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Capacity limitations in template-guided multiple color search

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Abstract

Visual selection of target objects relies on representations of their known features in visual working memory. These representations are referred to as attentional templates. We asked how the capacity of visual working memory relates to the maximal number of attentional templates that can simultaneously guide visual selection. To measure the number of active attentional templates, we used the contingent capture paradigm where cues matching the attentional template have larger effects than cues in a non-matching color. We found larger cueing effects for matching than non-matching cues in one-, two-, and also three-color search, suggesting that participants can establish up to three attentional templates. However, scrutiny of matching cue trials showed that with three attentional templates, larger cueing effects only occurred when the matching cue had the same color as the actual target. When the matching cue had a possible target color that was different from the actual target color, cueing effects were similar to non-matching cue colors. We assume that processing of a matching cue activates one of the three templates, which inhibits the remaining templates to the level of non-matching colors. With two colors, the inhibition from the activated template is less complete because the initial template activation is higher. Overall, only a maximum of two attentional templates can operate successfully in the contingent capture paradigm. The capacity of template-guided search is therefore far below the capacity of visual working memory.

Keywords

visual search, attentional capture, attentional template, visual working memory

Public Significance Statement

We often search for more than a single object at a time. For instance, we may search for our wallet and our phone when we leave for work. The current study shows that the number of simultaneous search targets is extremely limited. We estimate that only two objects can be searched for simultaneously, which is far less than the number of items we can store in working memory.

Introduction

Attention is guided to objects of interest by representations of their known features. It is typically assumed that these attentional templates are stored in visual working memory (Carlisle et al., 2011; Duncan & Humphreys, 1989; Eimer, 2014; Huynh Cong & Kerzel, 2021; Schneider, 2013). If attentional templates are stored in visual working memory, the question arises how the maximal number of attentional templates is related to the capacity of visual working memory. The latter was estimated to be around four items (Cowan, 2010; Luck & Vogel, 1997). In contrast, it was proposed that only one of the representations in visual working memory can act as attentional template (Olivers et al., 2011). On the other hand, there is also evidence that participants can activate multiple attentional templates concurrently and search for multiple target features at the same time (Ansorge & Horstmann, 2007; Ansorge et al., 2005; Berggren et al., 2019; Grubert et al., 2016; Grubert & Eimer, 2015, 2016; Huynh Cong & Kerzel, 2020; Irons et al., 2012; Kerzel & Witzel, 2019; Moore & Weissman, 2010; Ort et al., 2019). However, the absolute capacity threshold of template-guided visual search is yet unknown (see Ort & Olivers, 2020). To determine this threshold, we used the contingent attentional capture paradigm developed by Folk et al. (1992) and measured whether there are qualitative differences in visual search guided by one, two, or three attentional templates.

In this paradigm, search displays are preceded by spatially unpredictive cues. Attentional capture by the cue is reflected in shorter RTs for targets appearing at the same position as the cue compared with targets appearing at a different location. We refer to differences between invalid and valid cue trials (invalid - valid) as *cueing effects*. The prototypical result of contingent capture is that cueing effects with cues matching the target are larger than cueing effects with cues that do not contain any target features (e.g., Becker et al., 2019; Burnham, 2019; Jung et al., 2021; Kim et al., 2019; Ruthruff et al., 2020; Schönhammer et al., 2020). Therefore, the difference between matching and non-matching cues indicates that an attentional template for the target color was established. For instance, during search for red targets, red cues resulted in larger cueing effects than green cues, showing that participants had set up an attentional template for red (Folk & Remington, 1998). Without an attentional template for a specific color, cueing effects are the same for matching and non-matching cue colors (Folk & Anderson, 2010; Folk & Remington, 2008).

Experiments 1 and 2

In the current study, we explored the limits of multiple-color search by increasing the number of possible target colors from one to two (Experiment 1) and from one to three (Experiment 2). We used a color space where color corresponds to the rotation on a color wheel with equal luminance (Figure 1A-C). On this wheel, three colors can be separated by as much as 120°, which is easy to discriminate in perception and memory (Bae et al., 2014; Witzel & Gegenfurtner, 2013). Critically, the precision of color memory was found to vary only slightly between two and three colors (see Figure 2 in Zhang & Luck, 2008). Does this mean that three color-templates can guide selection as efficiently as two color-templates? To test this, observers were instructed to search for one, two, or three possible target colors (Figure 1D). The possible target colors were shown at the start of a trial. After a retention interval, participants searched for the stimulus that had one of the possible target colors. Search displays always contained a target-color and a distractor-color stimulus to ensure a color-specific search mode. Briefly before onset of the search display, a cue was shown that either matched one of the possible target colors (matching cue) or the distractor color (non-matching cue). In line with the contingent capture hypothesis, we expect larger cueing effects for target-color matching than for non-matching cues.

