z = .29$. This confirms the effective suppression of both colors, indicating that the suppressive mechanism can operate at a higher order for unpredictable stimulus features, even when the distractor probability is low.

Analysis of accuracies for the subsets of trials discussed above revealed equivalent accuracy in all conditions. None of the individual distractor types differed from the singleton distractor-absent condition (94.5%) in accuracy, for the red distractor: 94.9%, $t(23) = .60$, $p = .558$, $d_z = .11$; for the green distractor: 94.7%, $t(23) = .25$, $p = .806$, $d_z = .06$; for the slowest color: 94.2%, $t(23) = .39$, $p =.699$, $d_z = .09$; and for the fastest color: 95.4%, $t(23) = 1.68$, $p = .107$, $d_z = .28$.

In the present experiment, there was a 50% chance that the color of the search array items repeated from one trial to the next. As a result, it is possible that the observed suppression may have been driven in part by priming of the target color from one trial to the next, as opposed to suppression of the singleton distractor. To test that possibility, we separately analyzed distractor-present trials with the same task-relevant item color as the preceding trial (*color-repeat trials*; for example, a trial with a red singleton and green task-relevant items, like that in the upper left corner of Fig. 1, that is preceded by either a similar trial type or a trial with green task-relevant items and no singleton, like that in the lower left corner of Fig. 1), and distractor-present trials with a different task-relevant color as the preceding trial (*color-switch trials*). The results showed that both the color-repeat trials (675 ms) and the color-switch trials (695 ms) had significantly faster RTs than the color-singleton-absent condition (725 ms), for color-repeat trials: $t(23) = 5.41$, $p < .001$, $d_z = .56$; for color-switch trials: $t(23) = 5.54$, $p < .001$, $d_z = .30$. Analysis of accuracy showed that neither type of trial differed from the singleton distractor-absent condition (94.5%), for color-repeat trials: 94.7%, $t(23) = .22$, $p = .824$, $d_z = .05$; for color-switch trials: 94.7%, $t(23) = .34$, $p = .738$, $d_z = .07$. These analyses alleviate the concern that the observed suppression effect was mainly driven by priming of the target color from the preceding trial, and help attribute the effect to the requirements of the majority search task.

Experiment 2

The results of Experiment 1 revealed suppression of salient singletons even when their color was not predictable—there was a large singleton presence benefit. However, it is possible that in Experiment 1, as well as in the experiments of Ma and Abrams (2022), the singleton presence benefit actually reflected a singleton absence cost. In particular, the nonrelevant item in the displays of those experiments was a hexagon, which, as a six-sided polygon, is geometrically intermediate between the relevant shapes of square (a four-sided polygon) and circle (an infinite-sided polygon), and thus may have been easily confused with the circles and squares when all of the shapes were the same color (i.e., when the singleton distractor was absent). This possibility is supported by results from the probe task used in Ma and Abrams's Experiment 2. In that task, participants reported the identity of probe letters that were presented briefly on the shapes of the search array. When no singleton was present, participants were just as likely to report letters on the irrelevant shape as they were to report letters on the relevant shapes. Although such a result may also simply reflect the fact that the entire search array was attended on trials without a color singleton (a necessity of the majority search task), it remains possible that the finding of higher-order suppression was in part due to the similarities of the specific shapes that were used. To examine that possibility, in the present experiment, we repeated Experiment 1 from Ma and Abrams with more geometrically distinct shapes used for the relevant and irrelevant items: The relevant shapes were angular polygons (triangles and squares), and the irrelevant shape was a circle. Any suppression observed under those conditions would be more readily attributable to a singleton presence benefit as opposed to a cost associated with distinguishing the distractor shape from the relevant shapes on the distractor-absent trials.

Method

Participants A new group of 24 undergraduate students (seven males; 17 females) participated in the experiment. All participants reported normal or corrected-to-normal visual acuity, and normal color vision. Informed consent was obtained from individual participants.

Stimuli, procedure, and design Search displays are shown in Fig. 3. The experiment was similar to Experiment 1, except that the search array consisted of either three triangles (1.2° × 1.2°) and two squares (1.2° × 1.2°), or two triangles and three squares, plus a circle (1.5°). The triangle or the square was equally often the most prevalent shape. Here, as in the remaining experiments in the paper, we used the typical proportion of 50% for the presence of a color singleton distractor. After a practice block of 24 trials, participants performed two blocks of 96 trials each, each consisting of 48 color-singleton-absent trials, and 48 color-singleton-present trials.

Results and discussion

Trials with RTs more than two standard deviations from each individual participant's mean (separately for the color-singleton-absent, red color-singleton-present, and green color-singleton-present conditions; 4.3%), and trials with an incorrect response (5.8%) were not included in the RT analysis. All 24 participants met the 80% or greater overall accuracy criterion to be included in the analysis.

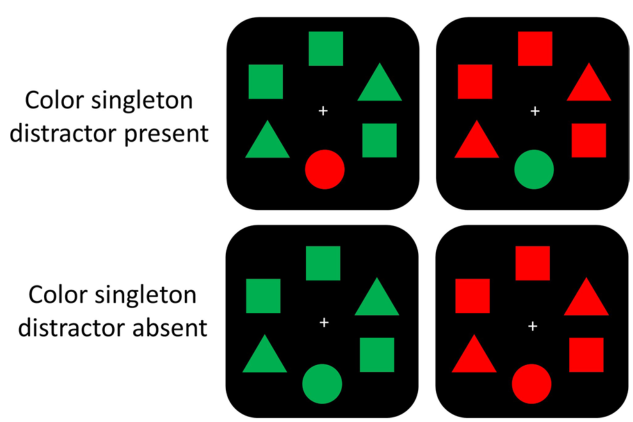


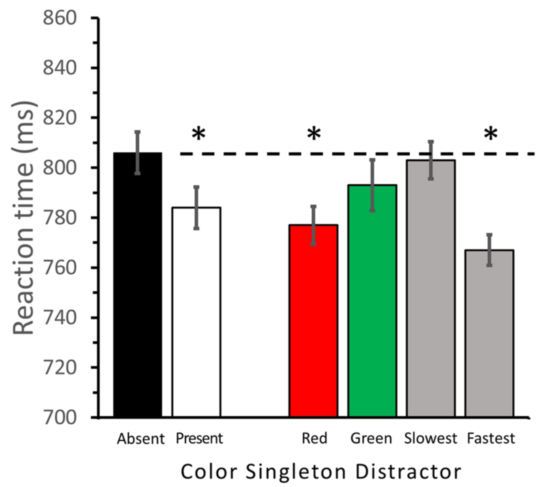
Fig. 3 Examples of search arrays used in Experiment 2. See text for additional details. (Color figure online)

Primary analysis Reaction times and accuracies are plotted in Fig. 4. A paired-samples t test showed that participants were significantly faster to report the majority search target in the color-singleton-present condition (784 ms) compared with the color-singleton-absent condition (806 ms), $t(23) = 2.71$, $p = .013$, $d_z = .55$. This singleton presence benefit indicates effective suppression of the unpredictable-color distractor. Consistent with the RT results, the same analysis on accuracy showed that the color-singleton-present condition (94.8%) was marginally significantly more accurate than the color-singleton-absent condition (93.5%), $t(23) = 1.99$, $p = .059$, $d_z = .41$.

