

# Using the Dual-Target Cost to Explore the Nature of Search Target Representations

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Eye movements were monitored to examine search efficiency and infer how color is mentally represented to guide search for multiple targets. Observers located a single color target very efficiently by fixating colors similar to the target. However, simultaneous search for 2 colors produced a dual-target cost. In addition, as the similarity between the 2 target colors decreased, search efficiency suffered, resulting in more fixations on colors dissimilar to both target colors, which we describe as a “split-target cost.” The patterns of fixations provide evidence to the type of mental representations guiding search. When the 2 targets are dissimilar, they are apparently encoded as separate and discrete representations. The fixation patterns for more similar targets can be explained with either 2 discrete target representations or a single, unitary range containing the target colors as well as the colors between them in color space.

*Keywords:* color search, dual-target cost, eye movements, top-down search guidance, search template

Visual search tasks make up a large part of everyday life. Typically these tasks involve searching for a single, known target in a field of distractors. However, we often search for more than one object at a time, as when locating both our keys and wallet, or in more critical instances, such as searching x-ray images for guns and bombs. How does the attentional system guide search to multiple targets?

Previous experiments with applied search tasks have tested performance in dual-target disjunctive search, in which, at most, one of two possible targets is present in the display. These experiments demonstrated a cost in dual-target search relative to the combined performance across two single-target searches, and have revealed that this cost is greatly reduced, if not eliminated, when the two targets share the same color (Menneer, Cave, & Donnelly, 2009; Stroud, Menneer, Cave, Donnelly, & Rayner, in press). The experiment reported here is a carefully controlled test of dual-target color search, and also extends the previous research by manipulating the similarity relationship between target colors.

Color is one of the most effective guiding features used to direct visual attention and eye movements in visual search (Williams, 1967; Williams & Reingold, 2001; Wolfe & Horowitz, 2004; Zelinsky, 1996). The use of color, as revealed through eye fixations, will provide evidence on how two target colors are represented during dual-target search.

Why might search for two targets be less effective than search for one target? Search guidance for a single target is controlled by an internal mental representation or template of the features belonging to the targets. The objects that are fixated during search will be determined by the target representation or representations that are directing search. In dual-target search, there are two general ways in which the two targets might be represented. The searcher may maintain two discrete representations that are either maintained simultaneously or alternated over time (Moore & Osman, 1993). Alternatively, a single unitary representation of a range of feature values might contain the features present in both targets, including any feature values that exist between the targets in the appropriate feature space. The current experiment tests these hypotheses by manipulating the relative similarity between the two target colors.

## Costs and Benefits of Multiple Target Search

In simultaneous search for multiple objects, what benefits or costs arise compared with separate searches for the individual targets? Efficient search has been demonstrated for multiple targets when they are linearly separable from distractors in stimulus space. For example, color targets that are adjacent to one another in color space give rise to efficient search compared with target colors that have distractor colors between them in color space (Dzmura, 1991; Stroud et al., in press; see also Bauer, Jolicouer, & Cowan, 1996). Similar results have also been shown for multiple

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targets defined by orientation (Barrett, Menneer, Phillips, Cave, & Donnelly, 2003). However, the efficiency of search guidance suffers when the similarity between targets decreases. In general, search for multiple targets is less efficient than search for a single object (Menneer, Barrett, Phillips, Donnelly, & Cave, 2007; Wing & Allport, 1972).

Dual-target costs have emerged in a number of different conditions. Searches for two targets had lower accuracy and longer search times compared with separate, individual searches for single color patches, oriented bars, and complex abstract shapes (Menneer et al., 2007) as well as familiar alphanumeric characters (Kaplan & Carvellas, 1965). In applied research, search of x-ray images for guns and bombs demonstrated similar dual-target costs (Menneer, Auckland, Donnelly, & Cave, 2006; Menneer et al., 2009). Eye movement patterns have revealed one major contribution to this cost. A dual-target search for targets that differed in color and shape resulted in increased fixations to distractor objects that were dissimilar to both targets (Stroud et al., in press). For example, when given an orange object and a blue object to search for, there was an unusually high number of saccades toward purple and green objects that did not resemble either of the targets. Even after extensive practice, dual-target costs were still present in accuracy (Menneer et al., 2009; Menneer, Donnelly, Godwin, & Cave, 2010) and in eye movement measures (Menneer et al., 2008).

In previous research, specific conditions were established under which searching for dual targets can be either efficient or inefficient (Menneer et al., 2007; Stroud et al., in press). These studies included stimuli that were constructed from two rectangles as abstract representations of guns, knives, and bombs, to emulate real world searches conducted by airport security screeners. The experiments encouraged color selectivity but required a difficult shape manipulation. For dissimilarly colored targets, the results showed a decrement in search performance, reflected in response time and accuracy. The eye movements further illustrated this dual-target cost, with an increase in fixations directed to colors that were dissimilar to either search target color. Due to the relative complexity of the stimuli, it is difficult to disentangle the effects of color and shape on search performance. The current experiment utilizes a similar paradigm but maintains tight control over the features and dimensions used.

Here we focus on the single dimension of color and, specifically, on how two colors are represented to guide search. Color is very effective at guiding search, and hue provides a circular stimulus space within which similarity can be manipulated while avoiding the confound of the upper or lower limits of the space (which can be a problem with features such as luminance or size).<sup>1</sup> The use of color in visual search introduces some factors that must be considered—in particular, similarities between targets and distractors, and also color category boundaries.

