Distractor Rejection in Visual Search Breaks Down With More Than a Single Distractor Feature

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Previous research has established that interference from irrelevant-but-salient color distractors occurs when observers search for variable-shape singletons among uniform shapes (singleton detection), but not when they look for a specific shape among mixed shapes (feature search). In the current study, we replicated this finding, and additionally, we introduced a random variation of color. Instead of always presenting the same target and distractor colors, colors were swapped randomly from trial to trial. With random color variation, interference from color distractors was generally stronger, and in particular, it also occurred in feature search mode, suggesting that observers were unable to focus on the relevant dimension (shape) even under the most favorable conditions. A second experiment showed that interference in feature search mode occurred with variable distractor color when target color was fixed, but not with variable target color when distractor color was fixed. Overall, the results question the view that interference in feature search is absent because observers monitor a single feature map (i.e., shape). Rather, random variation of an irrelevant feature induces participants to also monitor the irrelevant feature, which results in interference. Thus, complete distractor rejection is limited to situations with a single distractor feature.

Keywords: visual search, attentional capture, search mode, feature search, singleton detection

It is assumed that attention restricts processing of the incoming information to relevant stimuli and reduces interference from irrelevant distractors. For instance, we manage to follow a tennis match attentively despite the brisk movements or the loud sneezing of a fellow viewer. However, sometimes we do get distracted despite our intention to follow the match. Situations in which salient distractors interfere with attentional selection have been taken to support the view that attentional selection is driven by bottom-up characteristics of the stimulus (Theeuwes, 1991; van Zoest & Donk, 2005), whereas successful filtering of distracting stimuli was attributed to top-down attentional control (Ansorge, Horstmann, & Scharlau, 2010; Becker, Folk, & Remington, 2013; Folk, Remington, & Johnston, 1992). Most theories of attention acknowledge that bottom-up and top-down factors interact to control attentional selection (for reviews, see Burnham, 2007; Lamy, Leber, & Egeth, 2012; Theeuwes, 2010). Here, we were interested in the properties of distractors that cause distractor rejection to break down.

The current study used the additional singleton paradigm developed by Theeuwes (1991), which requires observers to search for a singleton on a relevant dimension, while a second singleton on an irrelevant dimension is presented. For instance, observers may be asked to search for a circle among squares and to indicate the orientation of a line inside the circle. On half of the trials, all display elements are green, but on the other half, one of the nontarget squares is red. Because color is irrelevant for the task, it can be ignored, but typical results show that reaction times (RTs) increase in the presence of the color singleton, suggesting that it captured attention. Theeuwes (1991) showed that disruption by an irrelevant singleton only occurred when it was more salient than the target singleton (but see Zehetleitner, Goschy, & Müller, 2012), emphasizing the importance of bottom-up factors in attentional selection.

Singleton Detection and Feature Search Modes

However, the capture of attention by irrelevant color singletons disappeared when the target was not a shape singleton, but a specific shape among various shapes (Bacon & Egeth, 1994; see also Pashler, 1988). This finding is problematic for the view that salient distractors capture attention in a bottom-up manner, because the distractor did not change. Rather, only the status of the target changed (shape singleton vs. specific shape). The interpretation of Bacon and Egeth (1994) was that observers in the additional singleton paradigm use a specific strategy to find the target: Instead of looking for the target shape, they look for any singleton. Because there is one relevant singleton and one irrelevant singleton, observers end up selecting the wrong singleton on some occasions, which increases RTs relative to distractor-absent trials. They referred to this search strategy as *singleton detection mode* and opposed it to feature search, in which observers look for a specific shape because the multishape search display requires them to do so.

Leber and Egeth (2006b) showed that singleton detection and feature search modes transfer to situations in which both search strategies are possible. Because the present experiments are modeled on their study, it will be described in some detail here. Leber and Egeth (2006b) compared interference from a salient color singleton in two groups of participants. In the singleton group, participants searched for a shape singleton that was drawn randomly from a set of three shapes (circle, diamond, or triangle), while all nontargets were squares (see Figure 1A). As there was no fixed target, observers were forced to search for the singleton shape. In the feature group, participants searched for a specific shape (circle) among heterogeneous nontarget shapes that included one diamond and one triangle with the remaining shapes being squares (see Figure 1B). Leber and Egeth (2006b) observed that interference from a color singleton was absent in the feature group, whereas it was present in the singleton group (see also Leber & Egeth, 2006a). In the subsequent test phase, all participants searched for a fixed singleton shape (see Figure 1C). Because the target was a singleton, but had a known feature, both singleton detection and feature search modes were possible. Interference from a color singleton during test was modulated by previous search strategy: Participants in the singleton group continued to show interference, whereas participants in the feature group continued to resist interference.

