Learned suppression for multiple distractors in visual search

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Abstract

Visual search for a target object occurs rapidly if there were no distractors to compete for attention, but this rarely happens in real-world environments. Distractors are almost always present and must be suppressed for target selection to succeed. Previous research suggests that one way this occurs is through the creation of a stimulus-specific distractor template. However, it remains unknown how information within such templates scale up with multiple distractors. Here we investigated the informational content of distractor templates created from repeated exposures to multiple distractors. We investigated this question using a visual search task in which participants searched for a gray square among colored squares. During "training", participants always saw the same set of colored distractors. During "testing", new distractor sets were interleaved with the trained distractors. The critical manipulation in each study was the distance (in color space) of the new test distractors from the trained distractors. We hypothesized that the pattern of distractor interference during testing would reveal the tuning of the suppression template: reaction times should be commensurate with the degree to which distractor colors are encoded within the suppression template. Results from four experiments converged on the notion that the distractor template includes information about specific color values, but has broad "tuning", allowing suppression to generalize to new distractors. These results suggest that distractor templates, unlike target templates, encode multiple features and have broad representations, which have the advantage of generalizing suppression more easily to other potential distractors.

Keywords: visual search, distractor template, suppression
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Public Significance Statement

Searching for relevant information within complex environments is cognitively challenging. Decades of research have suggested that successful search is supported by two attentional mechanisms - one that enhances relevant information (i.e., targets) and one that suppresses irrelevant information (i.e., distractors). While much of the research in attention has focused on the former, fewer studies have focused on the latter; those that have suggest that it is possible to actively suppress specific distractor features. No studies, to our knowledge, however, have examined the tuning of suppression templates when there are multiple distractors in a visual search scene, nor how well such templates might generalize to new stimuli. Considering that real world environments inevitably contain varied distractors that usually outnumber targets, it is critical to understand how multiple distractors are filtered during visual search. We address this question in a series of four studies. Our results demonstrate that suppression templates are built from experience with individual distractors, and that the representational tuning of each distractor is broad enough to generalize the new stimuli. This suggests that suppression templates may be optimized for generalizing suppression to other potential distractors in the visual environment, rather than being highly selective like target templates.
Introduction

Searching for relevant information within complex environments is cognitively demanding (Norman & Bobrow, 1975). Decades of research have found that successful search is facilitated by two attentional mechanisms: enhancement of relevant information (i.e., targets) and suppression of irrelevant information (i.e., distractors). Much of the research in attention has focused on the former, demonstrating that processing of target features is prioritized through changes in sensory "gain", which results in better target selection, but also erroneous selection of target-similar distractors (Desimone & Duncan, 1995; Treisman & Gelade, 1980; Treisman & Sato, 1990; Wolfe, 1994; Wolfe & Horowitz, 2004). Fewer studies have focused on the latter mechanism of distractor suppression, perhaps because suppression can occur as a passive local process (Cavanaugh, Bair, & Movshon, 2002; DeAngelis, Freeman, & Ohzawa, 1994; Reynolds, Chelazzi, & Desimone, 1999; Störmer & Alvarez, 2014). Recent studies, however, have found suppression to be more complex. Some have identified an active mechanism that is independent of target enhancement (Arita, Carlisle, & Woodman, 2012; Gaspelin, Leonard, & Luck, 2015, 2017; Sawaki & Luck, 2011; Gaspar & MacDonald, 2014; Hickey, Di Lollo, & McDonald, 2009; Marini, Chelazzi, & Maravita, 2013; Müller, von Mühlören, & Geyer, 2007; Noonan, Adamian, Pike, Printzlau, Crittenden, & Stokes, 2016; Cunningham & Egeth, 2016). Others have suggested that there may be a passive, but learned, process based on statistical exposure (e.g., Vatterott & Vecera, 2012; Geyer, Müller, & Krummenacher, 2008; Marini et al., 2013; Marini, Demeter, Roberts, Chelazzi, & Woldorff, 2016; Dixon, Ruppel, Pratt, & De Rosa, 2009; Müller, Geyer, Zehetleitner, & Krummenacher, 2009; Goschy, Bakos, Mueller, & Zehetleitner, 2014;
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Leber, Gwinn, Hong, & O’Toole, 2016; Reder, Weber, Shang, & Vanyukov, 2003). These studies differ in exactly how distractors are cued or learned over time, but all show it is possible to suppress specific distractors independently of target selection. However, no studies so far, have examined what happens when there are multiple distractors, despite the fact that real world environments inevitably contain varied distractors. Here, we investigate how multiple distractors are suppressed and test the idea that the attentional system builds broadly tuned suppression templates that include multiple distractors and is capable of generalizing suppression to new distractors.

The concept of an “attentional" or "target" template is commonly used in models of attention to describe the target representation in working memory used to set sensory gain, guide attention and eye-movements, and determine when search should be terminated (Bravo & Farid, 2009, 2012; Malcolm & Henderson, 2009; Mruczek & Sheinberg, 2007; Peelen, Fei-Fei, & Kastner, 2009; Vickery, King, & Jiang, 2005; Wolfe & Horowitz, 2004). In cognitive models, the idea of a target template for visual search is agnostic as to where it is encoded in the brain (cf. Myers, Rohenkohl, Wyart, Woolrich, Nobre, & Stokes, 2015; Ester, Sutterer, Serences, & Awh, 2016), and focuses instead on measuring its contents (or tuning) (Geng, DiQuattro, & Helm, 2017; Lee & Geng, 2017; Navalpakkam & Itti, 2007). For example, Navalpakkam and Itti (2007) interleaved target search trials with target probe trials. On probe trials, subjects indicated which they thought was the target out of several highly similar stimuli. Similarly, Geng et al. (2017) used probe trials that asked subjects to indicate the target color on a color wheel. In both studies, the response distribution from probe trials reflected the efficiency of target search, confirming that the contents of the template were related to distractor interference during visual search. This conclusion is consistent with decades of work in visual search that has indirectly inferred the
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contents of the target template through reaction time and accuracy during visual search tasks (Becker, Folk, & Remington, 2013; Duncan & Humphreys, 1989; Nagy & Sanchez, 1990; Treisman & Gelade, 1980; Wolfe, 1994; Wolfe & Horowitz, 2004).