Target-distractor similarity and distractor-distractor similarity affect efficiency in all types of visual search (Duncan & Humphreys, 1989; Treisman, 1988; Treisman & Gelade, 1980). Specifically, in color search, increased similarity between distractors and target(s) causes an increase in search time (Carter, 1982; Nagy & Sanchez, 1990), while a target that is linearly separable, in chromaticity or luminance, from heterogeneous distractors is detected efficiently (Bauer et al., 1999). However, this linear separability effect is modulated by target and distractor color categories

(e.g., red, pink, purple). When a target falls into a color category that is different from the distractor categories, it can be found efficiently despite being linearly nonseparable from distractors (Daoutis, Pilling, & Davies, 2006), and can be found as efficiently as a linearly separable target (Reijnen, Rich, Van Wert & Wolfe, 2007). Such research demonstrates that between-category search is more efficient than within-category search. However, it is worth noting conflicting findings in which search was not guided by linguistic color categories (Lindsey et al., 2010). All of these findings together emphasize the need to consider category boundary effects in this experiment.

The current experiment has three aims: (a) to evaluate the dual-target cost in color search, (b) to measure how this cost increases with decreased similarity between two target colors, and (c) to explore the nature of the target representation guiding dual-target search. Eye movements were monitored while participants located a T among pseudo-Ls. The eye movements revealed the features that were fixated and therefore indicated the features driving overt visual search (Findlay, 2004). The distribution of fixations to distractor colors is informative as to how the target colors are being represented. To investigate target representation during search, the main eye movement measure employed here is the probability that an object of a specific color is fixated at least once during each trial in which it appears.

The relative color similarity between the targets was manipulated and dual-target performance was compared against search for a single color. Previous findings suggest that search will be more difficult when the two targets are more dissimilar to one another (Barrett et al., 2003), and thus we predict that as the similarity between the target colors decreases, search efficiency will also decrease.

If search for two color targets produces high fixation rates to the target colors, and also to colors between them in color space, then it is possible that the two targets are being represented by a unitary color range representation. However, a similar fixation pattern might also be produced by two separate target color representations if a separate set of fixations is generated by each target color. The distractor colors in between the two color targets in color space could receive fixations triggered by either or both targets, and in some conditions this combination of fixations from both targets could produce a fixation rate as high as or higher than the fixation rates to the actual target colors. A simple mathematical model to be presented later shows the difficulty in distinguishing between a single color range representation and the representation with two separate targets.

## Method

### Participants

Sixty-four University of Massachusetts students with normal color vision and normal or corrected-to-normal acuity participated for course credit.

<sup>1</sup> Another circular dimension is provided by orientation of bars, but we have found in previous experiments that dual-target search in this dimension is difficult, and that participants tend to focus search on one of the targets and ignore the other (Menneer et al., 2007).

**Design**

There were three main factors. Color-step was defined as the position of a distractor’s color relative to the target color that was more similar to it; specifically, it was the number of steps between the distractor color and the nearer target color in the ring in Figures 1 and 2. The second factor was target-set, for which there were four levels: dual targets with one, two, or four color-steps between them, and single target. The third factor was target-presence (absent vs. present). The resulting design was a 7 (color-step) × 4 (target-set) × 2 (target-presence) mixed factorial design with target-set as the only between-participants factor. The primary dependent measure was the probability that an object with a particular color would be fixated once or more during each trial in which it appeared. Secondary dependent measures included response time (RT) and accuracy.

**Stimuli**

Stimulus objects consisted of “T”s and “L”s, each constructed from two rectangles 1.04° × 0.37° of visual angle. The T comprised one rectangle bisecting the other rectangle, resulting in 0.5° of offset. The pseudo Ls consisted of the two rectangles joined together with an offset of 0.3° on the short side and 0.7° on the long side. This configuration made the Ls less discriminable from the Ts and thus encouraged fixations.

Each object appeared in one of 16 separate colors drawn from a set of colors spaced in a ring in CIExyY space (see Table 1 and Figure 1). Because the color of each distractor was assigned independently, every search array had a wide variety of colors, but none of the arrays had all of the possible colors and some arrays

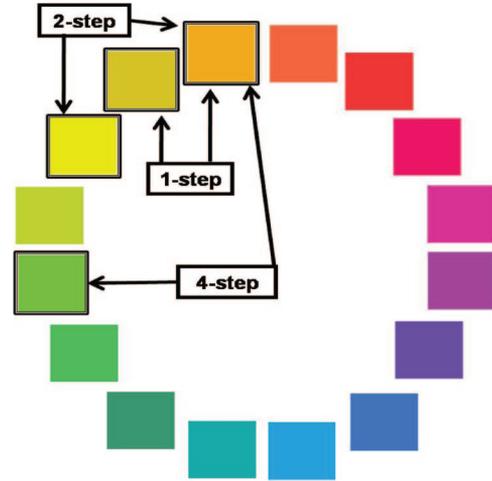


Figure 2. The 16 colors utilized for the current experiment, organized in a ring to show the relationships among them. The three labels represent three sets of possible target-color pairs, with different degrees of similarity between the two targets. Every possible 1-step, 2-step, and 4-step combination of the 16 colors was used in the experiment, with the colors balanced across participants. In addition to the dual-target conditions, a single-target condition was included.

had more color variation than others. The colors were also used by Menneer et al. (2007, 2010) and Stroud et al. (in press). They were chosen to have differences beyond the just-noticeable differences outlined by Wyszecki and Stiles (1982) and chosen such that no single color would visibly pop out from the others (see Figures 1 and 2). However, the color ring will cross a number of category boundaries, so in order to balance the impact of unavoidable category boundaries, all colors were used as targets across participants. Category effects are discussed further in the interpretation of the results.