Bacon and Egeth (1994) proposed the following mechanism to account for resistance to interference in feature search:

> Using the feature search strategy, observers presumably monitor a retinotopic feature map, and direct attention to the location of the element that generates activation in that map. There is no reason to suspect that the coding of features in maps corresponding to one dimension would be influenced by variation in some other, irrelevant dimension. On the other hand, the singleton detection strategy relies on detecting elements that differ from their surrounds. It may be that the process that computes feature differences cannot be restricted to a given dimension, but simply indicates the overall salience of each element; only after a highly salient element has been selected is it possible to determine the dimension on which the element is unusual. (p. 486)
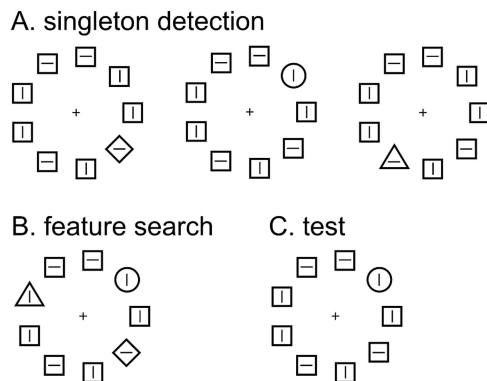

Figure 1. Examples of experimental stimuli during training (singleton detection, feature search) and test. (A) In singleton detection, participants searched for a randomly changing singleton shape (diamond, circle, or triangle) among homogenous nontargets. (B) In feature search, participants searched for a circle among various nontarget shapes. (C) During test, participants searched for a circle among homogeneous nontargets, which allows for singleton detection or feature search.

The idea that observers monitor the output of a single feature map in feature search mode resonates with feature integration theory (e.g., Treisman & Souther, 1985), where efficient search is accomplished by monitoring saliency signals in feature maps organized along perceptual dimensions such as orientation or color, while ignoring irrelevant feature maps. In contrast, the summation of saliency signals across feature maps in singleton detection mode is consistent with the notion of a master saliency map (Koch & Ullman, 1985) that guides attention to the most salient stimulus.

Current theories propose that the weight given to individual feature maps (Itti & Koch, 2001; Wolfe, 1994) or entire perceptual dimensions (Müller, Reimann, & Krummenacher, 2003) is adjusted according to top-down control settings. That is, feature maps corresponding to distracting stimuli receive little weight, which makes selection of distractors less likely. In contrast, feature maps corresponding to the target are given a high weight, which increases the likelihood of target selection. Thus, differential weighting of feature maps may provide a unified account for the effects of search mode in terms of the weight given to the irrelevant color distractors: In feature search mode, the weight of color is low because observers focus on shape, which eliminates interference from an irrelevant color singleton. In singleton search mode, more weight is given to color because observers search for any discontinuity, which results in interference from color singletons.

Effects of Learning in Feature Search Mode

The original account of search modes in terms of feature maps does not explain how the different search strategies are implemented, but there is evidence that some learning is necessary. Vatterott and Vecera (2012) investigated the time course of interference during feature search. In the first block of the experiment, participants performed a feature search task by searching for a circle among various shapes, but no color distractors were shown. In four subsequent blocks, they continued to perform the feature search task, and a new color distractor was introduced in each block of 48 trials. Interference was present in the first 24 trials of all four blocks, but not in the final 24 trials, suggesting that distractor rejection depends on the attentional tuning to specific distractor features and does not generalize to new distractors. Furthermore, Zehetleitner et al. (2012) made a similar claim, but focused on the test phase of Leber and Egeth's (2006b) paradigm. As described above, interference from color distractors was absent in feature search mode during training and test. However, when Zehetleitner et al. (2012) changed the distractor between training and test, interference emerged during test, showing that distractor rejection in feature search mode crucially depends on practice with the distractors.

The Present Study

In contrast to the studies by Vatterott and Vecera (2012) and Zehetleitner et al. (2012), the present study is not concerned with learning. Actually, we conducted analyses to rule out that our results are caused by practice-dependent changes in distractor rejection. Rather, we investigated the limits of distractor rejection after many encounters with the distractors. We pursue the hypothesis that variation of an irrelevant attribute induces participants to

pay more attention to the irrelevant feature. With reference to the above quotation from Bacon and Egeth (1994), we predict that random color changes induce observers in feature search to monitor not only the relevant shape maps, but also the irrelevant color maps, which would allow for interference from salient color singletons. In singleton detection mode, random color change would increase the impact of color distractors on the master saliency map. Curiously, the colors of target[1] and color singleton were fixed in previous studies on search modes (e.g., Bacon & Egeth, 1994; Lamy & Egeth, 2003; Leber & Egeth, 2006a, 2006b; Leber, Kawahara, & Gabari, 2009; Zehetleitner et al., 2012), possibly because the original account of Bacon and Egeth (1994) does not predict any effects of color variation.

Experiment 1

In the first experiment, target and singleton colors were randomly repeated or swapped in one group of participants, whereas they remained fixed in another group of participants. For each color group, the two search modes were induced by replicating the methods of Leber and Egeth (2006b) that were described above. The manipulation of color change only concerned the training phase. During test, display color was fixed for all participants and we evaluated whether the effects of color change would carry over from training to test.

Method

Participants. Sixty-four undergraduate psychology students participated for class credit. All reported normal or corrected-to-normal vision. The study was approved by the ethics committee of the Faculty of Psychology and Educational Sciences and was carried out in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki). Informed consent was given before the experiment started.

Apparatus and stimuli. Stimuli were displayed on a 22-inch flat-panel monitor with a refresh rate of 60 Hz and a pixel resolution of 1920 × 1080 (horizontal × vertical) that was viewed at a distance of 54 cm. The background was black, and the stimuli were either red or green. The colors had the same physical luminance of 15.6 cd/m². A white fixation cross was presented in the center of the screen. The search array was presented on a virtual circle with an eccentricity of 5°. The search array consisted of either 5 or 9 equally spaced items. For both set sizes, there was one element at the three o'clock position. The outline shapes were a circle (diameter 2.2°), a square (side length 1.7°), a diamond (square rotated by 90°), or a triangle (side length 2.4°). Stroke width and size were slightly adjusted to give about the same number of colored pixels for each shape (between 660 and 664). A vertical or horizontal gray line of 1.1° length and 15.6 cd/m² luminance was presented in the center of each shape. Stroke width was approximately 0.1° for all items.