To test whether two or three color-templates can be activated in parallel, we additionally compared cueing effects between two types of matching cues. In half of the cases, the cue had the exact same color as the target (matching/same). In the other half, the cue had a possible target color, but not the actual target color (matching/different). In previous multiple-color search studies, the cueing effects for matching cues did not depend on whether the cue color was the same or different from the actual target color (Grubert & Eimer, 2016; Irons et al., 2012; Kerzel & Witzel, 2019).

Differentiating between cueing effects with matching/same and matching/different cues is important because this allows distinguishing between two contradictory accounts of multiple template search. On the one hand, Moore and Weissman (2010, 2014) argued that processing of a color cue brings the cued color into the focus of working memory. Subsequently, a combination of feature- and space-based attention (Hopf et al., 2004) may enhance processing of stimuli sharing the cued color and location. However, this account of enhancement by the focus of working memory essentially assumes the activation of a single template at a time (the one activated by the cue) and therefore stands in contrast with any framework predicting that multiple attentional templates can be activated in parallel (Huynh Cong & Kerzel, 2021; Ort & Olivers, 2020). Importantly, the two accounts make opposed predictions about the cueing effects to be expected in matching/same and matching/different cue trials. The single-template account would predict larger cueing effects with matching/same cues than with matching/different cues because the cue enhances the actual target color at the cued location. In case of simultaneous activation of multiple attentional templates, however, cueing effects should be similar with matching/same and matching/different cues and both should be larger than cueing effects with non-matching cues.

Methods

Participants. In a previous study, we found cueing effects in a matching color to be 87-99 ms larger than cueing effects in a non-matching color (Exp. 2 and Exp. 3 in Barras & Kerzel, 2016). The partial etasquare of the respective within-participant interaction was .57 and .59, respectively. When aiming for a power of 0.8 with a type 1 error rate of 5%, the necessary sample size is 9 according to G*Power 3.1 (Faul et al., 2009). Because we ran a between-participant design, we could not rely on previous studies to calculate the effect size. We decided on 20 participants per group so that the critical interaction between group and cue color required a minimal $F(1, 38)$ of 4.1, which corresponds to a partial etasquare of .171. There were 20 undergraduate psychology students in Experiment 1 (4 male; age: M = 21.6 years, SD = 2.9) and Experiment 2 (2 male; age: M = 21.5 years, SD = 1.6). Students participated for class credit and reported normal or corrected-to-normal vision. The study was approved by the ethics committee of the Faculty of Psychology and Educational Sciences and was carried out in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki). Informed written consent was given before the experiment started.

Apparatus. Stimuli were displayed on a 22.5-inch LCD monitor at 100 Hz with a resolution of 1,920 × 1,200 pixels (VIEWPixx Light, VPixx Technologies Inc., Saint-Bruno, Canada), driven by an AMD Radeon HD 7470 graphics card with a color resolution of eight bits per channel. CIE1931 chromaticity coordinates and luminance (xyY) of the monitor primaries were R = (0.672, 0.312, 53.2), G = (0.091, 0.75, 123.4), and B = (0.1, 0.094, 20.5). The white-point of CIELAB was xyY = (0.274, 0.356, 194.6). Luminance is indicated in cd/m^2. Colors were measured with a ColorCAL MKII colorimeter by Cambridge Research Systems (Rochester, UK). Head position was stabilized with a chin/forehead rest at a viewing distance of 66 cm. The Psychtoolbox (Kleiner et al., 2007) was used to run the experiments.