Additional analyses The same analyses as in Experiment 1 were performed. The RT results showed that the red color singleton (777 ms) and the fastest (most suppressed) color (767 ms) led to significantly faster RT than the color-singleton-absent condition (806 ms), for red: $t(23) = 3.64$, $p = .001$, $d_z = .31$; for fastest color: $t(23) = 4.75$, $p < .001$, $d_z = .41$. Trials with a green color singleton (793 ms) and the slowest (least suppressed) color (803 ms) did not differ in RT from the color-singleton-absent condition, for green: $t(23) = 1.24$, $p = .228$, $d_z = .13$; for slowest color: $t(23) = .35$, $p = .728$, $d_z = .03$ (but see the following analysis of accuracy).

The analysis of accuracy showed suppression in the conditions that did not yield an effect on RT: the green color singleton distractor (95.8%) and the slowest color (95.7%) led to significantly higher accuracy than the color-singleton-absent condition (93.5%), for green: $t(23) = 2.95$, $p = .007$, $d_z = .55$; for the slowest color: $t(23) = 2.72$, $p = .012$, $d_z = .52$. Trials with a red color singleton distractor (93.8%) and the fastest color (94.0%) did not differ in accuracy from the color-singleton-absent condition, for red: $t(23) = .35$, $p = .733$, $d_z = .07$; for the fastest color: $t(23) = .53$, $p = .598$, $d_z = .11$.

To test the possibility of intertrial priming of the search array color, we also separately analyzed attentional suppression of the singleton distractor on color-repeat trials and color-switch trials. The results showed that the color-repeat trials (778 ms) had significantly faster RTs than the color-singleton-absent condition (806 ms), $t(23) = 3.09$, $p = .005$, $d_z = .28$. The color-switch trials (790 ms) had marginally significantly faster RTs than the color-singleton-absent condition; $t(23) = 1.84$, $p = .078$, $d_z = .17$. Note also that the distractor color on the color-switch trials matched the color of the task-relevant items on the preceding trial, potentially offsetting the suppression somewhat. Analysis of accuracy showed that the color-repeat trial (95.2%) had significantly



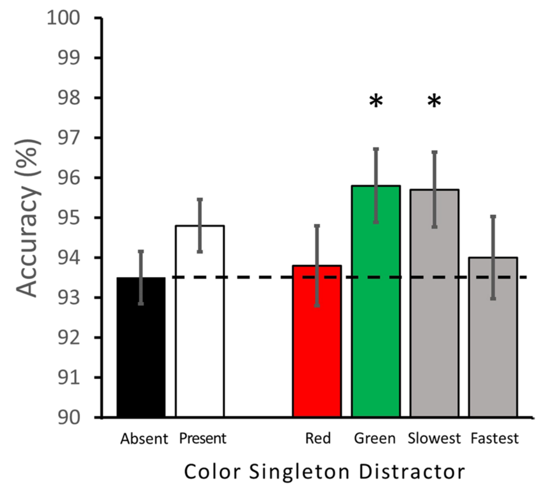


Fig. 4 Reaction time (left) and accuracy (right) from Experiment 2. Asterisks indicate conditions that significantly differed from the color singleton distractor-absent condition (see text for p-values). Error bars represent within-subject standard errors, calculated using the superb package in R (Cousineau et al., 2021). (Color figure online)

higher accuracy than the singleton absent condition (93.5%), $t(23) = 2.27$, $p = .033$, $d_z = .39$. The accuracy of the color-switch trial (94.5%) did not differ from the singleton absent condition, $t(23) = 1.36$, $p = .187$, $d_z = .25$.

Together the RT and the accuracy results confirm the effective suppression of both colors, providing evidence for higher-order suppression of unpredictable features even when the distractor shape is not confusable with the target shapes. Suppression was found in accuracy but not RT for some subsets of trials. We hesitate to speculate about the factors that might produce a singleton benefit in accuracy as opposed to reaction time; however, either measure provides evidence of suppression. A similar effect on accuracy as opposed to speed has not been observed in any of the other experiments reported here, or in the experiments of Ma and Abrams (2022), so the present pattern may simply be an isolated event.

Experiment 3

In Ma and Abrams (2022), and in most previous studies of suppression, the elements in the search task were presented in one of two colors (typically red or green). This raises two potential concerns. First, because there was a relatively high likelihood (50%) for the color of the task-relevant items to repeat from one trial to the next, it is possible that some of the distractor suppression observed was driven by priming of the target color on the preceding trial. Second, because only two colors ever needed to be suppressed, it is possible that participants adopted some strategy to specifically suppress either red or green elements when they were singletons. Of course, such a strategy would theoretically have been possible in the previous studies examining suppression (and it was not observed; Gaspelin & Luck, 2018b). Nevertheless, it leaves open the possibility that the limited number of colors artificially simplified the search task in a manner that permitted suppression that might not otherwise have been observed. To address those possibilities here, we repeated Experiment 1 from Ma and Abrams; however, instead of using only two colors, we used four. Two pairs of colors were used: green/magenta and blue/orange. On color-singleton-present trials, the two colors in each pair were separately assigned to the relevant and irrelevant items of the array.

Method

Participants A new group of 24 undergraduate students (four males; 20 females) participated in the experiment. All participants reported normal or corrected-to-normal visual acuity, and normal color vision. Informed consent was obtained from individual participants.