Training. The search mode was varied between participants. (1) Participants in the singleton detection group searched for a unique shape (diamond, circle, or triangle) among nontargets that were of identical shape (squares). Each unique shape occurred randomly in one third of the trials. (2) Participants in the feature search group searched for the same shape (circle) that occurred among heterogeneous distractors. There was always one diamond and one triangle, and the remaining shapes were squares.

Test. The search displays were the same for all participants. Participants searched for the same target (circle) among identical distractors (squares).

Between-subjects variables. There were four groups of participants resulting from the combination of search strategy (singleton detection, feature search) and stimulus color (fixed, random) during training. During test, stimulus color was fixed for all participants. When stimulus color was fixed, red and green were counterbalanced across participants. Sixteen students were randomly assigned to each of the four groups.

Within-subject variables. In the training and test phase, there were three within-subject variables: distractor condition (present, absent), set size (5, 9), and target orientation (horizontal, vertical). Each of the resulting eight conditions was shown 60 times in the training and test blocks, yielding two blocks of 480 trials for each participant. In distractor absent trials, all outline shapes had the same color. In distractor present trials, one distractor element had a different color. The various combinations of distractor presence, set size and target orientation were randomly ordered. Placement of target and distractors was randomized. In the training block of the random color group, the within-subject factor color (red, green) was added to the design. Red and green displays were randomly interleaved and equally likely.

Procedure. Participants were asked to report the orientation of the line inside the target shape by pressing one of two keys. The arrow-left and arrow-right keys on a standard keyboard were used, and the assignment of orientation to key was counterbalanced across participants. Participants were asked to maintain fixation on the central fixation cross, ignore the colors, and respond as rapidly as possible while keeping the error rate below 10%. After blocks of 96 trials, the error rate was shown for 15 s, forcing participants to take a short break.

During training, participants in the singleton group were asked to search for the item with a unique shape, whereas participants in the feature group were asked to search for the circle. During test, all participants were asked to search for the circle.

At the beginning of the experiment, participants practiced the experimental task until they felt comfortable with it. Practice trials were not recorded, but participants completed at least 30 trials. A trial started with the presentation of the fixation cross for a randomly selected duration between 0.5 and 1 s. Then, the search display appeared and stayed on the screen until a response was registered. The following response errors were reported to the participant by visual feedback: choice errors, anticipations (RTs < 0.2 s), and late trials (RTs > 2 s).

Results

Trials not meeting the online criterion of 2 s (0.8%) and the rare anticipations (less than 0.01%) were excluded from analysis. Subsequently, data were trimmed for each participant and condition by removing trials slower than 2.5 times the standard deviation of the respective condition mean. The trimming procedure was applied to all analyses reported below and typically resulting in the exclusion of about 2.7% of trials.

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[1] The target color was the same as the nontarget color. Because of its larger theoretical significance, we refer to the combined target/nontarget color as *target color*.

Training. Mean differences between distractor-present and distractor-absent trials (distractor effect) are shown in the top-left graph in Figure 2 and condition means are shown in Figure 3. Mean individual RTs were entered into a mixed-factors 2 (search group: singleton, feature) × 2 (color group: fixed, random) × 2 (distractor: presence, absence) × 2 (set size: 5, 9) analysis of variance (ANOVA). The results showed that RTs were shorter in the feature group than in the singleton group (776 vs. 904 ms), $F(1, 60) = 13.49$, $p = .001$, $\eta_p^2 = 0.184$, and in distractor-absent trials than in distractor-present trials (811 vs. 869 ms), $F(1, 60) = 120.37$, $p < .001$, $\eta_p^2 = 0.667$. The distractor effect was modulated by search group, $F(1, 60) = 44.95$, $p < .001$, $\eta_p^2 = 0.428$, showing that the distractor effect was larger in the singleton group (856 vs. 951 ms) than in the feature group (765 vs. 788 ms). Importantly, the effect of distractor condition was also modulated by color group, $F(1, 60) = 19.98$, $p < .001$, $\eta_p^2 = 0.25$, showing that the distractor effect was larger in the group with random color (808 vs. 891 ms) than fixed color (813 vs. 847 ms). The interaction of distractor condition and color group was not further modulated by search group ($p = .434$), showing that random color variation had a similar effect in singleton detection and feature search. The effect of set size was not significant ($p = .55$), suggesting that search was efficient.

We ran four planned t tests to examine whether the distractor effect was different from zero in the four groups of participants. The three-way interaction of search group, color group, and distractor presence, which would typically backup the follow-up t tests, was nonsignificant, but there is a strong theoretical interest in these tests. First, the follow-up t tests allowed us to check whether

Figure 3. Results from the training block of Experiment 1. Reaction times (RTs) in milliseconds are plotted on the y-axes. The symbols show mean RTs as a function of search mode (columns: singleton detection, feature search), color variation (rows: fixed color, fixed color), distractor (present, absent), and set size. Error bars show the between-subjects standard error of the mean. See the online article for the color version of this figure.

we replicated previous results. Second, they would show whether significant interference emerged with random colors where it is absent with fixed color. With fixed color, observers in the singleton group showed a significant distractor effect (66 ms), $t(15) = 6.51$, $p < .001$, whereas the distractor did not have an effect in the feature group (3 ms), $t(15) = 0.66$, $p = .518$, which replicates the results of Leber and Egeth (2006b). With random colors, observers showed a significant effect in the singleton group (123 ms), $t(15) = 7.77$, $p < .001$, and importantly, the effect was also significant in the feature group (42 ms), $t(15) = 4.69$, $p < .001$.