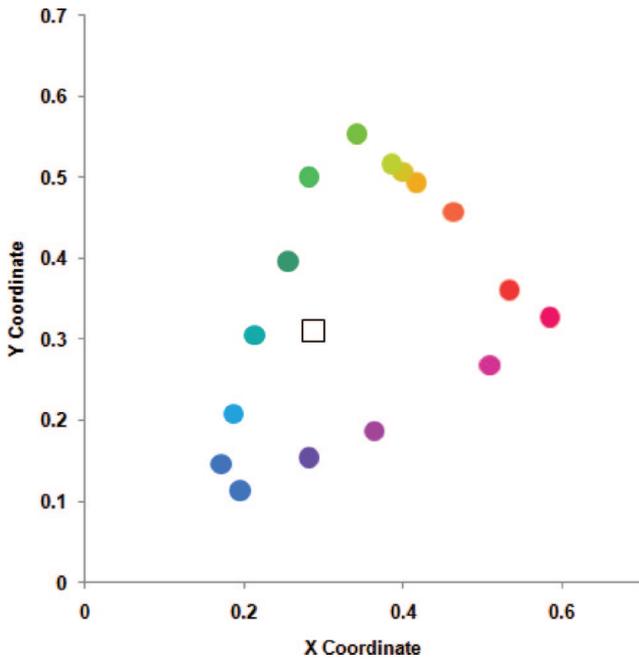


Figure 1. The coordinates in CIExyY color space of the stimuli created. The colors on the figure are approximate representations and luminance values ranged from 0.11 to 0.78 as a proportion of white luminance (16.2 cd/m<sup>2</sup>).

Table 1  
The Coordinates in CIExyY Color Space of the Stimuli Created

X	y	Y
0.463	0.457	0.44
0.417	0.493	0.52
0.4	0.507	0.78
0.386	0.517	0.55
0.342	0.554	0.40
0.282	0.501	0.42
0.256	0.396	0.23
0.214	0.305	0.32
0.187	0.208	0.34
0.172	0.146	0.20
0.195	0.113	0.11
0.282	0.154	0.14
0.364	0.187	0.19
0.509	0.268	0.18
0.585	0.327	0.21
0.534	0.361	0.27
0.287	0.31	1.00

Note. The third column is luminance as a proportion of white luminance, which had an absolute value of 16.2 Cd/m<sup>2</sup>. The last row represents the coordinates of white.

Each display contained 10 objects on a white background. All were Ls, except one that was replaced by a T on target-present trials. Each object was placed in one of 10 locations equally spaced around an imaginary circle with a radius of  $9.8^\circ$  of visual angle. Each object appeared at a randomly assigned orientation of  $0^\circ$ ,  $90^\circ$ ,  $180^\circ$ , or  $270^\circ$  (see Figure 3 for a sample array). The distractors came from a pool of objects without replacement, so that each combination of the 16 colors and four orientations was represented equally often, resulting in 38 instances of each possible combination across the experiment.

In the single-target search condition, each participant was assigned a single target color to search for throughout the entire experiment. In the dual-search conditions, each participant was assigned a specific color pair as targets. The color pair differed in similarity across participants. The entire experiment consisted of 256 trials, with the target appearing in 50% of the trials. Of those 128 trials, each target color of the pair appeared in 64 trials. Participants completed five practice trials prior to the experiment.

### Apparatus

The stimuli were presented on a 17-in Vision Master Pro 514 iiyama CRT monitor attached to a computer interfaced with an SR Research Limited Eye-Link II eye tracking system operating at a sampling rate of 250 Hz. Participants viewed the stimuli with binocular vision, but only the right eye was tracked. Participants were seated 57 cm from the monitor with the entire display subtending  $25.7^\circ \times 32.5^\circ$  of visual angle. Both pupil position and corneal reflections were tracked to no more than  $.40^\circ$  of visual angle error while participants kept their head stationary in a chin rest.

### Procedure

The Ishihara test for color deficiency was administered to ensure that participants had normal color vision (Ishihara, 1917). Participants were then shown a sample display and informed that they should search for a single T in each display and that the T would always be one of the specified target colors. Participants were

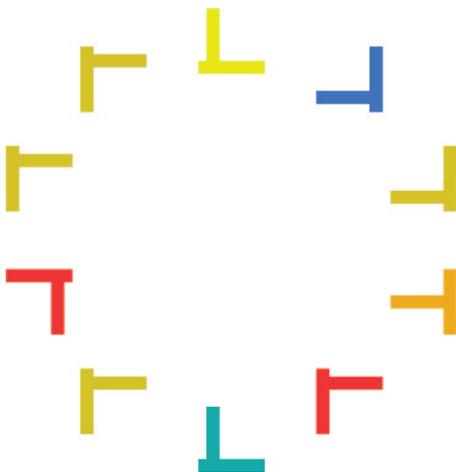


Figure 3. A sample array consisting of a target (T) and distractor (Ls). Each item was assigned one of the colors from the color ring in Figure 2.

notified that a target (T) would be present on 50% of the trials, and that two Ts would never be present in the same trial, thus making it a disjunctive or search task. Participants responded on a Microsoft game controller, with the right button signifying “present” and the left button representing “absent.” Participants were required to rest their index fingers on each button to assure fast responses. The testing session started with five practice trials. The order of events for each trial was as follows: (a) a dot appearing at the center of the screen, (b) presentation of the two possible target Ts for 1000 ms, (c) a central fixation point, (d) presentation of the search array until a response was given.

### Results

The main analyses compare the probabilities of fixation across different colors in the search array. The probability was calculated as the number of trials on which an object of a particular color was fixated once or more as a proportion of the total number of instances that the color appeared throughout the experiment. This measure was used first to test different possible accounts of how two targets can be represented; second, to examine strategies at the level of the individual; and finally, to assess color selectivity differences across target sets (single-target, 1-step, 2-step, 4-step separation). Additional analyses compared performance across target sets for accuracy and RT to confirm the dual-target cost. Where appropriate, planned comparisons with a Bonferroni correction ( $FWE = .05$ ) were conducted.