Stimuli, procedure, and design Search displays are shown in Fig. 5. The experiment was similar to Experiment 1, except that two pairs of colors: green/magenta and blue/orange were used to replace the red/green color pair. These specific color combinations were selected to maximize the salience of the color singleton (when present). The search array items appeared equally often in green, magenta, blue, and orange. A color singleton distractor was present on 50% of the trials. On a color-singleton-present trial, the singleton distractor appeared in the alternate color within the green/magenta pair or the blue/orange pair. After a practice block of 32 trials, participants performed two blocks of 96 trials each,

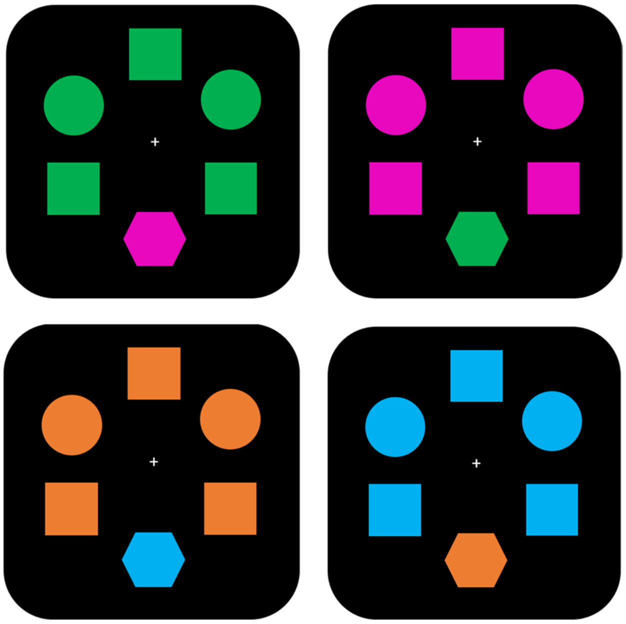


Fig. 5 Examples of search displays from Experiment 3 that contained color singleton distractors. Trials without distractors contained elements that were all one of the four colors shown. See text for additional details. (Color figure online)

each consisting of 48 color-singleton-absent trials and 48 color-singleton-present trials.

Results and discussion

Trials with RTs more than two standard deviations from each participant's mean (separately for the color-singleton-absent, and each of the color-singleton-present conditions; 4.8%), and trials with an incorrect response (3.8%) were not included in the RT analysis. All 24 participants met the 80% or greater overall accuracy criterion to be included in the analysis.

Primary analysis Reaction times and accuracies are shown in Fig. 6. A paired-samples *t* test showed that participants were significantly faster to report the majority search target in the color-singleton-present condition (764 ms) compared with the color-singleton-absent condition (826 ms), $t(23) = 6.82$, $p < .001$, $d_z = 1.39$. This singleton presence benefit indicates effective suppression of the unpredictable-color distractor. Consistent with the RT results, the same analysis on accuracy showed that the color-singleton-present condition (96.7%) was significantly more accurate than the color-singleton-absent condition (95.7%), $t(23) = 2.09$, $p = .048$, $d_z = .43$.

Additional analyses The same analyses as in the earlier experiments were performed on trials separately for each type of color singleton distractor. Results showed that the presence of a green (760 ms), magenta (775 ms), blue (762 ms), and orange (764 ms) color singleton all led to significantly faster RT compared with the color-singleton-absent trials (826 ms), for green: $t(23) = 6.83$, $p < .001$, $d_z = .64$; for magenta: $t(23) = 5.06$, $p < .001$, $d_z = .48$; for blue: $t(23) = 5.84$, $p < .001$, $d_z = .58$; for orange: $t(23) = 5.17$, $p < .001$, $d_z = .54$. This indicates that all four colors were suppressed across participants. We also further identified each individual's most suppressed (fastest) and least suppressed (slowest) color among the four. It was found that the presence of a singleton distractor in both the fastest (728 ms) and the slowest color (801 ms) led to significantly faster RT than the color-singleton-absent condition, for fastest color: $t(23) = 9.21$, $p < .001$, $d_z = .93$; for slowest color: $t(23) = 2.84$, $p = .009$, $d_z = .22$.

The same set of analyses on accuracy showed that the orange color singleton (97.4%) and the slowest color (97.2%)

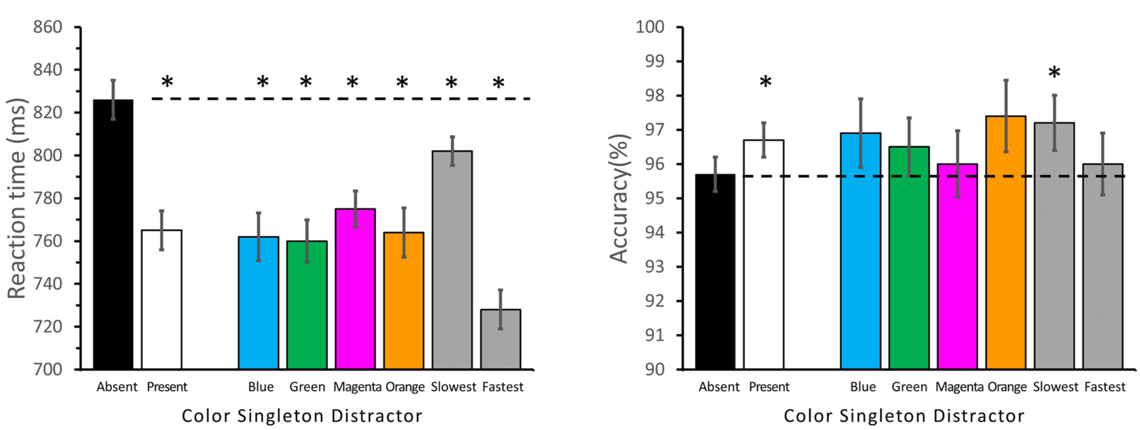


Fig. 6 Reaction time (left) and accuracy (right) from Experiment 3. Asterisks indicate conditions that significantly differed from the color singleton distractor-absent condition (see text for *p* values). Error bars represent within-subject standard errors, calculated using the superb package in R (Cousineau et al., 2021). (Color figure online)

produced significantly or marginally significantly higher accuracy than the color-singleton-absent condition (95.7%), for orange: $t(23) = 1.99$, $p = .058$, $d_z = .48$; for the slowest color: $t(23) = 2.41$, $p = .024$, $d_z = .48$. Trials with green (96.5%), magenta (96.0%), and blue (96.9%) color singletons, and the fastest color (96.0%) did not differ in accuracy from the color-singleton-absent condition, for green: $t(23) = 1.37$, $p = .183$, $d_z = .22$; for magenta: $t(23) = .43$, $p = .674$, $d_z = .09$; for blue: $t(23) = 1.52$, $p = .141$, $d_z = .34$; for the fastest color: $t(23) = .45$, $p = .654$, $d_z = .08$.