The same mixed 4-way ANOVA as above was run on mean proportion of choice errors. Errors were less frequent when the distractor was absent than when it was present (4.7% vs. 6.1%), $F(1, 60) = 16.72$, $p < .001$, $\eta_p^2 = 0.218$. The distractor effect was larger in the singleton group (4.8% vs. 7.3%) than in the feature group (4.5% vs. 4.7%), $F(1, 60) = 13.73$, $p < .001$, $\eta_p^2 = 0.186$. Errors were more frequent with five display elements than with nine (5.8% vs. 4.9%), $F(1, 60) = 12.16$, $p = .001$, $\eta_p^2 = 0.168$. There was a tendency for participants in the feature group to make fewer errors than in the singleton group (4.6% vs. 6.1%), $F(1, 60) = 3.86$, $p = .054$, $\eta_p^2 = 0.06$.

Test. Mean distractor effects are shown in the top-right graph in Figure 2 (condition means are not plotted). The same mixed 4-way ANOVA on mean RT showed that the presence of a distractor increased RT (670 vs. 681 ms), $F(1, 60) = 23.87$, $p < .001$, $\eta_p^2 = 0.285$. The distractor effect was larger in the singleton group (671 vs. 687 ms) than in the feature group (669 vs. 675 ms), $F(1, 60) = 6.09$, $p = .016$, $\eta_p^2 = 0.09$. Importantly, the distractor effect was larger in the random color group (661 vs. 677 ms) than in the fixed color group (679 vs. 685 ms), $F(1, 60) = 5.2$, $p = .026$, $\eta_p^2 = 0.08$. Again, the interaction of distractor effect and color group was not further modulated by search mode ($p = .967$).
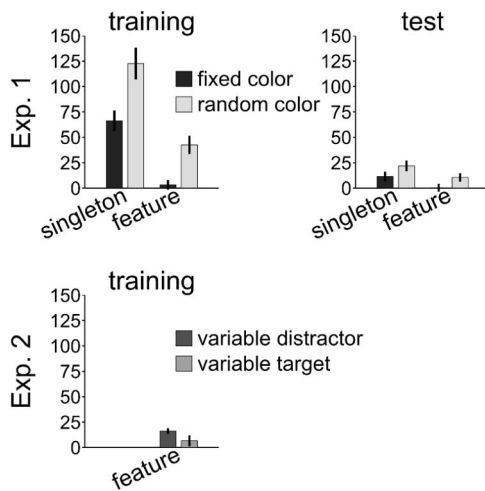

Figure 2. Distractor effects in Experiments 1 and 2. The y-axis plots the difference between distractor-present and distractor-absent trials in milliseconds. The top row shows distractor effects as a function of search type (singleton detection, feature search) and color variation (fixed, random) for the training and test blocks in Experiment 1. Note that search type and color variation were manipulated only during training, not during test. Results from the fixed color condition closely replicate those of Leber and Egeth (2006b). In Experiment 2, there was only a training block, and only the feature search condition was run. Either the distractor or the target color was variable. Error bars show the between-subjects standard error of the mean. Exp. = experiment.
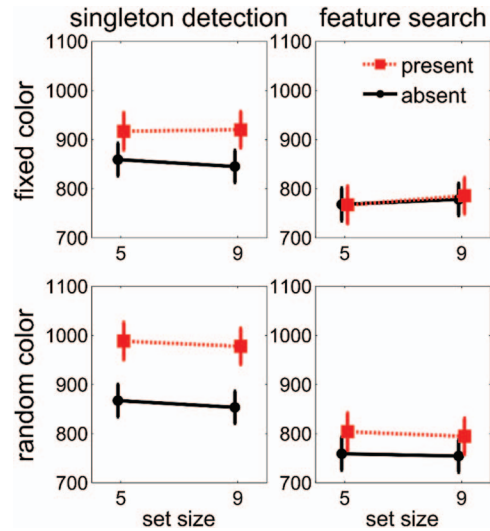
Furthermore, the interaction of distractor condition and set size approached significance, $F(1, 60) = 3.6$, $p = .063$, $\eta_p^2 = 0.057$, hinting at larger interference with a set size of nine (669 vs. 684 ms) than with five (671 vs. 678 ms).

With fixed color during training, the distractor effect was significant in the singleton group (11 ms), $t(15) = 2.41$, $p = .029$, but not in the feature group (0.4 ms), $t(15) = 0.1$, $p = .918$, which replicates the findings of Leber and Egeth (2006b). However, with random color during training, the distractor effect was significant in the singleton group (22 ms), $t(15) = 4.16$, $p = .001$, and also in the feature search group (11 ms), $t(15) = 2.58$, $p = .021$. We report uncorrected p values, but the significant tests remain significant after controlling the false discovery rate of a family of hypothesis tests (Benjamini & Hochberg, 1995).