#### Probability of Fixation: Unified or Discrete Target Representations?

One of the primary goals of the current study was to investigate the possible ways in which two target colors can be represented to guide search. The first possibility is a unified representation comprising a range of colors that includes the target colors as well as any colors between them in color space. Such a representation would cause the target colors and all intervening colors to be fixated at a similarly high rate. This account can be tested in the current data by comparing the fixation rates to target colors and intervening distractor colors. Alternatively, the target could be represented by two separate, discrete target representations, so that fixation rates to a distractor color would depend solely on similarity to the target colors. A color would not receive extra fixations simply because it is between the two targets in color space. Nevertheless, maintaining two separate representations might require extra resources or produce extra interference, and result in a dual-target cost compared to a search for just one target. The second alternative requires a more involved procedure for testing, which is described in the Appendix.

See Figure 4 for a summary of the probability of fixation results. Only the 2-step and 4-step target sets included distractor colors in between the two target colors, so these comparisons will focus on these two conditions. In Figure 4, these colors are represented by the points to the left of the shaded vertical bar (which indicates the target color). As can be seen in Figure 4, intervening colors were fixated more often in the 2-step than the 4-step Target-set, suggesting that participants were relying on separate representations between these conditions. In comparing the fixations to intervening distractor colors, it is worth remembering that the 2-step

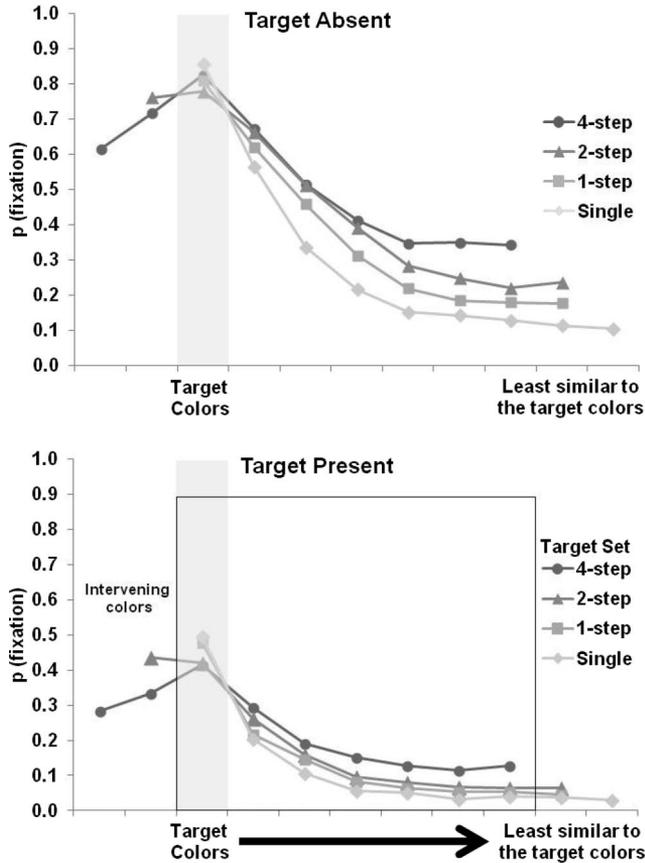


Figure 4. The probability of fixation for all four target sets for both target-absent (top panel) and target-present (bottom panel) trials. The x-axis represents the color relative to the target colors. These data are collapsed across all 16 target color pairs and the shaded bar represents the two target colors. The two points to the left of the shaded bar represent the three colors that are between the two targets on the color ring. The gray box within each panel outlines the data points common to all target sets; these points were used in the ANOVAs to assess color selectivity across target sets.

Target-set had only one intervening color, while the 4-step Target-set had three intervening colors, with two that were adjacent to a target color and the other that were 2 steps from each target. For target-present trials, participants fixated the intervening color in the 2-step Target-set more often than any of the intervening colors in the 4-step Target-set, both  $t > 2.05$ ,  $p < .05$ . When the target was absent, the intervening color in the 2-step Target-set only differed significantly from the midway intervening color in the 4-step Target-set,  $t(30) = 2.28$ ,  $p = .03$ .

To test for evidence of a unified target color representation, we also compared the fixation probabilities for the intervening colors against those for the target colors. For the 2-step Target-set, participants had trouble ignoring the single intervening color and fixated it at about the same rate as the target colors,  $t(15) = .47$ ,  $p = .963$ , consistent with a single color range representation. The 4-step Target-set yielded different results. On average, the three intervening colors received considerably fewer fixations compared with the two target colors,  $t(15) = 6.30$ ,  $p < .001$ , which strongly

suggests two separate, discrete target color representations in this condition.

The tests, so far, suggest that the target representation shifts from a single range to two discrete representations as the targets become less similar to one another. However, an additional test of the discrete account using the model described in the Appendix suggests a different, more parsimonious explanation. The 2-step Target-set results could be produced by two individual target color representations, with the fixation rate for the intervening color being a combination of two sets of fixations, each triggered by a different target representation. We tested this discrete target combination account by predicting the fixation rate for the intervening color based on the fixation rates for the distractors that were on either side of the target range (i.e., one step from each target but not between the targets). The fixation rate for the intervening color for the 2-step Target-set was not significantly different than the value predicted by the discrete target combination account for both target-present and target-absent trials ( $ps > .16$ ). The predicted values for the 4-step Target-set were also not significantly different from the actual 4-step fixation rates ( $ps > .37$ ).