Stimuli. There was a memory, a placeholder, a cue, and a target display (see Figure 1D). A central fixation cross (0.2° radius, 0.07° linewidth) was shown unless otherwise noted. In the memory display, colored disks (0.4° diameter) indicated the possible target colors. The location of the disks varied as a function of the number of possible target colors. If there was one possible target color, the disk replaced the central fixation cross. If there were several possible target colors, the disks were shown at 0.6° from the fixation cross (center-to-center). With two possible target colors, the disks were shown to the left and right. With three possible target colors, the disks were 120° of rotation apart, with one disk directly above the fixation cross. The placeholder display contained the fixation cross and four outline rings, all drawn in light gray. The distance from the center of the fixation cross to the center of the outline rings was 3°. The outline rings were composed of an inner and an outer circle with a radius of 1.2° and 1.4°, respectively. The linewidth was 1 pixel or 0.02°. In the cue display, all rings were filled. Three rings were filled with the same light gray as the circles and one ring with a color. In the target display, the letter T rotated by 90° clockwise or counter-clockwise was shown in each placeholder. The bars making up the rotated T were 1° long and 0.2° thick. Two of the Ts, the target and the distractor, were colored. The other letters were gray.

Stimuli were presented on a gray background with the chromaticities of the white-point and a lightness of L* = 45, which corresponds to a luminance of 29.2 cd/m^2. The placeholders, the achromatic cues and letters were light gray (L* = 61 or 58.7 cd/m^2). The three colors that served as cue, target and distractor colors were sampled along an isoluminant color wheel at a lightness of L* = 61 and a saturation of 59.

The actual target color was obtained by randomly selecting one of the 360 available colors of the color wheel. For ease of exposition, this color is assigned a rotation of 0°. The direction of rotation for the remaining colors was the same and randomly selected on each trial. In conditions with two possible target color, the second memorized target color was rotated by 120° from the target color. With three possible target colors, the third color was rotated by 240° from the target color. The distractor color was separated by 60° from the target color. In the search display, the 0° target color and the 60° distractor color were shown. The color of the cue was rotated by either 0°, 60° or 120°. As the target color and the direction of rotation were randomized, participants could not guess which of the several colors from the memory display would be shown. Further, the location of the colors in the memory display was randomized in conditions with more than one possible target color.

Design. The 128 combinations resulting from crossing the number of memorized target colors (1 vs. 2 in Experiment 1; 1 vs. 3 in Experiment 2), cue positions (left, right, top, bottom), target positions (left, right, top, bottom), cue colors (matching: rotation of 0° or

120°, non-matching: rotation of 60°), and response locations (left, right) were shown once in a block of trials. With one memorized target color, we continued to present the 120° cue color to balance the number of trials. However, these trials were not analyzed as the cue neither matched the memorized target color nor the distractor color. Four trial blocks were run, resulting in 512 trials per participant.

Procedure. A trial started with the presentation of the fixation cross for 1,000 ms. Then, the memory display was shown for 800 ms, followed by a blank screen for 700 ms. Then, the fixation cross reappeared together with the unfilled placeholder rings. After another 700-1100 ms, the cue stimuli were shown for 50 ms, followed by the unfilled placeholders for 100 ms and the target stimuli for 50 ms. The resulting cue-target SOA was 150 ms. After target offset, the unfilled placeholders remained visible until a response was registered.

Participants responded to the orientation of the target letter by clicking the corresponding mouse button (T rotated counter-clockwise: left button, T rotated clockwise: right button). They were instructed to respond as rapidly and accurately as possible while ignoring the cue display.

Practice started with the single-color task before the multiple-color task was introduced. Although the 120° color difference was far above color discrimination thresholds and the memorized colors belonged to different categories (cf. Figure 9 in Witzel & Gegenfurtner, 2013), we noted that bluish colors appeared more similar than other colors in our rendition of CIELAB-space (see also Bae et al., 2015). Therefore, we familiarized participants with these colors during practice of the multiple color task by selecting distractors in the bluish range. For each practice block, participants continued until they felt comfortable with the task, mostly for ~20 trials. Visual feedback informed participants about choice errors, anticipations and late trials. We considered trials with RTs longer than 1,250 ms as late, and shorter than 200 ms as anticipations. Anticipations were extremely rare and will not be reported. Every 64 trials, visual feedback about the percentage of correct responses and the median RTs were displayed for at least 2,000 ms during a self-terminated pause.

Results

For the analysis of RTs, we excluded trials with late responses (0.8% and 1.7% in Experiments 1 and 2, respectively), choice errors (12%, 15%), and trials with RTs longer than

2 *SD*s above the respective condition mean (~3%). For brevity, we conducted the analyses on cueing effects (invalid - valid cue trials), but analyses including the factor cue validity are reported in the supplementary materials. Mean RTs and cueing effects are shown in Figure 2.