The same ANOVA was also run on error rates. The only result was that error rates were higher in the feature than in the singleton group (4.5% vs. 3.1%), $F(1, 60) = 8.5$, $p = .005$, $\eta_p^2 = 0.057$.

Intertrial analysis of training block. We examined whether intertrial transitions of the relevant (shape) or irrelevant (color) attribute would affect distractor interference. The relevant shape feature varied only in singleton groups and the irrelevant color feature only in the random color groups. Therefore, relevant and irrelevant attributes were analyzed separately to include as many participants as possible. With respect to target shape repetition, Pinto, Olivers, and Theeuwes (2005) observed that interference from a color singleton was larger after the target shape changed than when it was repeated. However, this result was only obtained when distractor-absent and distractor-present trials were presented in separate blocks, not when they were randomly mixed (Lamy & Yashar, 2008).

Repetitions of target shape were only analyzed in the training session of singleton groups because the target shape did not change in feature groups or in test blocks. A 2 (color group: fixed, random) × 2 (target transition: repetition, alternation) × 2 (distractor: presence, absence) replicated shorter RTs when the distractor was absent than when it was present, $F(1, 30) = 94.85$, $p < .001$, $\eta_p^2 = 0.760$, and more interference from the distractor with random than fixed color, $F(1, 30) = 6.75$, $p = .014$, $\eta_p^2 = 0.184$. Furthermore, RTs were shorter when the target shape was repeated than when it changed (881 vs. 915 ms), $F(1, 31) = 21.18$, $p < .001$, $\eta_p^2 = 0.406$, but there was no interaction with distractor presence ($p = .505$), confirming that repetition of the task-relevant shape feature did not affect interference from the distractor (Lamy & Yashar, 2008).

Next, we tested whether repetition of the task-irrelevant color feature modulated interference. To this end, we determined for each trial in the training block of the random color groups whether the previous color was repeated or not. Color transitions could not be analyzed for the fixed-color groups or test blocks, because color did not change. The individual means were then subjected to a 2 (search group: singleton, feature) × 2 (color transition: repetition, alternation) × 2 (distractor: presence, absence) ANOVA. We replicated the effect of distractor presence, $F(1, 30) = 83.53$, $p < .001$, $\eta_p^2 = 0.736$, and the interaction of distractor presence and search group, $F(1, 30) = 18.75$, $p < .001$, $\eta_p^2 = 0.385$. In addition, RTs were shorter when stimulus color repeated than when it changed (839 vs. 859 ms), $F(1, 30) = 9.72$, $p = .004$, $\eta_p^2 = 0.245$. The interaction of distractor presence and color repetition, $F(1, 30) = 5.46$, $p = .026$, $\eta_p^2 = 0.154$, revealed that the distractor

effect was larger when the color changed (812 vs. 905 ms) than when it was repeated (803 vs. 875 ms). The following t tests show that effect of distractor condition was significant both after color repetition and color change: In the singleton group, the distractor effect was significant on repeat (113 ms), $t(15) = 7.57$, $p < .001$, and on change trials (131 ms), $t(15) = 6.75$, $p < .001$. In the feature group, the distractor effect was significant on repeat (31 ms), $t(15) = 3.7$, $p = .002$, and on change trials (56 ms), $t(15) = 4.48$, $p < .001$.

Analysis of practice effects. The following analyses were run to rule out that practice contributed to the larger interference with random color. For instance, Zehetleitner et al. (2012) reported that interference in singleton search mode decreased with practice from the first block of 240 trials to the second block of 240 trials. In the present experiment, participants in the group with random color encountered the exact same distractor on only half as many trials as participants in the fixed color group, because there were two distractor colors. Therefore, participants in the random color group may have been less practiced with the distractors and more interference occurred.

To explore effects of practice, we divided the 480 trials of the training block into the first and second half. We ran a mixed-factors 2 (search group: singleton, feature) × 2 (color group: fixed, random) × 2 (practice: first half, second half) × 2 (distractor: presence, absence) ANOVA on the training block. In addition to the results reported above, the ANOVA showed that RTs decreased from the first to the second half of the block (875 vs. 807 ms), $F(1, 60) = 68.43$, $p < .001$, $\eta_p^2 = 0.533$, but more so in the singleton group (962 vs. 848 ms) than in the feature group (789 vs. 765 ms), $F(1, 60) = 29.73$, $p < .001$, $\eta_p^2 = 0.331$. The interaction of practice and distractor, $F(1, 60) = 14.42$, $p < .001$, $\eta_p^2 = 0.194$, was modulated by the triple interaction of search group, practice and distractor, $F(1, 60) = 9.09$, $p = .004$, $\eta_p^2 = 0.132$, showing that the distractor effect decreased from the first to the second half in the singleton group (117 vs. 77 ms), but not in the feature group (26 vs. 21 ms), which replicates the work of Zehetleitner et al. (2012). There were no interactions of practice with color group (ps > .126). The same ANOVA on the test block did not produce any significant terms involving practice (ps > .10)8. Overall, practice with the distractor stimuli did not contribute to the effects of color group.

Vatterott and Vecera (2012) showed that interference occurred in feature search in the initial 24 trials, but not in the following 24 trials. Because participants in the present study started with at least 30 practice trials including both color distractors, it was unlikely that this pattern would replicate in the present study. To be sure, we ran the same ANOVA as in the previous section, but compared Trials 1–24 to Trials 25–48 instead of the first to the second half of the block (with 240 trials each). A significant interaction of trial number and distractor presence would confirm rapid attentional tuning to the distractor, but this interaction was neither significant during training ($p = .638$) nor during test ($p = .229$). None of the other interactions involving block and distractor presence were significant (ps > .157), including the three-way interaction of trial number, distractor presence, and color group, which may have indicated that the training effect was only present with fixed color (as in the work of Vatterott & Vecera, 2012).