**Probability of Fixation: Evidence From Individual Participants**

For additional insight regarding the nature of the guiding representations, we examined the data from individual participants. Figure 5 shows the differences between fixation probabilities for the target colors and the central intervening colors. The participants are ordered according to the magnitude of the differences; those farther to the right tended to fixate the targets much more than the intervening distractors, suggesting that they were using two separate representations for the two target colors that did not include the intervening colors.

Using the normal approximation method for binomial data, 95% confidence intervals were calculated for the differences shown in Figure 5 (between fixation probability for the target colors and fixation probability for the central intervening colors). Participants in the 4-step Target-set demonstrated individual differences in

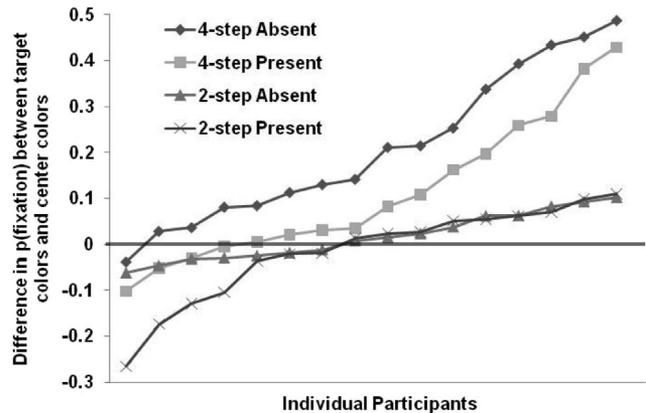


Figure 5. Comparisons of fixation probabilities for target colors and intervening distractor colors for each participant. Each point represents the difference in fixation probabilities between the target colors and the intervening colors for an individual participant. A value of 0 would indicate that the intervening colors were fixated at the same frequency as the targets.

their fixations on the intervening colors relative to the target colors. On target-present trials, 7 of the 16 participants fixated the target colors significantly more often than the intervening colors, while on target-absent trials, this number increased to 12 participants. These 4-step Target-set results contrast with the 2-step Target-set, in which none of the participants fixated the target colors significantly more often than the intervening color. These results are consistent with the original fixation rate analysis, again suggesting two discrete representations when two target colors are dissimilar to one another, and a unitary range (that includes the intervening color) when the two targets are similar to one another. However, as demonstrated by the discrete target representation model described in the Appendix, the high fixation rates of the intervening distractor color can also be explained by discrete representations.

### Probability of Fixation: Color Selectivity Across Target Sets

In order to compare color selectivity across the different target sets (single-target, 1-step, 2-step, 4-step separation), the fixation probabilities were submitted to a 4 (Target-set)  $\times$  2 (Target-presence)  $\times$  7 (Color-step) mixed ANOVA (see Figure 4). These analyses were conducted on the colors that were common across all target sets: the target-colored distractor and all colors one to six steps from the target. Only the distractor objects (Ls) were included, so that differences in the fixation rates reflected differences in color and not shape. These analyses will explore (a) color selectivity, (b) a dual-target cost in number of fixations, and (c) a “split-target cost,” lowering color selectivity when two targets were dissimilar.

Color selectivity is evident by viewing the peaks of the lines within the shaded region of both panels of Figure 4. Participants directed more fixations on objects of the target color than objects of other colors, with the probability of fixation decreasing as the similarity to the target color decreases,  $F(6, 360) = 460.71, p < .001$ . More objects were fixated on target-absent trials than target-present trials,  $F(1, 60) = 434, p < .001$ . Participants broadened search and fixated a wider range of colors on target-absent than target-present trials, resulting in a significant Target-presence by Color-step interaction,  $F(3, 60) = 2.99, p < .05$ .

The main effect of Target-set,  $F(3, 60) = 3.03, p < .036$ , was broken down using pairwise planned comparisons between the target sets. The dual target cost led to significantly more objects being fixated for the 4-step Target-set compared to the single-target search,  $F(1, 30) = 6.530, p = .016$ . Although participants made more fixations in the 2-step Target-set relative to the single-target search, the comparison did not reach significance,  $F(1, 30) = 3.879, p = .058$ . There was no significant difference between the 1-step Target-set and single-target search,  $F(1, 30) = 1.99, p = .168$ .

The split-target cost produced a significant Target-set by Color-step interaction in the main ANOVA, signifying that color selectivity decreased as the similarity between the target colors decreased,  $F(18, 360) = 4.33, p < .001$ . Planned comparisons between target sets revealed that significantly more fixations were made to colors dissimilar to the target color in the 4-step condition than in the 2-step, 1-step, and single-target conditions (all  $F_s > 3, p_s < .003$ ). Similarly, color selectivity was weaker in 2-step and in

1-step than in single-target conditions ( $p < .001$  and  $p = .014$ , respectively). However, these differences were more pronounced on target-absent trials, giving rise to a significant Target-set  $\times$  Target-presence  $\times$  Color-step interaction in the main ANOVA,  $F(18, 360) = 2.17, p = .004$ . When the target was present, it was located with relative efficiency, but when the target was absent, participants broadened search to include a larger range of colors. As the two targets decreased in similarity, there was a corresponding increase in this range of fixated colors, leading to inefficient search.

Although only the Ls were included in these analyses, participants fixated the target Ts at a much higher frequency than the target-colored Ls for all four target sets ( $p_s < .001$ ). This demonstrates that although color was a strong guiding feature in this experiment, participants utilized shape to guide search to a certain extent (see Table 2).