To test the possibility of intertrial priming of the search array color, we also separately analyzed attentional suppression of the singleton distractor on color-repeat trials and color-switch trials. The results showed that both the color-repeat trials (752 ms) and the color-switch trials (769 ms) had significantly faster RTs than the color-singleton-absent condition (826 ms), for color-repeat trials: $t(23) = 5.90$, $p < .001$, $d_z = .66$; for color-switch trials: $t(23) = 6.72$, $p < .001$, $d_z = .54$. Analysis of accuracy showed that neither type of trial differed from the singleton distractor-absent condition (95.7%), for color-repeat trials: 96.8%, $t(23) = 1.45$, $p = .161$, $d_z = .32$; for color-switch trials: 96.6%, $t(23) = 1.77$, $p = .091$, $d_z = .29$.

These results confirm effective suppression of all four colors regardless of repetition of the color configuration from the previous trial, demonstrating higher-order suppression of a larger set of colors than had been previously studied. The results help rule out the possibility that participants were somehow able to suppress the distractor based on its specific color when the color was only selected from a small set of two.

Experiment 4

In Ma and Abrams (2022) as well as Experiments 1–3 here, the color singleton distractor was one specific shape on all trials (a hexagon in Experiments 1 and 3, and in Ma & Abrams, 2022; a circle in Experiment 2). Thus, while the color singleton distractor was of unpredictable color, its shape was predictable. This may have limited its distractive effect somewhat, or otherwise facilitated suppression of it (Kim et al., 2023). This concern is partially alleviated by results from Experiment 2 of Ma and Abrams. In that experiment, probe letters presented briefly on the search array elements were not less likely to be reported when on the task-irrelevant hexagon shape when it was not a color singleton distractor, compared with the probe-letter-reports of the relevant shapes, suggesting that it was not the *shape* of the distractor item that caused it to be suppressed. However, an experiment that varies both the color and shape of the singleton distractor can more directly test that possibility, and we did that here. The present experiment employed the same general method as the earlier ones but made the task-irrelevant shape randomly either a hexagon or a square across trials (and also an unpredictable color), while participants searched through relevant shapes of circles and triangles.

Method

Participants A new group of 24 undergraduate students (six males; 18 females) participated in the experiment. All participants reported normal or corrected to normal visual acuity, and normal color vision. Informed consent was obtained from individual participants.

Stimuli, procedure, and design The search displays are shown in Fig. 7. The experiment was similar to Experiment 1 except that the task-relevant shapes were either three circles (1.4° × 1.4°) and two triangles (1.4° × 1.4°), or two circles and three triangles, equally often. For both possible most prevalent shapes (i.e., either circles or triangles), the task-irrelevant shape was either a hexagon (1.5° × 1.5°) or a square (1.2° × 1.2°), equally often. A color singleton distractor was present on 50% of the trials, equally often for the hexagon and square. The task relevant colors were equally often red or green, with the distractor, when present, green or red, respectively, in an unpredictable order. After a practice block of 24 trials, participants performed two blocks of 96 trials each, each consisting of 48 color-singleton-absent trials, and 48 color-singleton-present trials.

Results and discussion

Trials with RTs more than two standard deviations from each participant's mean (separately for the color-singleton-absent, red color-singleton-present, and green color-singleton-present conditions; 4.6%), and trials with an incorrect response (4.5%) were not included in the RT analysis. All

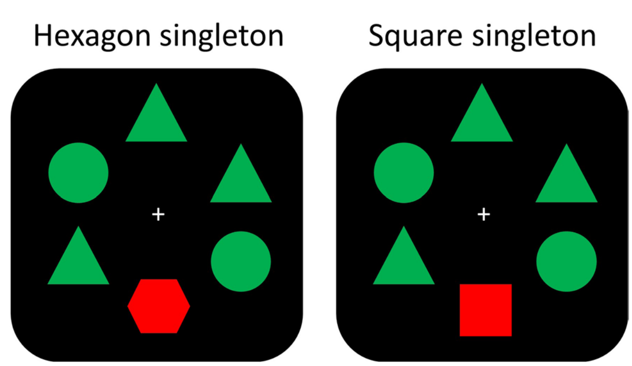


Fig. 7 Examples of search displays from Experiment 4 that contained color singleton distractors. The task-relevant shapes were randomly either all red or all green. See text for additional details. (Color figure online)

24 participants met the 80% or greater overall accuracy criterion to be included in the analysis.

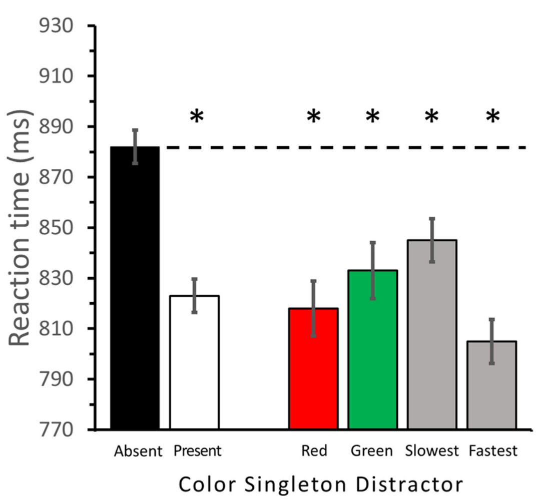
Primary analysis Results are shown in Fig. 8. A paired-samples *t* test showed that participants were significantly faster to report the majority search target in the color-singleton-present condition (823 ms) compared with the color-singleton-absent condition (882 ms), $t(23) = 9.03$, $p < .001$, $d_z = 1.84$. This singleton presence benefit indicates effective suppression of the unpredictable-color distractor. The same analysis on accuracy showed that the color-singleton-present condition (95.7%) did not differ in accuracy from the color-singleton-absent condition (95.3%), $t(23) = .66$, $p = .513$, $d_z = .14$.

Additional analyses The same additional analyses as earlier were performed. Both the presence of a red color singleton distractor (818 ms) and a green color singleton distractor (833 ms) led to significantly faster RT compared with the color-singleton-absent trials (882 ms), for red: $t(23) = 7.24$, $p < .001$, $d_z = .45$; for green: $t(23) = 5.41$, $p < .001$, $d_z = .33$. This indicates that both the red and green colors were suppressed across participants. We also further identified individuals' most suppressed (fastest) and least suppressed (slowest) color between the two. It was found that the presence of a singleton distractor in both the fastest (805 ms) and the slowest color (845 ms) led to significantly faster RT than the color-singleton-absent condition, for fastest color: $t(23) = 9.43$, $p < .001$, $d_z = .55$; for slowest color: $t(23) = 4.56$, $p < .001$, $d_z = .24$.