The concept of attentional templates has more recently been extended to suggest that distractor templates are also created during visual search to facilitate suppression (Arita et al., 2012; Cunningham & Egeth, 2016; Geng, 2014; Moher & Egeth, 2012; Sawaki & Luck, 2011; Vatterott & Vecera, 2012). For example, Arita et al. (2012) used a search display with items of two colors (e.g., red and blue) and a target defined by shape. Before the search display, observers were given a pre-cue indicating the color of the target (e.g., red), the distractor (e.g., blue), or neither (e.g., green). Arita et al. found shortest RTs with the target cue, but more interestingly, shorter RTs with the distractor cue than the neutral cue, suggesting that observers used the cue to create a template for distractor rejection (although see Beck & Hollingsworth, 2015; Becker, Hemsteger, & Pelier, 2016; Carlisle, 2017).

Arita et al., used an explicit distractor cue that changed on every trial, but similar conclusions have been drawn from studies in which distractor templates are learned over time. For example, Vatterot & Vecera (2012) found that interference by a salient color distractor (i.e., a color singleton) during target-search decreased after repeated exposures, but rebound each time the singleton changed into a new color. Thus, a specific suppression template must have been learned for the color of each singleton distractor over time (see also Noonan et al., 2016; Reeder, Olivers, & Pollmann, 2017). Moreover, because the location of the distractor was not predictable from trial-to-trial, observers must have learned what color (and not which location) to suppress. Other studies have found implicit learning of spatial locations to also facilitate distractor suppression. For example, Leber et al., (2016) found that an implicit spatial cue for distractor
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locations facilitated target selection even when subjects were not aware of the contingency. Together these results suggest that learned regularities about a wide variety of distractor characteristics can be used to facilitate their suppression.

In addition to behavioral studies, neurophysiological studies have found evidence for the active suppression of distractors (Andersen & Müller, 2010; Bridwell & Srinivasan, 2012; Gasper & McDonald, 2014; Khayat, Niebergall, & Martinez-Trujillo, 2010; Martinez-Trujillo & Treue, 2004; Noonan et al., 2016; Sawaki & Luck, 2011; Seidl, Peelen, & Kastner, 2012; Shin, Wan, Fabiani, Gratton, & Lleras, 2008; Snyder & Foxe, 2010; Suzuki & Gottlieb, 2013). For example, Gaspar & McDonald (2014) used the N2pc (an index of attentional processing; Luck & Hillyard, 1994) and Pd (an index of attentional suppression; Hickey et al., 2009; Sawaki & Luck, 2010) event-related potentials (ERPs) to explain RT differences in a target visual search task on trials with a singleton distractor. Shorter RTs occurred on trials when the singleton distractor elicited a Pd, presumably because the distractor was actively suppressed; and longer RTs occurred on trials when the distractor elicited an N2pc, signaling that attention was captured.

Measuring distractor processing directly without asking observers to make any overt responses is a great advantage of neurophysiological studies over the purely behavioral studies because asking observers to report directly on distractor features can change distractors from being "task-irrelevant" to “task-relevant”. Thus, the only way to probe distractor representations with manual behaviors is to indirectly observe their effect on target processing (see above).

The preceding studies suggest that it is possible to suppress specific distractor features, yet, to our knowledge, no studies have looked at the tuning of suppression templates for multiple distractors in a visual search scene, nor how well those templates might generalize to new stimuli. Considering that distractors usually outnumber targets in real world environments, it is critical to
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understand how multiple distractors may be filtered during visual search. We address this question by testing if distractor suppression for a "trained" set of distractors would generalize to new sets of "test" distractors. We expected RT and accuracy in response to the new "test" distractors to reflect their inclusion, or exclusion, from the distractor template: if the test distractors fall into the existing template, they should be suppressed, leading to shorter RTs. The exact strength of suppression should be commensurate with the inclusion of that feature within the tuning of the distractor template. However, if the existing template does not include features of a new test distractor, performance should suffer (i.e., producing longer RT, lower accuracy).

We attempted to control for changes in the target template by using colored distractors and a neutrally hued gray target.

We tested three alternative hypotheses for how multiple distractors could be encoded within a suppression template. The first is that the distractor template will include features from each of the trained distractors. Previous research has shown that multiple target templates are created when there are multiple targets (Beck, Hollingworth, & Luck, 2012; Grubert & Eimer, 2015; Menneer, Barrett, Phillips, Donnelly, & Cave, 2007; Menneer, Cave, & Donnelly, 2009; Moore & Osman, 1993; Neisser, Novick, & Lazar, 1963). If distractor templates are similar, they may contain information about each of the previously seen distractors. Such templates would suppress all of the previously seen distractors equally well and suppress new distractors commensurate with the amount of information shared with trained distractors.

The second hypothesis is that the template contains the average feature value of all the trained distractors. A single average representation may be more optimal if distractor templates require active maintenance by limited cognitive resources such as working memory (Baddeley & Hitch, 1974; for review Luck & Vogel, 2013). An "average" template would be consistent with
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previous studies that have found ensemble statistical representations of non-targets (Alvarez & Oliva, 2008; Chetverikov, Campana, & Kristjánsson, 2016, 2017a, 2017b). If the distractor template contains a summary statistic, then we would expect suppression to be greatest for distractors at the mean of the trained distractors and suppression to fall off monotonically with distance from the mean. Interestingly, this predicts that there will also be differences in the strength of suppression between trained distractors. That is, even amongst trained distractors, ones nearest to the mean will be better suppressed than those that more distant from the mean.