### Accuracy and Response Times

Error rates and RTs were each submitted to a 4 (Target-set)  $\times$  2 (Target-presence) mixed ANOVA. In line with the color selectivity analysis of the fixation probabilities, participants responded faster,  $F(1, 60) = 102.86, p < .001$ , and more accurately,  $F(1, 60) = 55.13, p < .001$ , on target-present trials than target-absent trials. Also, for RT, there was a main effect of Target-set,  $F(3, 60) = 10.2, p < .001$ . Planned pairwise comparisons between target sets revealed faster responses in single-target search than any of the dual-target searches (all  $p_s < .01$ ), and faster responses in 1-step than 2-step and 4-step (all  $p_s < .05$ ), although there was no significant difference in RT between the 2-step and 4-step target sets ( $p = .610$ ). In the main RT ANOVA, a significant Target-set  $\times$  Target-presence interaction,  $F(3, 60) = 5.20, p = .003$ , revealed that the differences across Target-sets were greater on target-absent than target-present trials (see Figure 6). The pattern of error rates was similar to the RT results, with fewer errors in single-target search than any of the dual-target searches (all  $p_s < .05$ ). There were fewer errors in 1-step than in 2-step ( $p < .01$ ) and 4-step ( $p < .01$ ), but no difference between 2-step and 4-step. The Target-set  $\times$  Target-presence interaction failed to reach significance ( $p = .591$ ).

In sum, the RT and error-rate analyses revealed two interesting patterns: a cost for searching for two colors compared with one, and a cost associated with increased separations in color space between the two search targets. These patterns were also revealed in the color selectivity analysis.

### Discussion

This experiment utilized well-controlled color stimuli to explore the degree to which observers can guide their fixations with

Table 2  
*The Probability of Fixation for Target-Colored Objects*

Target-set	Ts	Ls
Single	.88	.50
1-Step	.89	.48
2-Step	.90	.42
4-Step	.93	.41

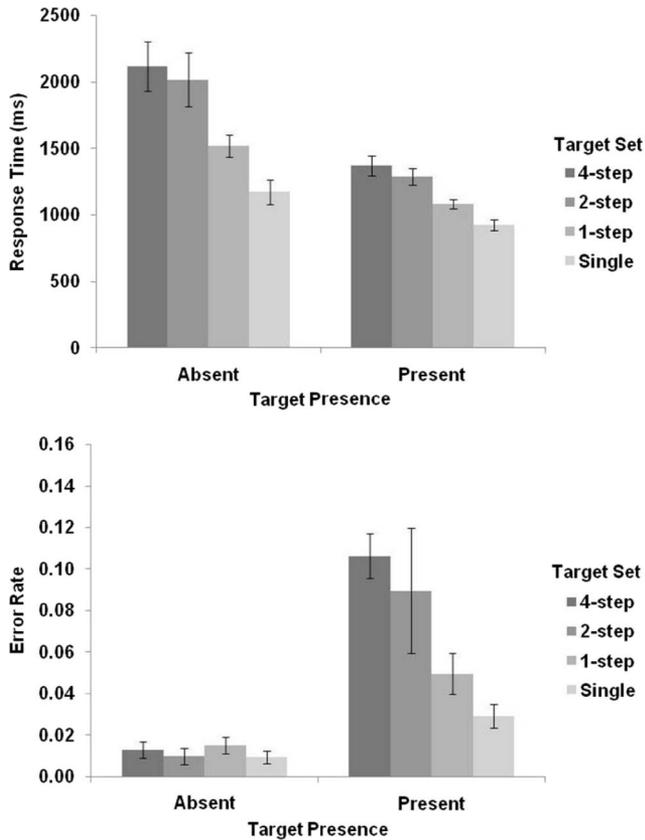


Figure 6. The response times (top panel) and error rates (bottom panel) across all four target sets.

dual-target representations defined primarily by color. Participants could effectively use color to guide search, but this color selectivity weakened with the distance between target colors in color space. On target-absent trials, this color selectivity also weakened, most likely reflecting a broadening of search after the target was not initially located. The current experiment had three main aims: (a) to evaluate the dual-target cost in color search, (b) to measure how this cost increases with decreased similarity between the two target colors, and (c) to investigate the target representations in dual-target search.

When searching for a single color, participants exhibited a high degree of color selectivity. The addition of a second target had varying effects depending on the similarity between the two target colors. A cost in the form of decreased color selectivity was observed even for two very similar target colors (1-step separation) and this cost increased as the dissimilarity between the two target colors increased. There were additional fixations as a result of the dissimilarity between the targets, which we refer to as a “split-target cost,” because it depends on the distance between the two target colors in color space. The additional fixations were directed toward all colors, including those very dissimilar to either target, and thus were detrimental to efficient search.

As noted earlier, color categories shape many aspects of color perception, and it is possible that they affect color search in this task. If search is guided by a representation of the color category

to which a target belongs, then we might expect more fixations to other colors in the same category. In dual-target search, as the distance between the two targets increases, the chance of the targets falling into different color categories (e.g., red, yellow) also increases. When targets fall in two separate color categories, there will be more distractors sharing a category with a target than when targets fall into the same color category. Thus, the split-target cost may be related in part to the number of color categories represented in the target set. This account predicts that a cost from multiple target categories would consist of fixations to distractors in the two target categories, but the costs in the fixation rates from the current experiment go beyond anything that can be attributed to color categories alone. In all conditions, there are extra fixations to distractors that fall far outside the target color categories, and therefore these extra fixations cannot be attributed to having two target categories rather than one.

In summary, the data strongly suggest that targets that are dissimilar to one another (4-step Target-set) are represented by two separate representations, and this theory is supported by the results of the discrete target combination model showing that fixation rates for colors between the targets can be explained by combining the fixation rates from colors that do not fall between the target colors. While the data from the 2-step Target-set show the type of pattern that would be expected if similarly colored targets were represented within a single, broad-range representation, the same discrete target combination model can explain the fixation rates for the 2-step separation in the same way as for the 4-step separation. Therefore, there is no evidence, or need, for two separate mechanisms for representing similar and dissimilar target colors.