Analysis of accuracy revealed no differences between the singleton distractor-absent condition and any of the other conditions containing subsets of the different distractor types. For the red distractor: 95.2%, $t(23) = .117$, $p = .908$, $d_z = .02$; for green: 96.1%, $t(23) = 1.23$, $p = .23$, $d_z = .26$; for the slowest distractor: $t(23) = 1.62$, $p = .118$, $d_z = .28$; and for the fastest: $t(23) = .099$, $p = .922$, $d_z = .02$.

To test the possibility of intertrial priming of the search array color, we also separately analyzed attentional suppression of the singleton distractor on color-repeat trials and color-switch trials. The results showed that both the color-repeat trials (830 ms) and the color-switch trials (820 ms) had significantly faster RTs than the color-singleton-absent condition (882 ms), for color-repeat trials: $t(23) = 5.10$, $p < .001$, $d_z = .36$; for color-switch trials: $t(23) = 8.89$, $p < .001$, $d_z = .42$. Analysis of accuracy showed that neither type of trial differed from the singleton distractor-absent condition (95.3%), for color-repeat trials: 95.1%, $t(23) = .27$, $p = .792$, $d_z = .05$; for color-switch trials: 96.1%, $t(23) = 1.16$, $p = .256$, $d_z = .24$.

We also considered the possibility that suppression was effective only for one of the two distractor shapes. To examine that, we conducted the same analysis as above, separately for trials containing square distractors and those containing hexagon distractors. The pattern for each distractor shape was identical to the overall pattern. RTs with a hexagon singleton were faster when the hexagon was a color singleton distractor (827 ms) compared with when it was not a color singleton (893 ms), $t(23) = 6.06$, $p < .001$, $d_z = 1.24$. And RTs with a square singleton were faster when the square was a color singleton distractor (817 ms) compared with when it was not a color singleton (875 ms), $t(23) = 6.00$, $p < .001$, $d_z = 1.23$. Accuracies for singleton distractor present conditions did not differ from those for the singleton distractor



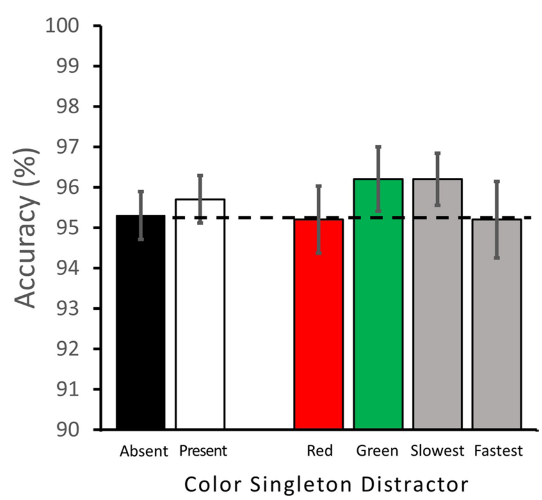


Fig. 8 Reaction time (left) and accuracy (right) from Experiment 4. Asterisks indicate conditions that significantly differed from the color singleton distractor-absent condition (all *p*s < .001). Error bars represent within-subject standard errors, calculated using the superb package in R (Cousineau et al., 2021). (Color figure online)

absent for either shape: for the hexagon (when a color singleton = 95.9%, when not a color singleton = 95.0%), $t(23) = 1.16$, $p = .257$, $d_z = .24$; for the square (when a color singleton = 95.5%, when not a color singleton = 95.7%), $t(23) = .24$, $p = .814$, $d_z = .05$.

The results show that participants were able to successfully suppress unpredictable-color singleton distractors when both the color and shape of the distractor were not known in advance, further bolstering the conclusions from the earlier experiments, and firmly establishing the capability of feature-blind, higher-order suppression of salient singletons.

Experiment 5

Experiment 4 showed that participants were able to suppress color singletons of unpredictable color even when their shape also was unpredictable. However, in that experiment, as in each of the previous experiments, the singleton distractor was always uniquely shaped, different from the shapes of the task-relevant items. If suppression of the singleton was performed on the basis of the uniqueness of its color, then people might also be able to suppress a color singleton even if its shape matched that of the relevant items. We tested that possibility here by including color singleton distractors that were sometimes of the same shape as the items relevant to the majority search. In order to do that, we instructed participants to ignore any color singletons, even if they happened to match the shape of the two shapes being compared in the majority search task.

Method

Participants A new group of 24 undergraduate students (eight males; 16 females) participated in the experiment. All participants reported normal or corrected-to-normal visual acuity, and normal color vision. Informed consent was obtained from individual participants.

Stimuli, procedure, and design Examples of the search displays are shown in Fig. 9. The experiment was similar to Experiment 1, except that on color-singleton-present trials, the task-irrelevant shape was either a circle (1.4° × 1.4°), a square (1.2° × 1.2°), or a hexagon (1.5° × 1.5°). For both possible majority shapes (i.e., either circles or squares), the task-irrelevant shape was equally often each of the three possibilities. On color-singleton-absent trials, the task-irrelevant shape was always a hexagon. Items in the array were either all red or all green (equally often), except that on trials with a color singleton distractor, the singleton appeared in the alternate color. A color singleton distractor was present on 50% of the trials. As in the earlier experiments, participants pressed one key to indicate if circles were more prevalent than squares and another key to indicate if squares were more prevalent; they were explicitly informed that any uniquely colored items were to be excluded from the comparison. Trials were presented in random order. After a practice block of 24 trials, participants performed three blocks of 96 trials each, each consisting of 48 color-singleton-absent trials, and 48 color-singleton-present trials.

Results and discussion

Trials with RTs more than two standard deviations from each participant's mean (separately for the color-singleton-absent, red color-singleton-present, and green color-singleton-present conditions; 4.5%), and trials with an incorrect response (5.8%) were not included in the RT analysis. All 24 participants met the 80% or greater overall accuracy criterion to be included in the analysis.