First, we assessed whether attentional templates could be established for one, two, and three possible target colors. Use of an attentional template is indicated by larger cueing effects with matching/same than non-matching cues. To evaluate whether this difference changed as a function of the number of possible target colors, we subjected individual cueing effects to a 2 (experiment: 1, 2) × 2 (number of possible target colors: 1 vs. 2/3) × 2 (cue type: matching/same =0°, non-matching=60°) mixed-factors ANOVA. Cueing effects were larger with one than with two/three possible target colors (18 vs. -4 ms), $F(1, 38) = 16.88$, $p < .01$, $\eta_p^2 = .308$, and with matching/same than with non-matching cues (43 vs. -30 ms), $F(1, 38) = 170.80$, $p < .01$, $\eta_p^2 = .818$. Importantly, the difference between matching/same and non-matching cues did not change as a function of number of possible target colors, $p = .18$, showing that attentional templates were established for one and two/three possible target colors. Conducting the same ANOVA on choice errors showed smaller cueing effects with one than two/three possible target colors (-1.7% vs. 1.7%), $F(1, 38) = 6.59$, $p = .01$, $\eta_p^2 = .148$, which is opposite to the difference observed in RTs. Therefore, a speed-accuracy tradeoff may underlie the effect of the number of possible target colors. Further, cueing effects were larger with matching/same than non-matching cues (1.9% vs. -1.9%), $F(1, 38) = 10.16$, $p < .01$, $\eta_p^2 = .211$.

Second, we compared cueing effects with matching/different, matching/same and non-matching cues in two- and three-color search. Matching cues could either have the same color as the actual target (matching/same=0°) or the other possible target color (matching/different=120°). Non-matching cues had the distractor color (non-matching=60°). The simultaneous activation of multiple attentional templates predicts similar cueing effects for matching/different and matching/same cues, whereas the single template hypothesis predicts smaller cueing effects for matching/different than matching/same cues. Individual cueing effects were subjected to a 2 (experiment: 1, 2) × 3 (cue type: matching/different=120°, matching/same=0°, non-matching=60°) mixed-factors ANOVA. The main effects of cue type, $F(2, 76) = 17.60$, $p < .01$, $\eta_p^2 = .317$, and experiment, $F(1, 38) = 11.92$, $p < .01$, $\eta_p^2 = .239$, were modulated by the two-way interaction of experiment and cue type, $F(2, 76) = 3.31$, $p = .046$, $\eta_p^2 = .08$. We followed up on the significant two-way interaction by comparing matching/different cues to the other cue types, separately for each experiment. In Experiment 1, with two possible target colors, matching/different cues resulted in cueing effects similar to matching/same cues (35 vs. 37 ms), $p = .92$, but larger effects than with non-matching cues (35 vs. -27 ms), $t(19) = 3.33$, $p < .01$, Cohen's $d_z = 0.74$. In Experiment 2, with three possible target colors, matching/different cues resulted in cueing effects smaller than matching/same cues (-32 vs. 20 ms), $t(19) = 3.22$, $p < .01$, Cohen's $d_z = .72$, but similar to non-matching cues (-32 vs. -27 ms), $p = .34$. These results suggest that two attentional templates were set up in two-color search, but that a qualitative different mechanism was at work in three-color search.

Conducting the same ANOVA on choice errors yielded a main effect of cue type, $F(1, 38) = 5.49$, $p < .01$, $\eta_p^2 = .126$, showing that cueing effects were smaller with non-matching cues (0%) than with matching/same (7%) and matching/different (3.5%) cues. A follow-up ANOVA excluding non-matching cues found no effect, *p*s > .13, suggesting that cueing effects were similar for matching/same and matching/different cues.