In terms of theories of search (e.g., Guided Search, Wolfe, Cave, & Franzel, 1989), these results suggest that it is possible to represent two separate colors to guide search simultaneously, albeit with some cost in search guidance. One account for the current results is that target features are represented via a distribution of activation centered on the target feature itself. The spread of this distribution appears to increase with target dissimilarity, such that activation (fixation rate) of neighboring (similar) colors is raised as well as the baseline activation for all colors. This gradient in color activation is reminiscent of the spatial gradients of attention found in spatial cuing studies (Downing & Pinker, 1985; LaBerge & Brown, 1989).

These results are focused on search for objects within the dimension of color. It is important to investigate whether similar results can be generalized to other dimensions such as orientation, size, or even depth. Converging multidimensional results would solidify this notion of a split target cost, and contribute both to theories of attention and to practical applications. The results will help refine models of visual search by stressing the importance of the similarity between the search targets.

In the applied realm, whenever search is needed for multiple items that contain different colors (e.g., airport security search for guns, knives, and explosives), the results show that it is important to consider the similarity of the colors of the targets. It may seem productive to search simultaneously for distinctly different objects, but the results of the current project argue against that strategy. If it is impossible to redesign the task so that search can be guided toward two similar colors, then search should be split into separate phases for each individual target.

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Appendix

A Discrete Target Combination Model for Predicting Fixation Rates

The calculations described here are designed to predict the fixation rate of the intervening, or “inside,” distractor colors that are in between the two target colors on the color ring. The assumptions underlying the predictions are that each of the two target representations can independently generate fixations and that the total fixation rate for a given intervening color will be the sum of those generated by the two representations. The fixation rate triggered by a single target color that is a certain number of steps away from a given distractor color can be determined from the fixation rates for the “outside” colors. Starting with the mean fixation probabilities in Figure A1, we arbitrarily selected one of

the two targets ( $T_1$ ), and numbered both the inside colors ( $i_1, i_2, i_3, \dots$ ) and the outside colors ( $o_1, o_2, o_3, \dots$ ) according to their distance from that target color.

As can be seen from the graph in Figure A1, colors that are more than five steps from a target color are still fixated on a small proportion of trials. The first stage in constructing this model was to use the fixation rate for the color most different from the targets as a baseline ( $o_b$ ), and subtract that value from the fixation rates for all colors. This stage prevents the baseline from being included twice when the fixation probabilities from the two targets are combined. The next stages of the model are described separately for the two target sets that contained intervening colors between the target colors.

4-Step Target-Set

For the 4-step Target-set, there are two different types of intervening colors between the two target colors (see Figure A1).

One of the intervening colors is equidistant (two steps away) from either target color. To estimate the fixation rate to this color ( $i_2$ ), we combined the fixation rates based on the activation from both targets. To determine the rate of fixations that would be triggered by each target, we looked at the fixation rates for the outside colors that are two steps away from a target ( $o_2$  and  $o_{10}$ ) and combined these two probabilities, using the or probability for non-mutually-exclusive events:

$$i_2 = o_2 + o_{10} - (o_2 * o_{10})$$

The other two intervening colors ( $i_1$  and  $i_3$ ) are one step away from one target and three steps away from the other target. To estimate the fixation rate for  $i_1$ , the relevant outside values would be  $o_1$ , which is one step away from  $T_1$ , and  $o_9$ , which is three steps away from  $T_2$ :

$$i_1 = o_1 + o_9 - (o_1 * o_9)$$

A similar procedure was used to estimate  $i_3$ , using  $o_3$  and  $o_{11}$ .

To test the model for the distractors one step and three steps from each target color, the fixation rate predictions from the model for each participant were averaged over  $i_1$  and  $i_3$  and compared against the observed mean fixation rates for the two inside colors one step from either target. For the distractor two steps from both targets, the predictions were generated for  $i_2$  and compared with the observed fixation rates to the single distractor two steps inside the targets. Paired samples *t*-tests compared the observed values from the 16 participants in each condition against values predicted by the model for each participant. Separate tests were run for the two types of intervening colors for both target-absent and target-present trials. For all inside fixation rates, the model predicted values that were not significantly different from those observed (see Table A1).