Primary analysis Results are shown in Fig. 10. A paired-samples t test showed that participants were significantly faster to report the majority search target in the color-singleton-present condition (817 ms) compared with the color-singleton-absent condition (869 ms), $t(23) = 10.40$, $p < .001$, $d_z = 2.12$. This singleton presence benefit indicates effective suppression of the unpredictable-color distractor despite the

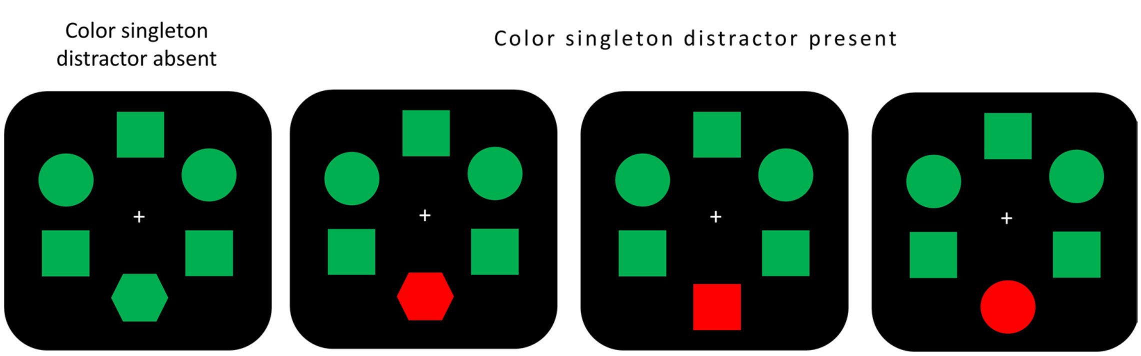


Fig. 9 Examples of search displays from Experiment 5. See text for additional details. (Color figure online)

fact that the distractor sometimes had the same shape as the task-relevant items. The same analysis on accuracy showed that the color-singleton-present condition (94.8%) was marginally more accurate than the color-singleton-absent condition (93.7%), $t(23) = 1.98$, $p = .060$, $d_z = .40$.

Additional analyses The same additional analyses as earlier were performed. Both the presence of a red color singleton distractor (814 ms) and a green color singleton distractor (822 ms) led to significantly faster RT compared with the color-singleton-absent trials (869 ms), for red: $t(23) = 8.45$, $p < .001$, $d_z = .34$; for green: $t(23) = 7.07$, $p < .001$, $d_z = .30$. This indicates that both the red and green colors were suppressed across participants. We also further identified individuals' most suppressed (fastest) and least suppressed (slowest) color between the two. It was found that the presence of a singleton distractor in both the fastest (801 ms) and the slowest color (835 ms) led to significantly faster RT than the color-singleton-absent condition, for fastest color: $t(23) = 11.51$, $p < .001$, $d_z = .44$; for slowest color: $t(23) = 6.45$, $p < .001$, $d_z = .21$.

Analysis of accuracy revealed no differences between the singleton distractor-absent condition and any of the other conditions containing subsets of the different distractor types. For the red distractor: 94.8%, $t(23) = 1.87$, $p = .075$, $d_z = .30$; for green: 94.7%, $t(23) = 1.26$, $p = .220$, $d_z = .22$; for the slowest distractor: 94.8%, $t(23) = 1.59$, $p = .126$, $d_z = .27$; and for the fastest: 94.7%, $t(23) = 1.45$, $p = .162$, $d_z = .24$.

To test the possibility of intertrial priming of the search array color, we also separately analyzed attentional suppression of the singleton distractor on color-repeat trials and color-switch trials. The results showed that both the color-repeat trials (812 ms) and the color-switch trials (822 ms) had significantly faster RTs than the color-singleton-absent condition, for color-repeat trials: $t(23) = 9.97$, $p < .001$, $d_z = .35$; for color-switch trials: $t(23) = 7.95$, $p < .001$, $d_z = .30$. Analysis of accuracy showed that the color-repeat trials (96.2%) had significantly higher accuracy than the singleton distractor-absent condition, $t(23) = 5.73$, $p < .001$, $d_z = .71$. The accuracy of color-switch trials (93.5%) did not differ from that of the singleton distractor-absent condition, $t(23) = .26$, $p = .800$, $d_z = .05$.

We also considered the possibility that suppression was not effective for all three distractor shapes, especially for distractors that were the same shape as the task-relevant items. To examine that, we conducted the same analysis as above, separately for trials containing circle, square, and hexagon distractors. The pattern for each distractor shape was identical to the overall pattern. RTs on trials with a circle, square, and a hexagon color singleton distractor present were each significantly faster compared with the color-singleton-absent condition, for circle distractor: 812 ms, $t(23) = 9.35$, $p < .001$, $d_z = 1.91$; for square distractor: 816 ms, $t(23) = 6.60$, $p < .001$, $d_z = 1.35$; for hexagon distractor: 822 ms, $t(23) = 7.19$, $p < .001$, $d_z = 1.47$. Accuracies of the circle and square color singleton distractor-present conditions did not differ from that of the singleton distractor-absent condition: for circle distractor: 93.9%, $t(23) = .34$, $p = .740$, $d_z = .07$; for square distractor: 93.9%, $t(23) = .28$, $p = .785$, $d_z = .06$. Accuracy in the hexagon color singleton distractor present condition (96.4%) was significantly higher than that in the singleton distractor-absent condition, $t(23) = 5.43$, $p < .001$, $d_z = 1.11$.

The results show that participants were able to successfully suppress unpredictable-color singleton distractors even when the distractor appeared in one of the relevant target shapes. This suggests that suppression of the unknown-color distractor is not driven by a shape-based strategy that filters out any non-target shapes, but is instead due to deprioritization of unique colors regardless of their specific color (and

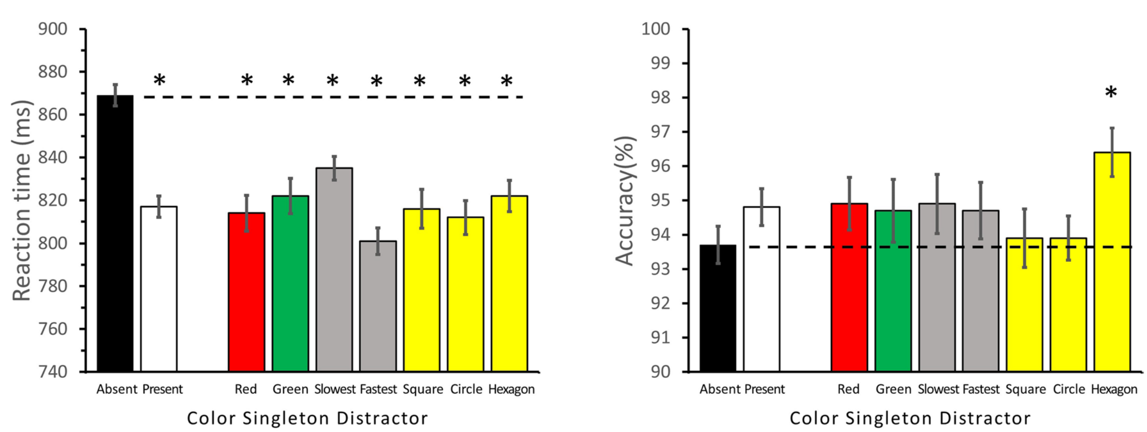


Fig. 10 Reaction time (left) and accuracy (right) from Experiment 5. Asterisks indicate conditions that significantly differed from the color singleton distractor-absent condition (all *p*s < .001). Error bars represent within-subject standard errors, calculated using the superb package in R (Cousineau et al., 2021). (Color figure online)

regardless of their particular shape). The results bolster the conclusions from the earlier experiments supporting true feature-blind suppression.