A final, albeit unlikely, alternative is that there are no distractor templates created for multiple targets. In this case, all new and old distractors will have similar performance during the testing phase of the experiments. Another variation of this idea is that the distractor template is so general that it only applies to a feature dimension (e.g., color), but not to specific features within a dimension. For example, Harris, Becker, & Remington (2015) found in a spatial cueing paradigm that red and green targets were cued by non-target color cues (e.g., blue), but not by cues from other feature dimensions (e.g., motion). They took this as evidence for dimension-specific, but not feature-specific, attentional cueing. Figure 1 illustrates schematic tuning curves from the alternative hypotheses.

<Figure 1>

**Experiment 1**

We test the hypothesis that a suppression template will be created from multiple recurring distractors. We also probe the width of the template's tuning by using two new "test" distractor sets to see whether suppression generalizes. One, the "close" set has new distractors that differ
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from trained distractors by 22.5° each and the "far" set contains distractors that differ by 180° in color space (see Figure 2A). We hypothesize that a distractor template built from trained distractors will generalize suppression to new close distractors, but not far ones. However, if the distractor template contains non-specific information such as “colored objects” (in contrast to the gray target), we would expect similar suppression for all distractors (i.e., trained, close, and far ones) during the testing phase.

Method

Participants. Twenty undergraduates from UC Davis (mean age=21.3 years, SD=2.4, range=18-27; 9 males; 1 left-handed) participated for course credit or monetary payment at $10/hour. We estimated that 20 participants would be needed based on medium to large effect sizes obtained in a previous paper examining a similar topic (Geng et al., 2017). All had normal or corrected-to-normal vision and provided informed consent in accordance with NIH guidelines provided through the UCD Institutional Review Board.

Stimuli and apparatus. Stimuli were displayed on a 24-in. Dell LCD monitor (we used two Dell LCD monitors, one with a spatial resolution of 1920 x 1200 pixels and the other with 1920 x 1080 pixels), with a refresh rate of 60 Hz. Stimuli were generated using MATLAB (www.mathworks.com), with Psychtoolbox extensions (Brainard, 1997; Pelli, 1997). Each participant sat in a sound-attenuated dimly lit room, 60 cm from the monitor.

Search displays contained colored squares and a gray square. Colors for distractors were chosen from 16 equally spaced colors that only varied in hue (CIELAB space; L* = 70, center: a
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= 0, b = 0, radius of 39; Figure 2; Table 1, from Bae, Olkkonen, Allred, & Flombaum, 2015).

Each color was therefore 22.5 degrees of visual angle from the next nearest color. This corresponds to $\Delta E_{ab}^* = 15$ (i.e., the distance metric between two CIELAB colors). This $\Delta E_{ab}^*$ between colors is well above the threshold of just noticeable differences (JND), which is about $\Delta E_{ab}^* = 2.3$ (MacAdam, 1942). The gray color for the target stimulus was generated by averaging all 16 distractor colors. Each square subtended $1.29^\circ \times 1.29^\circ$ (all visual angles calculated from a viewing distance of 60 cm) and was located in one of four quadrants and centered $1.80^\circ$ horizontally and vertically from the fixation cross. The target appeared equally in each location in a random order. The distractors appeared randomly in the remaining three locations. On each trial, each square was randomly assigned one number (1 through 4) drawn in white. Subjects manually reported the number on the target square with a keyboard. We used four aligned number keys (1-4) on the top of the keyboard rather than the number pad to avoid Simon effects as much as possible (Simon, 1969). The numbers (1-4) were randomly assigned to each of the four colored squares on each trial to avoid systematic response biases based on the target number. Auditory feedback was either a three “chirp” sequence lasting 300-msec for correct responses, or a single high-pitched 100-msec tone followed by an additional 3-sec blank period after incorrect responses.

The colors used were counterbalanced between subjects (i.e., a warm-color and a cool-color group). In detail, the warm-color group (N=10) saw three warm color distractors (16, 2, 4; each $45^\circ$ apart; see Table 1, $\Delta E_{ab}^* = 30$ between two colors) during training (i.e., the trained set of colors). During testing, the trained color displays were interleaved with two new display sets. The first included three new warm close colors (1, 3, 5; each $45^\circ$ apart) that were shifted one step from the trained distractors; and the second included three new cool far colors (8, 10, 12; each
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45° apart) that were shifted eight steps from the trained distractors. The cool-color group (N=10) was trained on three cool colors (8, 10, 12) and tested on that set plus a new set of cool close colors (7, 9, 11), and a set of three warm far colors (16, 2, 4). Note that the close colors for the warm-color group were identical to the far colors for the cool-color group (the reverse was true for the cool-color group). Importantly, the two most similar trained and close colors (e.g., trained color 2 and “close” colors 1 and 3; see Figure 2A) were clearly distinguishable based on a $\Delta E^*_{ab} = 15$. Because the group factor was not an a priori question, and also adding more factors would result in underpowered analyses, we did not include “group” as another factor in RT analysis, and only focused on RT differences across distractor sets during testing.

<Table 1>

<Figure 2>

Design and procedure. Participants completed four practice trials before the main experiment. The main experiment included a "training" phase (total of 128 trials) followed by a "testing" phase (total of 256 trials). During training, the target appeared with one distractor on the half of the trials (set size 2) and with three distractors on the other half of trials (set size 4). Initially, we were interested if any set size effect would diminish over time as an indicator of learning, but there were no differences between the two set size displays in either the first or second half of training ($F < 1$). The target was always gray and the distractors were always the same three colors. During testing, the target appeared with one of three types of distractors display (trained, close, far). Only set size 4 trials were used during testing. The trained distractors were identical to those seen during training; close distractors and far distractors were new. Trained distractor displays appeared six times more frequently (192 trials) than the close or far distractor trials (32
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trials each). The uneven distribution of distractor sets during testing was used to maintain
distractor expectations developed during training.