Discussion

We investigated the limits of multiple color search in the contingent capture paradigm. The hallmark of attentional selectivity in the contingent capture paradigm is that cueing effects are larger for cues matching the attentional template than for non-matching cues. Consistent with the idea that observers can set up at least two attentional templates in parallel, it was demonstrated that cueing effects were larger to cues matching one of two possible target colors than for non-matching cues (Ansorge & Horstmann, 2007; Ansorge et al., 2005; Grubert & Eimer, 2016; Irons et al., 2012; Kerzel & Witzel, 2019). Our results in Experiments 1 and 2 mirror these findings and support the assumption of co-activation of multiple attentional templates during multiple color search. Importantly, the difference between matching/same and non-matching cues did not change as a number of possible target colors, showing that attentional templates had been set up even with two and three possible target colors. In contrast to previous findings (Grubert & Eimer, 2016; Irons et al., 2012; Kerzel & Witzel, 2019), RTs showed larger cueing effects with one than with two/three templates. However, the opposite result was observed in choice errors, suggesting that there was a speed-accuracy tradeoff, which prevents firm conclusions.

For the two-color search in Experiment 1, we found larger cueing effects for matching/same and matching/different cues compared with non-matching cues, which suggests that both attentional templates were activated simultaneously. Critically, this does not seem to be the case for three attentional templates. The cueing effects observed in the three-color search of Experiment 2 were substantially reduced for matching/different as compared to matching/same cues. In fact, cueing effects with matching/different cues were similar to non-matching cues. These results demonstrate that the processing of three possible target colors was altered fundamentally compared to two possible target colors, suggesting that the absolute capacity threshold of template-guided visual search in the contingent capture paradigm is two, which is well below the proposed four-item capacity limit of visual working memory (Cowan, 2010; Luck & Vogel, 1997).

Our findings appear partly contradictory because the difference between matching/same and non-matching cues suggests that attentional templates were set up regardless of the number of possible target colors, but the comparison of matching/same and matching/different cues suggests that the number of attentional templates was limited to two. These apparently contradictory findings can be understood if the time course of template activation and mutual inhibition are considered. Inhibition between multiple templates was investigated by Grubert et al. (2016) in an electrophysiological study using the N2pc component as a marker of attentional selectivity. N2pc components decreased from one- to two-color search, and also from two- to three-color search, reflecting reduced color selectivity in multiple as compared to single color search. The decline was attributed to mutual inhibition of co-activated color templates. This idea is illustrated in Figure 3, where mutual inhibition decreases the activation of multiple attentional templates. We assume that the maximal activation of each template is reduced by inhibitory input from the other templates. Further, there may be feedback loops between attentional templates in visual working memory and perceptual input (Ort et al., 2019). The selection of matching cues through attentional templates enhances perception of the selected stimulus, which in turn increases the activation of the attentional template itself. The idea of feedback loops is consistent with Moore and Weissman (2010, 2014) who argued that processing of a color cue brings the cued color into the focus of working memory. After selection of a cue matching one of the possible target colors, we assume that the activation returning into visual working memory has a fixed strength regardless of the number of templates. The reason for the fixed strength is that the recurrent activation reflects the bottom-up characteristics of the cue display, which is unrelated to the number of attentional templates. Critically, the fixed activation from the selected cue represents a larger proportion of the total activation with three compared to two attentional templates. As a result, the impact of inhibition from the cued attentional template is larger in three- than two-color search. In fact, the activation of the uncued attentional templates in three-color search may be reduced to a level corresponding to the bottom-up activation from non-matching cue colors. In contrast, the initial activation of individual templates in two-color search is higher and the bottom-up activation returning from the selected cue represents a smaller proportion, which prevents deactivation of uncued attentional templates to the level of non-matching colors.

Taken together, there is intact selection of the cue with up to three attentional templates, but in three-color search, the subsequent processing loops reduce the number of active templates from three to one. The reason is that the initial activation of three templates is low and the increased activation of one template after presentation of the cue display inactivates the remaining templates. As a result, target processing at the location of matching/different cues is similar to non-matching cues. Thus, template guided search is limited to only two attentional templates in the contingent capture paradigm.