Discussion

The results showed that displays with randomly changing colors resulted in stronger interference from a color distractor. This was true for singleton detection and feature search modes. Also, the larger interference with random colors transferred to a test block with constant color. Note that the colors in individual trials were the same in the random color and fixed color groups. The difference was in the sequence of colors (fixed vs. variable). Furthermore, the analysis of intertrial effects suggests that interference was larger after a color change. However, effects of color variation carried over to the test block where color did not change. Thus, intertrial transitions may contribute, but do not explain the effects of random color variation. Also, practice did not modulate the stronger interference with randomly changing colors.

Experiment 2

In Experiment 1, we reasoned that the random color variation increased attention to the irrelevant dimension, which in turn increased interference from a distractor. As target and distractor color were swapped and therefore correlated, we sought to disentangle their individual contributions. Therefore, a third color was added to red and green, which allowed us to fix the color of one element, while independently varying the color of the other. In the variable target group, the target color was randomly magenta in 50% of the trials, while the distractor color was fixed. In the variable distractor group, the distractor color was randomly magenta in half of distractor trials (i.e., in 25% of the total trials), while the target color was fixed. We repeated the training block of the feature search task from the previous experiment, which typically results in zero interference. Only trials with red or green stimuli were analyzed to assure equal saliency. As a result, 50% of the trials were discarded in the variable target group and 25% of the trials in the variable distractor group. To compensate for the lost trials, we doubled the total number of trials from 480 to 960. Furthermore, we did not run a test block because the transfer from training to test does not clarify how variations of target or distractor color contribute to the results of Experiment 1. In summary, unlike Experiment 1, Experiment 2 included only a training session and no test session. In addition, only the feature search task was included.

Method

Participants. Thirty-six students from the same pool of participants as above participated in the experiment. Eighteen were randomly assigned to the variable-distractor group and 18 to the variable-target group. None of them had participated in Experiment 1.

Within-subject and between-subjects variables. The within-subject variables were as in the training block of the feature group in Experiment 1 with the following exceptions. Participants completed 960 trials, 480 distractor-present trials and 480 distractor-absent trials. As in Experiment 1, red and green were counterbalanced as target and distractor colors across participants. Magenta was isoluminant to red and green. In the variable-distractor group, the color of the distractor was randomly magenta on 240 of the 480 distractor-present trials, whereas the target color was fixed

throughout. In the variable-target group, the color of the target was randomly magenta on 480 of the 960 trials, whereas the distractor color was fixed.

Results

The online and offline criteria for late responses resulted in the exclusion of 0.4% and 2.8% of the trials in the group with variable distractor and 0.3% and 2.9% in the group with variable target. The percentage of excluded anticipations was very small (<0.01%). The analyses were restricted to red and green stimuli. The groups were analyzed separately because of the unequal distribution of trials in the two groups.

Mean distractor effects are shown in the bottom-left graph in Figure 2, and condition means are shown in Figure 4. Mean individual RTs were entered into a 2 (distractor: presence, absence) $\times$ 2 (set size: 5, 9) ANOVA.

In the variable-distractor group, there was an effect of distractor, $F(1, 17) = 31.99$, $p < .001$, $\eta_p^2 = 0.653$, but no effect of set size ($p = .166$) or interaction. RTs were 16 ms shorter in distractor-absent trials than in distractor-present trials (709 vs. 725 ms). The distractor effect in the present analysis was significantly smaller than the distractor effect in the group with feature search and random color of Experiment 1 (16 vs. 42 ms), $t(17.99) = 2.77$, $p = .013$. The analysis of choice errors showed a tendency for more errors with a set size of 5 than with a set size of 9 (5.6% vs. 4.9%), $F(1, 17) = 4.33$, $p = .053$, $\eta_p^2 = 0.203$.

In the variable-target group, neither the effect of distractor, $F(1, 17) = 1.48$, $p = .24$, $\eta_p^2 = 0.08$, nor any other effect reached significance. RTs were 687 and 693 ms in distractor-absent and distractor-present trials, respectively. The ANOVA on choice errors showed no significant effects. The mean error rate was 4.4%.

Analysis of intertrial effects. For each trial, we determined whether the color of the variable element (distractor or target) was repeated. The individual means from the variable-distractor and variable-target groups were then subjected to separate 2 (color transition: repetition, alternation) $\times$ 2 (distractor: presence, absence) ANOVAs. Results from the variable-distractor group confirmed the effect of distractor presence, $F(1, 17) = 28.10$, $p < .001$, $\eta_p^2 = 0.623$. The interaction of distractor color transition and distractor effect, which was significant in Experiment 1, was not significant in the present analysis, $F(1, 17) = 1.65$, $p = .216$, $\eta_p^2 =$
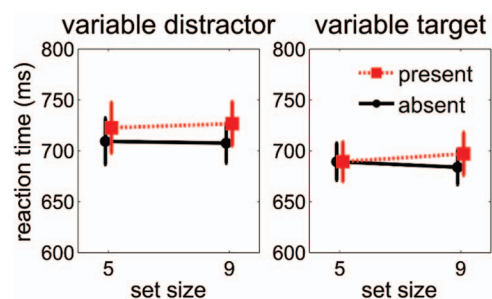

Figure 4. Results from Experiment 2. The left and right graphs show the results from the variable-distractor and variable-target groups as a function distractor (present, absent) and set size. Error bars show the between-subjects standard error of the mean. Note that the scale is twice as large as that in Figure 3. See the online article for the color version of this figure.