Each trial began with a 200-ms blank followed by a fixation display for 200-ms and the
target search display. Participants were instructed to search for a target gray square and report the
number in it (1, 2, 3, 4) using a keyboard as rapidly as possible without sacrificing accuracy. The
search display was removed immediately after response or a fixed duration (2-sec for set size 4
or 1.5 sec for set size 2). Offset of the search display was followed by 200-ms of a white fixation
and auditory feedback. Because accuracy was emphasized over speed, overall accuracy was high
and we therefore focused on analyses of RT data. Figure 3 illustrates example trials from training
and testing in Experiment 1.

<Figure 3>

**Results and discussion**

Overall accuracy was high (mean: 98.5%; SD: .9) and therefore we only use RT in
subsequent analyses. Inaccurate trials and trials with RTs longer than 3SD above each
individual's mean were removed (3.0%).

The primary purpose of this experiment was to determine if suppression of a trained set
of distractors would generalize to new sets of distractors. The visual search trials during the
training phase contained only one set of colors and were not analyzed. To compare the three
distractor sets from the testing phase, a one-way ANOVA was conducted with distractor set
(trained, close, far). The ANOVA revealed a significant main effect, $F(2, 38) = 13.97, p < .001,$
$\eta^2_p = .42, BF_{10} = 619.4$. Subsequent pairwise t-tests showed significantly longer RTs for *far*
distractors than *trained* and new *close* distractors, $t(19) = 4.41, p < .001, d = .99, BF_{10} = 103.9,$
and $t(19) = 3.95, p < .001, d = .88, BF_{10} = 41.4$, respectively. In contrast, there was no significant
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difference in RTs between trained distractors and close distractors, $t(19) = .32, p > .7, d = .07, \text{BF}_{01} = 4.1^1$. The Bayes Factor indicates that the comparable RTs between trained and close distractors were 4.1 times more likely to be observed if the null hypothesis were true than if the alternative hypothesis were true. A Bayes factor of 3 or greater is generally considered analogous to a $p$ value of $< .05$. (Morey, Rouder, & Jamil, 2014; Rouder, Morey, Speckman, & Province, 2012; Wetzels, Matzke, Lee, Rouder, Iverson, & Wagenmakers, 2011 for guidelines on the interpretation of Bayes factor magnitudes).

These findings suggest that the "tuning" of the distractor template created by three trained distractors was broad enough to suppress the new close distractors, but narrow enough to exclude new far distractors. Recall that the close distractors during testing were each shifted one color index ($22.5^\circ$) from the trained distractors. This provides evidence that training induced the creation of relatively broad distractor templates from multiple colors; this rules out the possibility that the distractor template contained only all non-gray hues, or was based solely on enhancing selection of the gray target independent of distractor colors. Figure 4 shows the RTs from the testing phase in Experiment 1.

<Figure 4>

**Experiment 2**

Experiment 1 provided evidence for the formation of a suppression template for multiple distractors. In Experiment 2, we test whether the distractor template contains representations of

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1 Failing to reject the null hypothesis with classical statistics could occur due to limitations in statistical power, even when a true difference is present (type II error). One approach to increase confidence in the null hypothesis is to compute the Bayes Factor (BF), which generates a readily interpretable odds ratio of evidence for vs. against the null hypothesis (e.g., Rouder, Speckman, Sun, Morey, & Iverson, 2009). The Bayes factors is written as BF$_{10}$ when the evidence is in favor of H1 and as BF$_{01}$ when the evidence is in favor of H0. We computed the BF for all statistical analyses using JASP 0.8.1.2 (JASP Team, 2017), with the default prior width of 0.707.
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each of the trained distractor colors or only a single value reflecting the mean of the three trained
distractors (Figure 1A vs. Figure 1B). The training phase was similar to Experiment 1, but now
each of the distractors appeared alone with the target during the testing phase. If the distractor
template is centered at the mean of the trained colors, then RTs should be shorter on test trials
with the center distractor color (which was also the group average) than the other two colors (i.e.,
the \textit{left-sided} and \textit{right-sided} colors).

\textbf{Method}

\textit{Participants.} Twenty undergraduate students from UC Davis (mean age=21.9 years, SD=3.8,
range=19-34; 6 males; 2 left-handed) participated. All had normal or corrected-to-normal vision
and provided informed consent in accordance with NIH guidelines provided through the UCD
Institutional Review Board.

\textit{Stimuli and procedure.} The design and procedure were identical to those of Experiment 1
except for the following: displays in the training phase (252 trials total) always had one gray
target presented with three distractors (i.e., always set size 4), and the testing phase (72 trials
total) always had one target presented with one of the three trained distractors, one at a time (i.e.,
set size 2; 24 trials each). There were no new distractors introduced during testing. Figure 4
illustrates search displays during training and testing. Colors 16, 2, and 4 (see Table 1) were used
for the warm-color group (N=10) and colors 9, 11, and 13 for the cool-color group (N=10).
Importantly, because the three distractors were each 45° of color angle away from its nearest
neighbor, the mean of all three distractors was equivalent to the center distractor color. We refer
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to this mean color as the center color and the other two as the left-sided and right-sided
distractors, respectively (the left vs. right designation was arbitrarily assigned). Figure 5
illustrates example trials from training and testing in Experiment 2.

<Figure 5>

Results

As in Experiment 1, overall accuracy was high (mean: 96.8%; SD: 2.3%) and we again
concentrate analyses of interest on RT. RT values greater than 3SD from the individual mean
were trimmed (4.8%).

The data from the testing phase were entered into a one-way ANOVA with three
distractor sets (center, left-sided and right-sided). The main effect was not significant, $F < 1$,
$BF_{01} = 7.0$. A BF of 7 provides substantial evidence for the null hypothesis and suggests that all
trained distractor colors were equally suppressed. RTs were no shorter for the center color, which
was the arithmetic mean of all three trained distractors, than the two side colors. This suggests
that the distractor template equally represents each of the trained color values and not the mean
value of all trained distractors; this provides evidence in favor of the hypothesis that the template
includes "distinct" information about each trained distractor and against the hypothesis that it
contains the "average" of trained distractors (Figure 1A cf. 1B). Figure 6 shows the RTs from the
testing phase in Experiment 2.