General discussion

The present experiments help to bolster and extend the results reported by Ma and Abrams (2022) in which participants effectively suppressed salient color singleton distractors even when their color was unpredictable. We showed here that the suppression still occurs when the distractor probability is relatively low (Experiment 1), when the task-irrelevant shape is distinctly different from the relevant ones (Experiment 2), when the colors of the search array and singleton distractor are more varied (Experiment 3), when the distractor shape is unpredictable (Experiment 4), and when the distractor sometimes appears in the same shape as the task-relevant items (Experiment 5). In each case, the search benefitted in speed and/or accuracy when a distractor was present in the display, indicating that it had been suppressed.

Comparison with previous studies

The experiments reported here and in Ma and Abrams (2022) used a search task that differed from the tasks that have been used by earlier researchers to study suppression. In the earlier tasks, participants were asked to search an array of heterogenous shapes for one specific target shape, and to report an attribute of the target (such as the location of a dot inside it; e.g., Gaspelin et al., 2015). Using that general paradigm, numerous researchers have found that participants are able to suppress salient task-irrelevant distractors when their color is known in advance (e.g., Chang & Egeth, 2019, 2021; Gaspelin et al., 2015, 2017; Stilwell et al., 2019, 2022; Stilwell & Gaspelin, 2021). However, when using that paradigm, if the color of the salient distractor changes randomly from trial to trial, suppression is not observed (Gaspelin & Luck, 2018b). Because participants' attentional set in those cases involved localization of a unique-instance item, any suppression of unique things in general (i.e., a color singleton of unpredictable color) may have been counterproductive to the primary goal of the task, and thus may not have been deployed.

In the majority search task used here and in Ma and Abrams (2022), subjects searched not for a single-instance target shape, but instead evaluated the entire display to identify the one of two possible shapes that was most prevalent. As a result, the attentional set did not involve locating a single-instance item, and as shown here (and in Ma & Abrams, 2022), people are indeed capable of suppressing unique elements in general (i.e., salient color singletons), even when their specific color is unpredictable. Thus, the present results show that people do have the ability to produce higher-order attentional suppression. That is, it is possible to suppress an item not only based on first-order information (a specific color), but on higher-order information (a unique color).

In some ways, our approach is similar to that used by Bacon and Egeth (1994). They found that searches for a uniquely shaped target were unable to avoid distraction by a uniquely colored distractor, whereas searches for a pre-specified target shape could avoid such distraction (but see Theeuwes, 2004). Likewise, here we also have shown that a simple change in the attentional search mode can have a dramatic effect on the influence of salient, unpredictable, task-irrelevant distractors. In both cases, changes in the participants' attentional control settings revealed capabilities that might not otherwise have been seen.

Singleton-rejection mode

The differences between the majority search task used here and the search tasks used previously to study various aspect of attentional selection and capture can be characterized as involving distinct search modes. *Search modes* here refers to differences in the top-down attentional set imposed by the constraints of the search task, or the attentional set adopted by a participant that might be permitted by a particular search task. Examples of two commonly used paradigms and the majority search task are shown in Fig. 11, along with the search modes they are believed to induce and the attentional selection phenomena they are capable of revealing.

The leftmost column of Fig. 11 shows the *additional singleton task* introduced by Theeuwes (1992). In a typical version of this task, participants are instructed to search for and identify a feature (such as the dot location as shown in the figure) of the sole unique shape in the display—a shape singleton. The specific target shape on a trial is not predictable—what is known is that it will be the one single-instance shape in the display—either a diamond among circles, or a circle among diamonds, for example. Participants are thought to adopt a *singleton-detection mode* in this situation, in which their attentional set specifically is tuned to detect and attend to unique things (Bacon & Egeth, 1994; Pashler, 1988). On some trials, a distracting ("additional") color singleton is also present in the display. Common findings are that target selection is impaired by the presence of the salient additional singleton, indicating that the additional singleton had captured attention (Bacon & Egeth, 1994; Gaspelin et al., 2015; Theeuwes, 1992, 2004). The findings suggest that singleton-detection mode is unable to be tuned to a singleton on a specific dimension (such as shape, the target-defining dimension), and hence a singleton even in a task-irrelevant dimension will capture

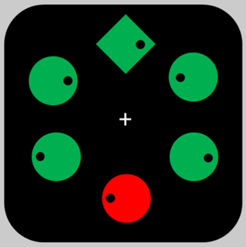
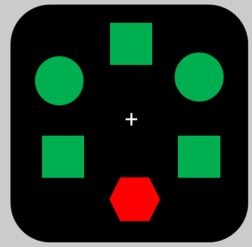
	Additional singleton task	One-target search	Majority search
Target	A shape singleton	A prespecified shape	Multiple instances of one of two prespecified shapes
Attentional control setting	Singleton-detection mode	Feature-search mode	Singleton-rejection mode
Search array example			
Suppression possibility	None	First-order suppression	Second-order or global-salience suppression

Fig. 11 Common visual search paradigms (left and middle columns) and the majority search task from the present study (right column). See text for additional details. (Color figure online)

attention. Suppression of the distractor in this paradigm (i.e., a distractor presence benefit) has not been reported.

The middle column of Fig. 11 shows a slightly but importantly different *one-target search* task, in which participants are able to effectively ignore salient color singletons of known color when their target is defined by shape. In this situation, the target is defined as a specific shape (e.g., a diamond) among an array of heterogeneous shapes. Participants here would be unable to use a singleton-detection mode to find the target because it is not a shape singleton. Instead, it is thought that participants adopt a *feature-search mode* in which they search for the specific target-defining feature (Bacon & Egeth, 1994; Leber & Egeth, 2006). A common result is that the presence of an irrelevant color singleton of a known color does not impair target identification in this situation (Bacon & Egeth, 1994; but see Theeuwes, 2004, for an alternative interpretation). However, if the color of the singleton in the one-target search task is unpredictable, people are unable to avoid distraction from it (Gaspelin & Luck, 2018b). That result suggests that people are unable to suppress uniquely colored items in general under a feature-search mode.