0.088, but the numerical trends followed the results of Experiment 1: The distractor effect was numerically larger after a change of the distractor color (705 vs. 726 ms) than after a repetition (712 vs. 726 ms). The smaller sample size (18 vs. 32) or the overall smaller distractor effect (16 vs. 42 ms) may explain the inconsistent result. The analysis of color transitions in the variable target group did not yield any significant effects (ps $> .242$).

Analysis of practice effects. In neither group did the distractor effect change over the course of the experiment. We compared the first to the second half and the first 24 trials to the second 24 trials, but the distractor effect did not evolve over the course of the experiment. At the same time, RTs decreased from the first half to the second half of the experiment with variable distractor (737 vs. 697 ms), $F(1, 17) = 23.65$, $p < .001$, $\eta_p^2 = 0.582$, and with variable target (707 vs. 672 ms), $F(1, 17) = 14.66$, $p = .001$, $\eta_p^2 = 0.463$, confirming benefits of practice.

Discussion

Random changes of the distractor color resulted in interference, whereas random changes of the target color did not, suggesting that random variation of the distractor color contributed more strongly to the results of Experiment 1. However, interference in feature search when target and distractor swapped color was much larger than interference when only the distractor color changed (42 vs. 16 ms). Presumably, the effects of changes of distractor color are amplified by the concomitant changes of target color. In particular, the larger interference after a color change in Experiment 1 (which was not replicated in Experiment 2) suggests that interference increases when the target color becomes the distractor color on subsequent trials. Consistent with this idea, Hickey, Olivers, Meeter, and Theeuwes (2011) observed that swaps of the irrelevant color increased RTs relative to no-swap trials in distractor-present trials, and Lamy and Zoaris (2009) found that search slopes were steeper after swaps of the irrelevant color than after no-swap trials. While intertrial effects relating to irrelevant color changes clearly merit further research (for a review, see Lamy & Kristjánsson, 2013), we would like to point out that our main result, the break-down of distractor rejection with random color changes, cannot be reduced to effects of intertrial transitions: Experiment 1 showed that effects of random color change transferred to the test block where the relevant and irrelevant attributes were fixed, and Experiment 2 did not find significant effects of intertrial transitions despite significant capture.

General Discussion

The present experiments show that random variation of a color distractor increases interference. When target and distractor colors were randomly swapped in Experiment 1, interference from the color distractor increased in both singleton detection and feature search modes. Notably, there was significant interference even in feature search mode, which is thought to resist interference from distractors. Experiment 2 clarified that random variation of only the distractor color produced interference in feature search, whereas random variation of only the target color did not. Overall, we suggest that random variation of an irrelevant feature increases attention to the irrelevant feature maps, which makes it more difficult to reject distractors.

The present results suggest that resistance to interference in feature search mode is not entirely explained by the monitoring of a single, task-relevant feature map (see Bacon & Egeth, 1994). Resistance to interference also relies on the down-weighting of irrelevant feature maps, which is not possible when the irrelevant feature changes randomly. While previous work (Vatterott & Vecera, 2012; Zehetleitner et al., 2012) showed that efficient distractor rejection required practice (see also Geyer, Müller, & Krummenacher, 2008; Müller, Geyer, Zehetleitner, & Krummenacher, 2009), the current study showed that even with substantial practice, efficient distractor rejection is not possible if the distractor color is unpredictable. The implication for the present findings for models inspired by feature-integration theory (Itti & Koch, 2001; Müller et al., 2003; Wolfe, 1994) is that only known and fixed feature maps may receive a low or zero weight. If to-be-ignored elements vary, the weight of the irrelevant dimension increases and interference results. From an ecological point of view, it makes sense to ensure monitoring of new or variable features because they may correspond to potentially important changes in the environment. In contrast, invariable features of the environment can be more safely ignored.

Related Studies

Theeuwes and Burger (1998) concluded that it is only possible to ignore an irrelevant color singleton when both the target and distractor colors are known and remain fixed over trials. In contrast, we conclude that it is sufficient to fix the distractor color to reduce interference. Why would interference be more widespread in Theeuwes and Burger's (1998) study than in the present study? There are two important differences that may explain the discrepancy. The first difference is that search in the present experiments was efficient ("parallel") as shown by the nonsignificant effects of set size, whereas search was nonefficient ("serial") in Theeuwes and Burger's (1998) study. It is not entirely clear whether results obtained with nonefficient search carry over to efficient search. In nonefficient search, the size of the attentional window is small to allow for item-by-item inspection, whereas it is large in efficient search. Because the size of the attentional window is thought to modulate effects of attentional capture (e.g., Belopolsky, Zwaan, Theeuwes, & Kramer, 2007; Kerzel, Born, & Schönhammer, 2012; Vatterott & Vecera, 2015), the results may differ. Another important difference is that color was task-relevant in the work of Theeuwes and Burger (1998) because target and distractor letter were from the same set and differed only in color. In contrast, color was completely response-irrelevant in the present study.