<Figure 6>

Experiment 3A

Having found evidence in Experiment 1 that the distractor template contains broad
representations of each of the trained colors (see Figure 1A), we next wished to test the
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consequences of overlapping feature representations on the strength of suppression. To do so, we
created two new testing phase distractor sets. Both included the central trained color, but they
differed in the inclusion of two new distractors. One set included two new *inner* distractors, each
of which lies at the intersection between two trained distractors; the other included two new
*outer* distractors, which neighbored only one of trained distractors (see Figure 7). We
hypothesized that suppression would be stronger for new *inner* test distractor set because
suppression would be stronger for stimuli that activate multiple representations within the
suppression template. In addition to this primary question, we also wished to control for potential
effects of the training procedure, which differed in the first two experiments. Perhaps seeing the
distractors only one at a time during training (as in set size 2 displays) would produce "narrower"
representations that generalize less well than seeing distractors sometimes as a group (as with
mixed set size 2 and 4 displays; see Experiment 1).

<Figure 7>

**Method**

*Participants.* Because we wished to test the effects of distractor set size during the training on
the generalization of suppression during the testing phase, two groups of participants were
included (each N=20). The "set size 2" group only saw one distractor at a time during training
and the "set size 4" group saw one distractor at a time on the half of trials and three distractors
simultaneously on the other half of trials during training (same as Experiment 1). The color sets
during the testing phase were identical in both experiments and were always presented in set size
4 displays.
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Twenty undergraduates from UC Davis (mean age=20.5 years, SD=2.2, range=18-34; 2 males; 1 left-handed) participated in the "set size 2" group. Another 20 undergraduates from UC Davis (mean age=21.3 years, SD=2.0, range=18-27; 3 males; 3 left-handed) participated in the “set size 4” group. All had normal or corrected-to-normal vision and provided informed consent in accordance with NIH guidelines provided through the UCD Institutional Review Board.

Stimuli and Procedure. The design and procedure of the “set size 4” trials were identical to those of Experiment 1. The design and procedure of the “set size 2” trials were identical to those of Experiment 2 with the exception that only set size 2 displays were used during training and only set size 4 displays were used during testing. Importantly, however, both groups saw the same distractor displays during the testing phase. The exact colors shown to subjects in each experiment were counterbalanced. The warm-color groups (N=10 in each experiment) saw the following: three trained distractors (16, 2, 4, each 45° apart in color space; see Table 1), three new inner color distractors (1, 2, 3, each 22.5° apart), and three outer color distractors (15, 2, 5, each 67.5° apart); the cool-color groups (N=10 in each experiment) saw the following: three trained distractors (9, 11, 13), three new inner colors (10, 11, 12) and three new outer colors (8, 11, 14). The new inner and outer color sets both included the center color from training, but differed in the two side colors: the inner colors were all within the range of trained colors (i.e., each 22.5° from the center color) whereas the outer set had more distant side colors (i.e., each 67.5° degrees from the center color). Importantly, all of the new side colors were 22.5° degrees from the originally trained side colors. Figure 8 illustrates example trials from training and testing in Experiment 3A.

<Figure 8>
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Results and Discussion

Trials with RTs longer than 3SD above the mean were removed (3.9% in “set size 4” group and 3.6% in “set size 2” group). As in previous experiments, overall accuracy was high (mean: 97.6%; SD: 1.3% in “set size 4” group; mean: 97.9%; SD: 1.4% in “set size 2” group).

First, in order to understand whether the training procedure affected performance during testing, we compared RTs from the two groups using a 2 group (set size 2, set size 4) x 3 test distractor set (trained, inner, outer) repeated measures ANOVA. The analysis revealed neither a main effect of group nor any 2-way interaction between group and distractor set ($F(2, 76) = .61$, $p = .55$, $BF_{10} = 1.4$ for 2-way interaction; $F(1, 38) = .04$, $p = .84$, $BF_{01} = 1.8$ for main effect of group). Performance on the test displays was not affected by whether subjects saw the distractors individually (“set size 2” group) or mixed between set sizes 2 and 4 (“set size 4” group). There was, however, a significant main effect of distractor set, $F(2, 76) = 6.28$, $p = .003$, $\eta_{p}^2 = .14$, $BF_{10} = 11.5$.

Pairwise t-tests conducted between the three distractor sets revealed that RT was significantly longer for the outer distractor set than inner distractor condition, $t(39) = 3.52$, $p = .001$, $d = .56$, $BF_{10} = 27.9$, and marginally longer than trained distractor set, $t(39) = 1.95$, $p = .058$, $d = .31$, $BF_{01} = 1.1$. RT on inner distractor trials did not differ from trained distractors trials, $t(39) = 1.62$, $p > .1$, $d = .26$, $BF_{01} = 1.8$, although the BF indicates that the evidence for the null hypothesis in this case was relatively weak (see Experiment 4 and Discussion). These findings show that new distractors within the trained color range (i.e., inner distractors) were
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suppressed as well as the trained distractors and significantly better than new distractors from outside of the trained color range (i.e., outer distractors). This suggests that the training phase produced broad distractor templates and that new distractors that intersected two template distributions were better suppressed than those that only intersected one. There was strong evidence that suppression was greater for new distractors that shared features with two trained distractors compared to one, but the difference between the trained condition and the other two conditions was less clear. We return to this issue in Experiment 4 (see also Discussion). Figure 9 shows RTs from the testing phase in Experiment 3A.