On a last note, we found same location costs with non-matching cues. Same location costs refer to longer RTs at the cued than at the uncued location, which is the opposite of the cueing benefits that are typically observed with matching cues. In previous studies where the target was the only colored stimulus in the display or accompanied by a single colored nontarget, cueing effects with non-matching cues were generally absent (Folk & Remington, 1998) or small cueing benefits were observed (Harris et al., 2019). However, same location costs occurred when all items in the target display were colored (Eimer & Kiss, 2010; Kerzel, 2019; Lamy et al., 2004). It may be tempting to ascribe same location costs to attentional suppression (Gaspelin & Luck, 2018). However, suppression should only occur when the non-matching color is known before trial onset, but same location costs also occurred with unpredictable colors (Carmel & Lamy, 2014). In addition, electrophysiological correlates of attentional suppression were absent in conditions producing robust same location costs (Kerzel & Huynh Cong, 2021; Schönhammer et al., 2020). It was suggested that same location costs are related to object updating (Carmel & Lamy, 2014, 2015). This account considers the cue and target to be part of the same object. On invalid trials, the color at the cued location changes between cue and target, which entails object updating costs and results in slower responses to targets at the cued location (see also Büsel et al., 2021; Schoeberl et al., 2020). However, same location costs are only observed when the target is shown in a display with varied nontarget colors, not when it is the only colored stimulus (Kerzel, 2019; Kerzel & Huynh Cong, 2021). Possibly, same location costs are masked in search with a single colored stimulus because there is larger attentional capture if cue and target are both single colored