While the present research shows that random changes on the irrelevant dimension increase distraction in the additional singleton paradigm, a number of previous studies have shown the same for the relevant dimension. For instance, searching for a known shape singleton that does not change over trials (fixed-singleton search; Theeuwes, 1992) reduces interference from a color singleton compared to searching for a random shape singleton (mixed-singleton search; Theeuwes, 1991). Whereas the target singleton remains the same in a block of trials in fixed singleton search (i.e., a diamond), it changes roles with the context elements in mixed singleton search. For instance, the diamond may be the target singleton among circles on one trial, whereas the circle may be the target singleton among diamonds on the next trial. Similar to

the present study, it was shown that trial transitions modulate the distractor effect. Pinto et al. (2005) showed that distractor interference was larger when the target singleton changed than when it was repeated. However, this may only hold true when the presence of the distractor is blocked. When distractor presence varied from trial to trial, target repetition no longer affected interference (Lamy, Carmel, Egeth, & Leber, 2006; Lamy & Yashar, 2008), whereas larger interference was confirmed with mixed singleton search than with fixed singleton search.

With respect to fixed versus mixed singleton search, Lamy and Yashar (2008) concluded that observers use their knowledge of the target feature in fixed-feature search, which reduces distractor interference. In contrast, they rejected an account in terms of priming of popout. Priming of popout denotes that RTs in mixed singleton search are shorter when the target has the same feature on consecutive trials (Maljkovic & Nakayama, 1994). If interference decreases on trials with target repetition, this suggests that a rather passive priming mechanism instead of knowledge about target features explains the reduction of interference. However, Lamy and Yashar (2008) did not find decreases in interference when the target feature was repeated in mixed-feature search with random distractor presence (which we replicated), pointing to expectancies to explain the advantage of fixed-over mixed-feature search. In the present study, distractor presence varied randomly from trial to trial, and color repetition reduced interference compared to color changes (see intertrial effects in Experiment 1). Thus, the passive priming of target color facilitated search (RTs were shorter) and decreased the impact of salient distractors (the distractor effect was smaller). Nonetheless, intertrial priming cannot explain why the effect of color variation carried over to the test block where color was fixed. Thus, both priming and observer expectations regarding stimulus color modulated interference in the present experiments.

Neural Basis

Although we have not explored the neural basis of efficient and inefficient distractor rejection, the recent literature has identified an event-related potential (ERP) component that may reflect the suppression of task-irrelevant, but salient, stimuli. The P_D is a positive deflection over contralateral posterior sites about 200–300 ms poststimulus (e.g., Burra & Kerzel, 2014; Gaspar & McDonald, 2014; Hickey, Di Lollo, & McDonald, 2009; Hilimire, Mounts, Parks, & Corballis, 2011; Sawaki, Geng, & Luck, 2012; Sawaki & Luck, 2011). It is tempting to propose that distractor suppression, as indexed by the P_D, underlies efficient distractor rejection in feature search. However, this conclusion is premature.[2] As outlined in the introduction, processes unrelated to distractor suppression, such as the down-weighting of irrelevant dimensions may prevent distractor interference. Also, suppression signals arising from the distractor may compete with selection/enhancement signals arising from the target when the two items fall within the same receptive field, which would actually produce an increase in RTs on distractor trials (Gaspar & McDonald, 2014). Thus, distractor rejection at the behavioral level can only be linked to distractor suppression at the electrophysiological level if the two are measured together. Because we have only measured behavior, it would be premature to link distractor rejection in the present experiments to distractor suppression as indexed by the P_D.

In most studies using the additional singleton paradigm, the target and distractor colors were fixed in blocks of trials while the target shape was fixed in some studies and variable in others (e.g., Bacon & Egeth, 1994; Lamy et al., 2006; Lamy, Leber, & Egeth, 2004; Leber & Egeth, 2006b; Pinto et al., 2005; Theeuwes, 1991, 1992; Zehetleitner et al., 2012). However, there is one controversial ERP study in which the target shape and the irrelevant color were randomly swapped (Hickey, McDonald, & Theeuwes, 2006). Hickey et al. (2006) investigated an electrophysiological correlate of attentional deployment in the time range from 200 to 300 ms, the N2pc. They found an N2pc to salient color singletons, indicating attentional capture. Subsequent studies were unable to replicate this finding in fixed-singleton search (Töllner, Müller, & Zehetleitner, 2012; Wykowska & Schubö, 2010) or observed a P_D to the color distractor when responses were fast (Jannati, Gaspar, & McDonald, 2013; McDonald, Green, Jannati, & Di Lollo, 2013). However, Burra and Kerzel (2014) clarified that an N2pc to salient color singletons obtains when target and distractor shapes are swapped randomly, whereas a P_D was observed when the target shape remained fixed (see also Gaspar & McDonald, 2014; Hilimire & Corballis, 2014; Jannati et al., 2013). The present study suggests that the random variation of color increases interference and may have increased the chances of finding an N2pc in the work of Hickey et al. (2006) compared to studies reporting the absence of an N2pc to the color singleton.

In summary, the present study shows that interference is stronger when the irrelevant attribute of a distractor varies randomly. Efficient rejection of the distractor is limited to cases where the irrelevant feature of the distractor remains the same. In particular, random changes of the irrelevant feature result in interference even under most favorable conditions (feature search).

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[2] Thanks to John J. McDonald for pointing this out to us.

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