Experiment 3B

In Experiment 3A, we found better suppression for the inner distractor colors compared to outer colors during testing, and no effect of distractor set size during the training phase. We attributed the difference between inner and outer distractor test sets to the tuning of feature representations within the distractor template. However, an alternative explanation is that the target "popped" out more on inner trials because the distractors were more homogeneous in color (Duncan & Humphrey, 1989), despite being 22.5 degrees apart. That is, the gray target might be easier to find on inner trials because the distractors in that set were more similar to each other than those in the outer set. Experiment 3B was conducted to test this alternative. Experiment 3B was identical to Experiment 3A, but now the inner color group was replaced with a color group that was equally homogenous (each color 22.5° apart), but selected from the opposite side of the
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color wheel from the trained distractor colors (157.5° from the center trained color). This condition is referred to as the far condition (see colors 10-12, Figure 2A). The outer distractors remained the same as in Experiment 3A (67.5 degree apart from each other). If homogeneity were the source of our previous results, we would expect to see shorter RTs for the homogenous far distractors than for the heterogeneous outer distractors.

Method

Participants. Twenty undergraduates from UC Davis (mean age=20.1 years, SD=1.4, range=18-23; 7 males; 4 left-handed) participated. All had normal or corrected-to-normal vision and provided informed consent in accordance with NIH guidelines provided through the UCD Institutional Review Board.

Stimuli and Procedure. The warm-color group (N=10) saw three trained distractors (16, 2, 4; 45° apart; see Table 1), three outer color distractors (15, 2, 5; 67.5° apart), and three far color distractors (10, 11, 12; 22.5° apart); The cool-color group (N=10) saw a different set of three trained distractors (9, 11, 13), three close colors (8, 11, 14) and three far colors (1, 2, 3). The design and procedure were same with those in Experiment 1. Figure 10 shows example trials from Experiment 3B.

<Figure 10>

Results and Discussion
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RTs longer than 3SD above the mean were removed (3.6%). Overall accuracy was high (mean: 97.8%; SD: 1.4%).

Differences in RT performance between distractor displays during the testing phase were assessed with a one-way ANOVA of distractor set (trained, outer, far). There was a significant main effect of distractor set, \( F(2, 38) = 11.74, p < .001, \eta^2_p = .38, \text{BF}_{10} = 201.8 \). Pairwise t-tests revealed the RT on trained distractor displays was shorter than outer distractor trials, \( t(19) = 2.18, p < .05, d = .49, \text{BF}_{10} = 1.6 \), and far distractor trials, \( t(19) = 4.86, p < .001, d = 1.09, \text{BF}_{10} = 260.0 \). Importantly, RT on outer distractor trials was also shorter than on far trials, \( t(19) = 2.58, p < .05, d = .58, \text{BF}_{10} = 3.1 \), which means the data were 3.1 times more likely to be observed if there is a true difference between performance on outer and far trials than if there is not. RT was longer on far distractor trials even though the distractor set was more homogenous in color than the outer set. This suggests that the distance from trained distractors is a more important factor for generalizing suppression than distractor homogeneity. Although distractor homogeneity contributes to the speed of target selection, it is not the most dominant factor in the generalization of distractor suppression. This result supports the idea that distractor templates are created from trained distractor features and that the suppression template can override sensory effects. Figure 11 shows RTs from the testing phase in Experiment 3B.

<Figure 11>

Experiment 4
Multiple distractor suppression

The results from Experiment 3 suggest that representations within the distractor template are broadly tuned over specific distractor features and overlap with each other despite being 45° apart in color space. We hypothesized that the broad tuning could be beneficial because it generalizes suppression better to other potential distractors. Unlike target templates, distractor templates are not likely to be more optimal when very precise because distractors tend to be highly variable and less predictable than targets within a visual environment. If this is true, one might expect that colors that intersect (i.e., are in-between) two trained colors would be even better suppressed than an originally trained color. In Experiment 3 we found that inner colors were better suppressed than outer colors; however, there was no difference between the inner and trained colors. One possible reason for this null difference (despite numerical trends and a relatively weak BF) may be that the inner color set included one of the previously trained colors. Therefore, the combination of all three colors may not have been a careful test of differences between new distractors that sit at the intersection of two trained colors vs. the previously trained colors. In Experiment 4, we only used two colors during training, and tested a total of five colors: the two previously trained ones (similar to all other experiments), one inner color, which was exactly between the two trained colors, and two outer colors that flanked the trained colors.

Method

Participants. Twenty undergraduate students from UC Davis (mean age=21.1 years, SD=2.0, range=18-25; 9 males; 2 left-handed) participated. All had normal or corrected-to-normal vision
Multiple distractor suppression

and provided informed consent in accordance with NIH guidelines provided through the UCD Institutional Review Board.

Stimuli and procedure. The warm-color group (N=10) saw two trained colors (1, 3; 45° apart), two new outer test colors (16, 4; 90° apart), and one new inner color (2); the cool-color group (N=10) saw two cool trained colors (10, 12), two new outer colors (9, 13), and one new inner color (11) during testing.

During training, the target appeared with one distractor on the half of trials and with the other distractor on the other half of trials in random order. During testing, the target appeared with one of five distractor sets –two trained, two outer, and one inner distractor. Figure 12 illustrates example trials from Experiment 4.

<Figure 12>

Results

RTs longer than 3SD above an individual's mean were removed (4.3%). Overall accuracy was high (mean: 97.1%; SD: 1.7%).