stimuli. In general, it may be that cueing effects reflect the sum of cueing benefits from attentional capture and same location costs from object updating (Carmel & Lamy, 2014, 2015). Changes in the balance between attentional capture and same location costs may determine the overall size of the cueing effects. For instance, it is possible that changes in this balance contributed to differences between one- and multiple-color search. It is known that attentional capture increases with higher working memory load (De Fockert, 2013; Lavie et al., 2004). As the load is higher in multiple-color search, larger cueing effects are expected in two/three than one-color search. Consistent with this idea, we observed larger cueing effects in choice errors with two/three- than one-color search. However, there was an effect in the opposite direction in RTs, suggesting there was speed-accuracy tradeoff. Another explanation for same location costs is that in search tasks with varied nontarget colors, there is little signal enhancement at the location of non-matching cues, which results in slower responses to targets appearing at the cued location (Kerzel & Huynh Cong, 2021). Overall, more research is needed to resolve the debate on the causes of same location costs.

In sum, the simultaneous activation of multiple attentional templates in the contingent capture paradigm is limited to two colors. Performance in three-color search shows some evidence of contingent capture, but is limited by the activation of a single color in the focus of attention.

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Open Practices Statement

Neither of the experiments reported in this article was formally preregistered. The data is available at https://osf.io/gqfa8/ and requests for the program code can be sent via email to DK.

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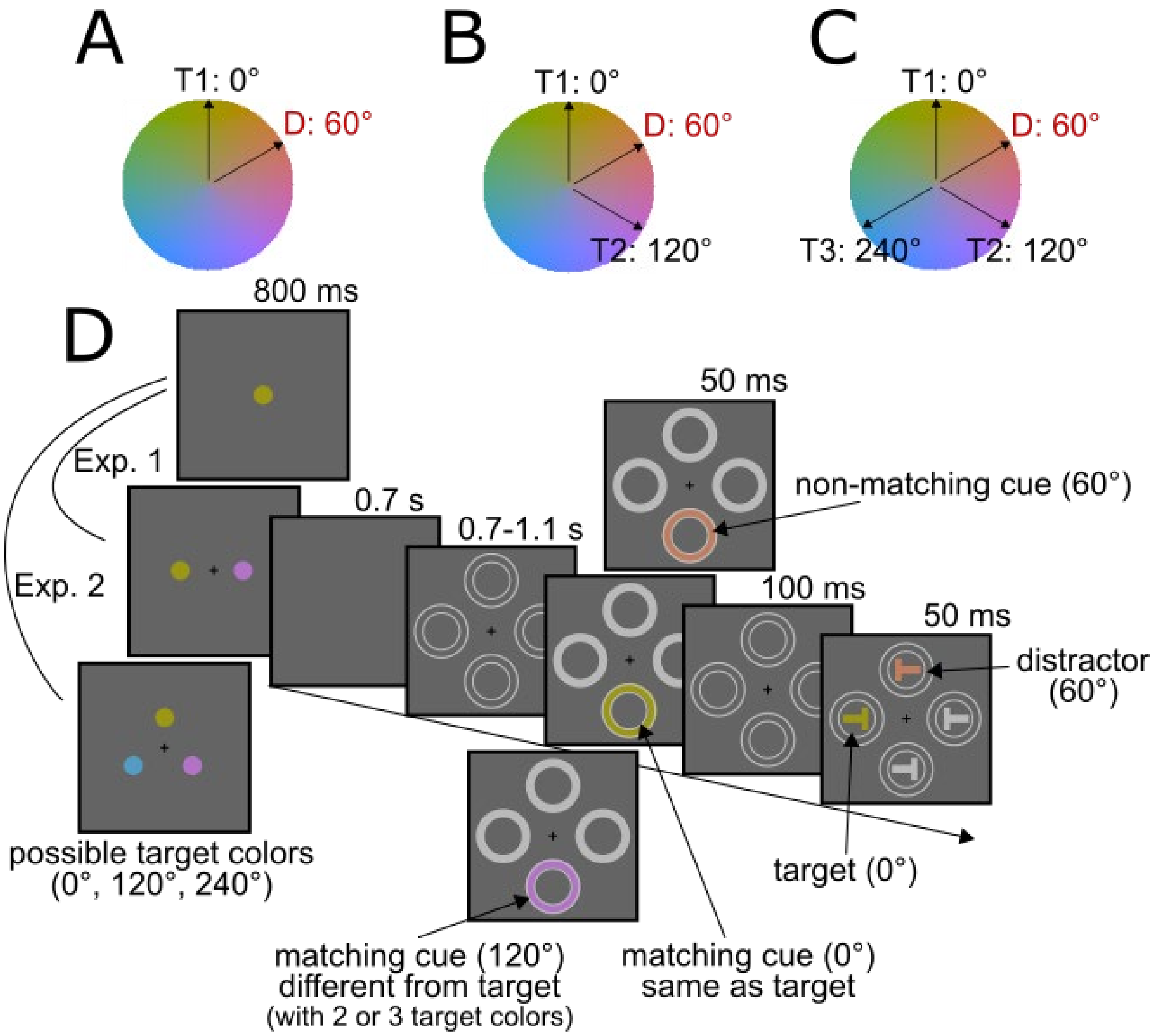