The majority search task of the present study is shown in the rightmost column of Fig. 11. In this task, participants are asked to identify the most prevalent of two shapes, each of which appears multiple times in the display. Here, as in the one-target search, because the target is never a singleton, singleton-detection mode would be ineffective. Additionally, because the majority search task requires assessment of the relative prevalence of two shapes, feature-search mode would also not be a feasible strategy. Instead, because the target of the search is defined by the most repeated instances, it is likely that participants adopt a *singleton-rejection mode* to filter out shapes with no repeated instances. Such a strategy would be effective in the majority search task because the only relevant items in the display each appear multiple times; however, any unique element (whether a unique shape or a unique color) could be effectively ruled out in the search. Under these conditions people can suppress uniquely colored items regardless of their color (as shown here and in Ma & Abrams, 2022). The results suggest that the singleton-rejection mode adopted to perform the majority search task allows participants to suppress unique things in general, since the target of the search is never a singular instance—unlike the situation in either the additional singleton task or the one-target search task. Importantly, the use of the majority search task has revealed that higher-order suppression is possible. That capability was not revealed by the tasks used by earlier researchers (shown in Fig. 11) because suppression of unique elements in general would not have been an expeditious way in which to perform those tasks.

Other evidence suggestive of higher-order suppression

It is also worth noting that several other researchers have reported results that appear to be consistent with higher-order suppression. For example, Burra and Kerzel (2013) and Sawaki and Luck (2010) observed an event-related potential, P_D, believed to be associated with suppression, even in response to salient distractors with unpredictable color. However, in those studies there was no behavioral evidence that the distractor had been suppressed relative to nonsalient distractors. Additionally, Won et al. (2019) found equivalent elimination of capture by either a predictable-color or unpredictable-color distractor when the probability of a distractor was high. And Vatterott et al. (2018) found that participants were better at suppressing a novel-color distractor after training in a search task with unpredictable-color distractors. Nevertheless, in those studies there also was no evidence that such distractors were suppressed below the level of non-salient distractors. These results raise the question of how it is that attentional suppression should be defined. In particular, can suppression be inferred based on the absence of capture, or is a reduced response to salient distractors relative to non-salient ones necessary to conclude that suppression has taken place? Given the fact that attentional selection can be affected by multiple facilitatory and inhibitory factors, the answer at the present time is not straightforward.

Target feature enhancement

One explanation that has been considered for previous demonstrations of (first-order) suppression is that features associated with the target were enhanced, as opposed to features associated with the distractor being suppressed. This is possible because in many studies, the target color remained constant throughout the session (e.g., Chang & Egeth, 2019, 2021; Gaspelin et al., 2015, 2017). Indeed, recent evidence provides some support for this possibility (Oxner et al., 2022). Such an explanation is not viable for the present results, however, because the colors of the singleton distractors during a session were the same as the colors of the relevant items—enhancement of any of the colors used would have been expected to *reduce* suppression of the color singleton distractors. Given that, it is possible that the suppression reported here actually underestimates the true magnitude of suppression that might have otherwise been observed in the absence of target feature enhancement.

Computational requirements of the majority search task

It is worth considering the possibility that the higher-order suppression reported here was due in part to the "computation" that participants needed to perform when determining the shape that was in the majority, and not due solely to aspects of the visual search task and the attentional set. Results from our earlier study argue against that. In Experiment 2 of Ma and Abrams (2022), "probe" trials were interspersed among search trials similar to those in the present experiments. On the probe trials, a letter appeared briefly in each stimulus shape, and participants were instructed to abandon the majority search task and report as many letters as possible. Thus, the probe trials required no computation of shape prevalence. Importantly, on the probe trials participants were significantly less likely to report the letter that had appeared on the color singleton distractor, indicating that the distractor had been suppressed (even though its color, was unknown). Those results make it clear that computation of the relative number of shapes per se is not responsible for the higher-order suppression that we observed.

Attentional window account

The present findings also may be informative with respect to the "attentional window" account of attentional suppression results. According to this account, salient color singletons do not interfere with search in some tasks (and might be referred to as "suppressed") because the focus of attention (the attentional window) in those tasks is very small (Theeuwes, 2023). According to this explanation, when the attentional window is small, observers are able to resist capture by salient distractors not by actively suppressing them, but instead by simply not selecting them when the display is searched. Other researchers have presented arguments against such an explanation (Gaspelin et al., 2023). The explanation also seems unlikely to account for the present findings (and the earlier ones reported by Ma & Abrams, 2022) because the requirements of the majority search task seem on the surface likely to require that participants adopt a large attentional window because they are required to compare the relative prevalence of two shapes, each of which has multiple instances in the display. In addition, the attentional window account maintains that featural information regarding the distractor provides the basis for avoiding attending to the location of the distractor. However, in the majority search task, because the color of the singleton distractor is unpredictable, simple (color) featural information would be inadequate for accomplishing that goal—so at a minimum, some additional mechanism is necessary to account for the higher-order suppression that we observed.

The mechanism of suppression

Earlier explanations of suppression have suggested that the suppression can be accommodated by guided-search conceptualizations of attention (e.g., Wolfe, 2021) in which attentional selection is presumed to be guided by an attentional priority map (Gaspelin & Luck, 2018a). The suppression is thought to arise from a downweighting of the to-be-suppressed distractor based on activity in a feature map—in this case for color—that represents the locations of the various colors in the scene. The present results are also consistent with such explanations, but with an important difference. For first-order suppression, the downweighting was presumably produced by a suppressive mechanism that selected a specific feature value (i.e., a specific color). In the present case, the existence of higher-order suppression indicates that it is possible to suppress any highly activated location in the color feature map regardless of the specific color value. If this is correct, it suggests that higher-order suppression may be accomplished very differently from first-order suppression. In particular, the downweighted location is selected not on the basis of a specific color, but based on color differences in the scene.

It is also possible that higher-order suppression operates at a different level of representation within the visual system than first-order suppression. One possibility is that suppression is applied based not on the activity in a (color) feature map of the scene, but instead on the basis of a global salience map that combines input from various feature maps (i.e., for color, shape, and other visual attributes) and represents salience more generally throughout the scene. Because the experiments to date have only examined suppression of distractors that were unique in color, more work will be needed to distinguish between these possibilities.

Summary

When people search for a unique single-instance shape, they are unable to suppress salient color singletons of unpredictable color. However, as shown here, when the task is to identify the most prevalent of several shapes, people can suppress such distractors in a feature-blind manner. The ability to produce such higher-order suppression facilitates efficient search when the search goal is to evaluate multiple-instance elements in a scene. Thus, as suggested by some of the foundational work on visual attention (e.g., Bacon & Egeth, 1994; Folk et al., 1992), changes in the attentional set required by a search task may reveal previously unknown capabilities of the human attention system.

The data and materials for all experiments are available online https://osf.io/f235r/. None of the experiments was preregistered.

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