The testing data were entered into a one-way ANOVA with three levels of distractor set (outer, trained, inner). There was a significant main effect of distractor set, $F(2, 38) = 6.91, p < .005, n^2 = .27, BF_{10} = 13.4$. The pair-wise t-test revealed that the RT for the inner distractor was shorter than trained distractors, $t(19) = 3.32, p < .005, d = .74, BF_{10} = 12.0$, and the outer distractors, $t(19) = 2.55, p < .05, d = .57, BF_{10} = 2.9$. The RT for trained distractors was not different from the outer distractors, $t(19) = .09, p > .9, d = .02, BF_{01} = 4.3$. 
Multiple distractor suppression

Consistent with our hypothesis, suppression of a new test distractor that intersects two trained distractors is stronger than for the original trained distractors. The Bayes Factor indicates that the data are 12 times more likely to occur if the hypothesis that suppression of the inner distractor is different from trained distractors is true than if the null hypothesis is true. This constitutes strong evidence in favor of the alternative hypothesis (H1). This finding suggests that the representation of trained distractors within the suppression template overlap considerably, and that suppression is stronger for distractors that activate more than one of these representations.

Although these results are also consistent with the idea that there was a benefit for the mean of the two trained distractors (by definition, "inner" and "mean" were identical in this experiment), we interpret these results within the context of the previous experiments that showed no additional benefit for the mean distractor compared to other trained distractors (e.g., see Experiment 2). Figure 13 shows RTs from the testing phase in Experiment 4.

<Figure 13>

General Discussion

In a series of four experiments, we examined how multiple distractors are suppressed and tested our hypothesis that the attentional system builds broadly tuned suppression templates that include multiple distractors that generalize suppression to new distractors. In Experiment 1, we found that three trained distractors create a distractor template broad enough to suppress new distractors that were shifted one step (22.5° each) in color space (i.e., the “close” distractors), but narrow enough to exclude very distant new distractors. This finding ruled out the possibility that
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the distractor template is non-selective and defined in opposition to the target (e.g., containing all non-gray hues). In Experiment 2, we found that all trained colors were equally suppressed, which suggests that the distractor template includes an equal representation of all trained color values, not just the center (mean) color. This finding provided evidence against a second alternative hypothesis that the distractor template contains only the “average” value of multiple trained distractors. While it has been previously shown that it is possible to create ensemble representations of non-target elements (Alvarez & Oliva, 2008; Chetverikov, et al., 2016; 2017a, 2017b), our data suggest that it is also possible to create templates with multiple learned features. These results are not contradictory, as there may be two mechanisms for distractor suppression and the use of ensemble information or specific features depends on the complexity and regularities of the visual scene.

Moreover, because the trained distractors in Experiment 2 were relatively far away from each other (each 45° apart, spanning 90° of color space), the finding that all three distractors were suppressed equally also addresses a possible alternative explanation for the results in Experiment 1. The alternative explanation is based on models of attention in which the target representation is shifted away from distractors in order to optimize the distinctiveness of targets from distractors (Becker, 2010; Navalpakkam & Itti, 2007; Geng et al., 2017). In Experiment 1, it is possible that instead of building a distractor template, the single gray target was shifted away from the trained colors (i.e., toward the opposite side of the color wheel). For instance, if the trained distractors were warm colors – red, orange, and yellow, the representation of the gray target might have been shifted towards an opposite color, e.g., green. If this target-shift occurred, RTs to the far colors in Experiment 1 may have been longer not because they were excluded from the distractor template, but because they were closer to the shifted target representation.
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However, this model would also predict suppression to be strongest for the mean of the three trained values in Experiment 2. This is because the shift of the target away from the all distractors would effectively increase the distance between the target and the central distractor the most (especially given the 90° spread of colors in Experiment 2). The results of Experiment 2 were inconsistent with this model and instead suggest that mechanisms for distractor suppression in this study are likely to be separate from those of target enhancement.

In Experiment 3, we found better suppression of testing phase color sets that included new distractors that intersected the representation of two trained color distractors (i.e., inner colors) than those that only intersected one. This was true even though the distance of both the new inner and outer distractors were each 22.5° from one of the trained distractors. The only difference was that the inner distractors were 22.5° away from two trained distractors whereas the outer distractors were neighbors of only one trained distractor. The fact that suppression was stronger for the inner test colors, and the effects of distractor homogeneity were ruled out in a control experiment, suggests that distractor templates are broad and overlapping; and new distractors that activate more than one representation are better suppressed.

Similarly, in Experiment 4, we found the distractor template created by two trained distractors suppressed a new single distractor that was unseen during training, but intersected both trained distractor better than the trained distractors themselves. This supports the notion that broad distractor templates that overlap confer a suppression advantage to new distractors that lie at their intersection. This idea is distinct from that of a template built from the arithmetic mean of trained distractors since the mean is always the central tendency of all the trained distractors, but the number of intersections between representations depends on the number of stimuli in the scene and their distance from each other.
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However, it is likely the exact patterns of results found in our experiments are a function of the stimulus context used. For example, although we always found stable difference between the new testing phase distractor sets when compared to each other, the relationship between each of those (e.g., *inner, outer*) to the *trained* set differed across experiments. Such apparent differences might be due to the total range of distractor colors seen during the testing phase (see Figure 2). For example, there was a greater range of distractor colors during the testing phase in Experiments 1 and 3 than in Experiment 4. Thus, the exact tuning of distractor features within the suppression template may evolve based on distractor values present in a visual scene during the testing phase. We attempted to control for this by continuing to include a greater proportion of trained distractors during the testing phase than new distractors, but we could not be sure that the templates were not modified. This suggests that distractor templates may be highly flexible and sensitive to the global feature statistics of the sensory environment. Exactly how this is computed over time needs to be fleshed out in future experiments.

It is worth noting that the equidistant colors on the color space can sometimes fall into different category labels, which may have two effects. First, it is possible that test colors from the same category (e.g., two colors from “pink” category) might be more easily suppressed than those from different categories (e.g., one color from “pink” and one color from “orange”). However, this account cannot fully explain the results (e.g., from Experiment 1): Although the three “close” colors were from three different color categories (“pink”, “orange”, and “yellow”; Bae et al., 2015) and the three “far” colors were only from two categories (two colors from “blue” and one color from “green”; Bae et al., 2015), we found a stronger suppression for “close” distractors than “far” distractors.
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Another possible effect of color category is that new “test” colors that fall into the “trained” color categories will be better suppressed. However, this account also cannot fully explain the results. For example, in Experiment 4, the color categories of both the “inner” (“pink”) and “outer” (“pink” and “orange”) conditions were contained within the “trained” color categories (“pink” and “orange”). However, we found a significant difference between the “inner” and “outer” color distractors. Therefore, even though the test colors were within the trained color categories, performance still differed depending on the distance of the specific test colors from the trained colors. Thus, while it is likely that color categories play a role in template formation, they cannot completely explain our current results.