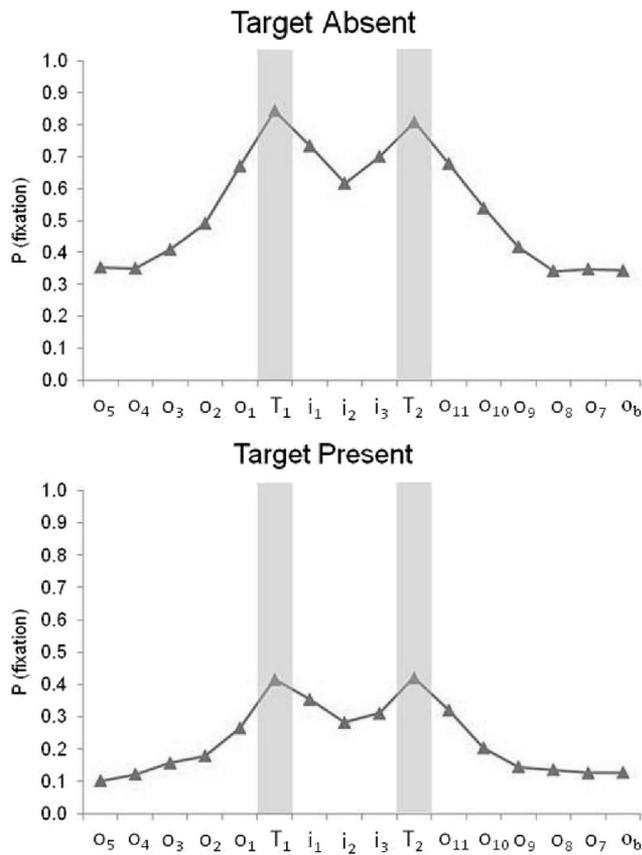


Figure A1. The probability of fixation for the 4-step target-set for all 16 distractor colors. The two target-colored distractors are signified by the gray shaded squares and the distractors are labeled relative to the distance from  $T_1$  in color space. The ‘i’ values represent distractors inside the target colors while the ‘o’ values represent colors outside of the target range. Note that  $o_b$  denotes the baseline fixation rate that was subtracted from all values contributing to the model.

(Appendix continues)

Table A1

The Results of the Paired Samples *t*-tests Comparing the Observed Fixation Probabilities Against the Predicted Values, Based on the Model for the 4-step Target-set

	Predicted	Observed	<i>t</i> (15)	p-value
Target Absent				
1-step ( $i_1 + i_3$ )/2	.3733	.3744	.046	.964
2-steps ( $i_2$ )	.3166	.2736	.870	.398
Target Present				
1-step ( $i_1 + i_3$ )/2	.1853	.2053	.770	.453
2-steps ( $i_2$ )	.1254	.1550	.931	.367

### 2-Step Target-Set

In the 2-step Target-set, there is only one inside color, and it is equidistant from both targets in color space. Its fixation rate,  $i_1$ , can

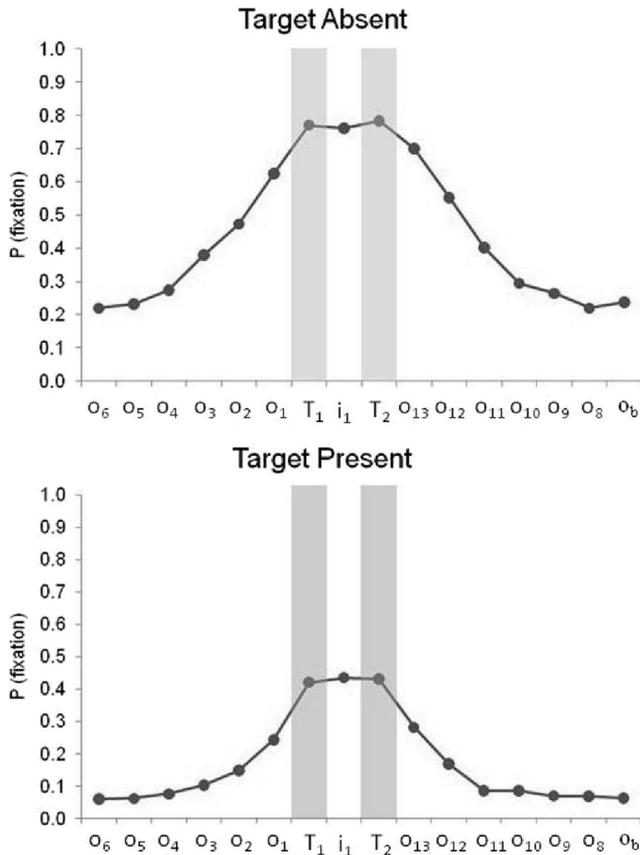


Figure A2. The probability of fixation for the 2-step target-set for all 16 distractor colors.

Table A2

The Results of the Paired Samples *t*-tests Comparing the Observed Fixation Probabilities With the Predicted Values Based on the Model for the 2-step Target-set

	Predicted	Observed	<i>t</i> (15)	p-value
Target Absent				
1-step ( $i_1$ )	.5218	.5252	.140	.890
Target Present				
1-step ( $i_1$ )	.3059	.3717	1.49	.158

be estimated using the outside colors that are one step away from either target ( $o_1$  and  $o_{13}$ ). However, each of these distractors is also three steps from the other target, and thus the fixation rates for  $o_1$  and  $o_{13}$  not only represent fixation rates for distractors one step from  $T_1$  but include rates for distractors three steps from  $T_2$ . Therefore, the fixation rates for distractors three steps from  $T_2$  needed to be subtracted from the fixations rates for  $o_1$  and  $o_{13}$ . We used  $o_3$  and  $o_{11}$  to determine the effect of a distractor three steps outside and removed them from  $o_{13}$  and  $o_1$ , respectively, to estimate the effect of a single distractor one step outside, which we will call  $e_1$  (see Figure A2).

First,  $o_1$  is the combination of the effects of the first target, which is one step outside ( $e_1$ ), and the second target, which is three steps outside ( $o_{11}$ ):

$$o_1 = e_1 + o_{11} - (e_1 * o_{11})$$

We know  $o_1$  and  $o_{11}$ , and we can rearrange this equation to allow us to determine  $e_1$ :

$$o_1 - o_{11} = e_1 - (e_1 * o_{11})$$

$$o_1 - o_{11} = e_1(1 - o_{11})$$

$$(o_1 - o_{11}) / (1 - o_{11}) = e_1$$

Likewise,  $o_{13}$  and  $o_3$  can be used to estimate the effect of being one step outside of the other target ( $e_{13}$ ). Now we are ready to estimate the fixation rate for the inside color:

$$i_1 = e_1 + e_{13} - (e_1 * e_{13})$$

Paired samples *t*-tests were again conducted on the predicted versus the observed values. The results showed that the predicted values were not significantly different from observed values (see Table A2).

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