Together, our results suggest that the distractor template contains broadly tuned and overlapping distractor representations. This profile is consistent with the different function of distractor templates from target templates. Instead of emphasizing precision, distractor templates may operate most effectively when they are broad. While broad target templates would increase the number of false positive target selections, broad distractor templates aid visual search by generalizing suppression and reducing the number of false alarms in complex environments. In other words, having broad and overlapping templates may be the most optimal way to efficiently suppress expected distractors while still generalizing to other distractors that are likely to be non-targets. For example, when searching for a melon among a bunch of apples, broad tuning over small-round, reddish objects will be more efficient than building suppression templates for specific apple exemplars or even varieties. The question of how broad suppression templates are and whether there is an upper limit on the number and width of these templates requires further study.

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2 We thank an anonymous reviewer for raising this question.
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In conclusion, the results from these experiments suggest that distractor templates that contain multiple distractor features are created in response to experience, and that the tuning of these templates is relatively broad. New experiments are necessary to determine whether the distractor representations are held in separate templates that each create independent working memory demands (Chelazzi, Miller, Duncan, & Desimone, 1993; Desimone & Duncan, 1995; de Fockert, Rees, Frith, & Lavie, 2001) or whether the feature values of different distractors are somehow combined into one working memory template. Another intriguing possibility is that distractor templates are not actively maintained in the same way as target representations and are instead held implicitly or passively within sensory cortex (Stokes, 2015; Stokes, Thompson, Nobre, & Duncan, 2009; Chelazzi et al., 1993; Postle, 2015; Leavitt, Mendoza-Halliday, & Martinez-Trujillo, 2017). However, our results clearly show the existence of distractor representations that generalize suppression to new distractors with varied features.
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References


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JASP Team (2017). JASP (Version 0.8.1.2).


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Figure 1. Schematic tuning curves from three hypothesized distractor templates. D1, D2, D3 refer to the three distractors used in the training phase. A. Three overlapping, broadly tuned, but distinct distractor templates, B. A single template centered on the average of the three trained distractors, C. No template, or template with no color-specificity.

Table 1. 16 colors’ coordinates in CIELAB color space (a* = 0, b* = 0, L* = 70, Radius = 39)

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Figure 2. A. Color wheel illustrating colors used in these experiments (from Bae et al., 2015). Each color is 22.5° away from the nearest color. Arrows indicate colors used for the warm-color group in Experiment 1. Gray arrows indicate the trained colors, pink arrows indicate new close colors, and green arrows indicate new far colors. B. Colors used each of the experiments (D1,
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D2, D3 refer the distractors used in training phase; T1, T2, T3 refer trained colors; N1, N2, N3 refer new colors). Only colors for the warm-color group are illustrated. The number inside each square is an index for each color; the ab’ values for each color index are given in CIELAB space in Table 1.

Figure 3. Example search trials from training and testing phase in Experiment 1. A. A gray target appeared with one or three colored distractors from the training set. B. Illustration of trained and far search trials during the testing phase. A gray target always appeared with three colored distractors drawn from the trained set, a new close set, or a new far set of distractors (see text for details).

Figure 4. RT results from Experiment 1 as a function of distractor set. Error bars show ±1 within-subjects standard error of the mean († indicates a marginal p value (.05 < p < .1); * indicates p < .05; ** indicates p < .01; *** indicates p < .001).
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Figure 5. Example search displays from Experiment 2. A. During the training phase, the gray target always appeared with three colored distractors. B. During the testing phase, the gray target always appeared with one of the three trained distractors. The locations of the target and distractors were randomly chosen.

Figure 6. RT results from Experiment 2 as a function of distractor set. Error bars show ±1 within-subjects standard error of the mean.
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**Figure 7.** Schematic tuning curves from hypothesized distractor templates. Three overlapping, broadly tuned distractor templates. Arrows illustrate the two new color sets. The two new colors in the "inner" test condition (black) are encoded by two trained templates and the two new colors in the "outer" test set (gray) are encoded by only one. Notice that the middle trained color (D2) was included in both new color sets (I: inner, O: outer), symbolized by the gray and black arrows.

**Figure 8.** Example search trials from Experiment 3A. A. (Upper) The “set size 4” group saw the gray target with one or three colored distractors during the training phase. (Bottom) The “set size 2” group saw the gray target always with one of the three possible colored distractors during the training phase. B. During the testing phase, the gray target always appeared with
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three simultaneous distractors from the trained, inner, or outer distractor sets (trained and inner distractor sets are illustrated).

Figure 9. RT results from Experiment 3A as a function of distractor set. Error bars show ±1 within-subjects standard error of the mean.

Figure 10. Example search trials from Experiment 3B. A. During training, the gray target appeared with one or three colored distractors. B. During testing, the gray target always appeared with one of three distractor sets – trained, outer, or far distractors (trained and far conditions are illustrated).
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Figure 11. RT results from Experiment 3B. RT as a function of distractor set. Error bars show ±1 within-subjects standard error of the mean.

Figure 12. Example search trials from Experiment 4. A. In the training phase, the gray target randomly appeared with one of two distractors. B. In the testing phase, the gray target appeared with one of five distractors – the two trained, two new outer, and one new inner colors (an inner color and an outer color trial are shown).
Figure 13. RT results from Experiment 4. RTs as a function of distractor set. Error bars show ±1 within-subjects standard error of the mean.