Figure 1. Illustration of experimental stimuli (not drawn to scale). Panels A-C illustrate a set of possible target and distractor colors. There were one, two, or three possible target colors (T1, T2, T3) and one distractor color. Panel D shows the sequence of stimuli. Observers memorized the possible target colors shown in the initial display. One of the possible target colors was shown together with a distractor in the search task. Briefly before the target display, a cue display was shown. The cue was in a possible target color or in the distractor color.

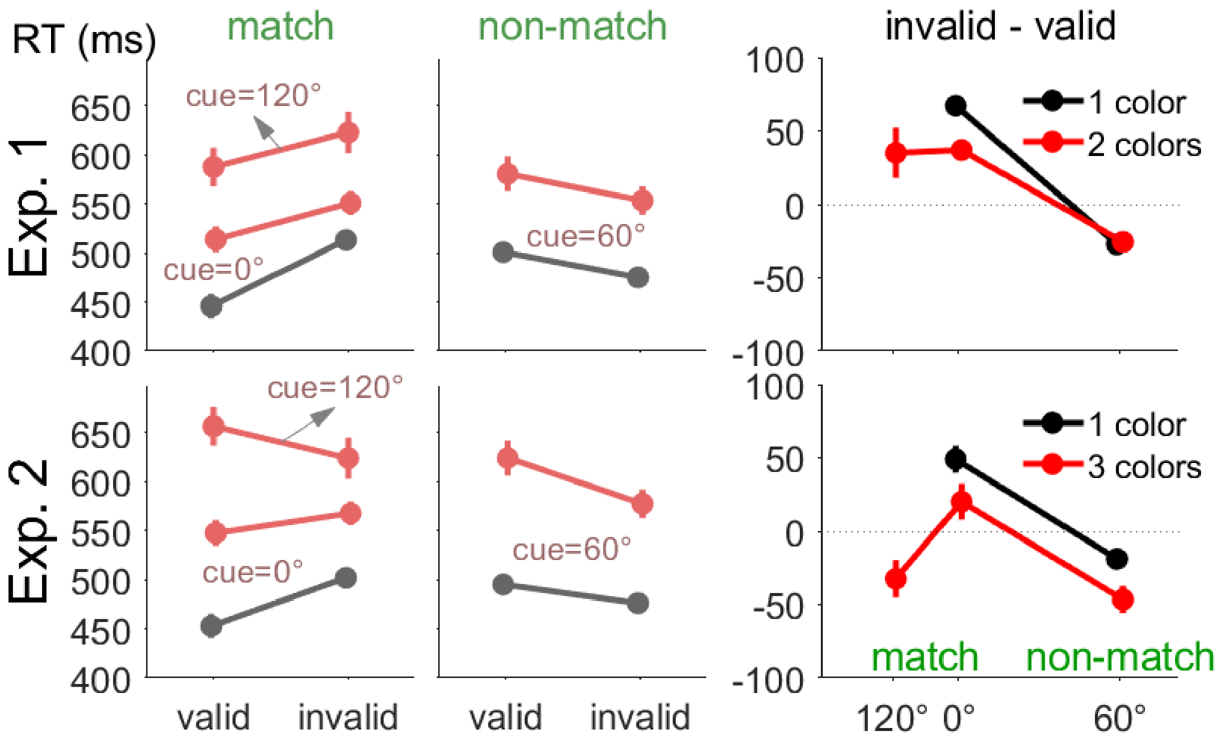


Figure 2. Reaction time (RT) results in Experiments 1 and 2. The left and center columns show mean RTs. The right column shows the differences between invalid and valid trials (cueing effects). Matching/different and matching/same cues correspond to colors with rotations of 120° and 0°, respectively. The non-matching cue color corresponds to a rotation of 60°. Error bars show the standard error of the mean.

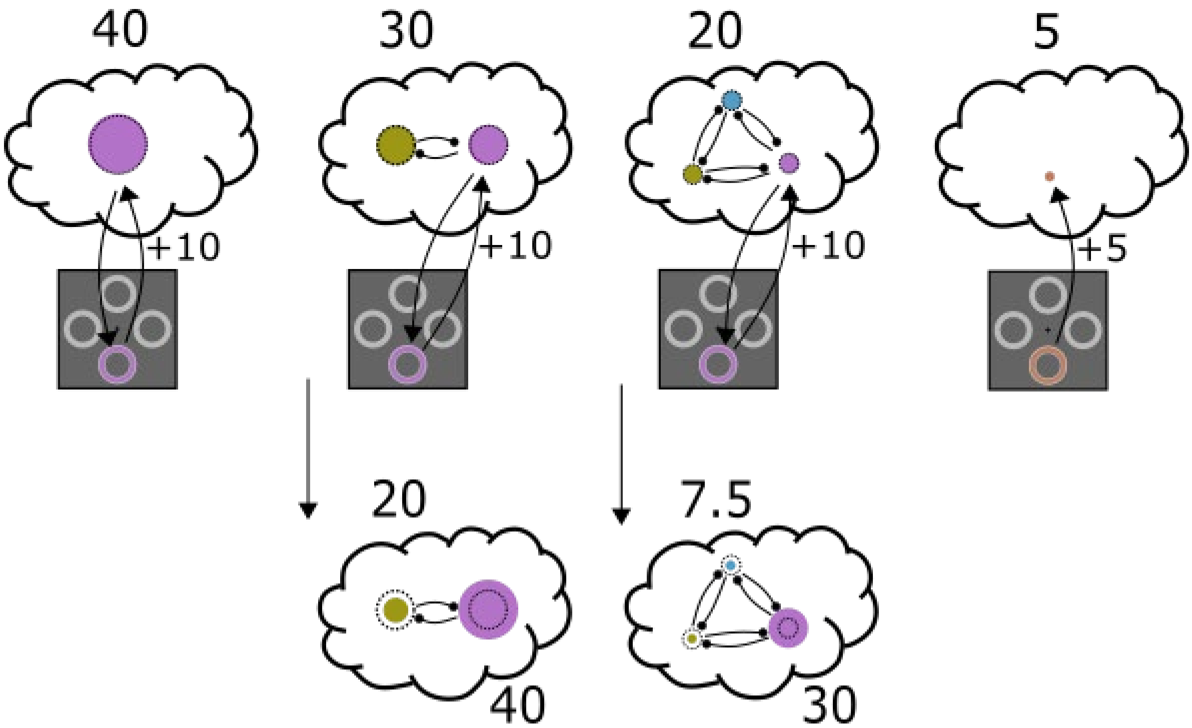


Figure 3. Schematic illustration with numerical examples of mutual inhibition and feedback loops in multiple target search. The clouds represent visual working memory, and the colored disks represent the attentional templates. The numbers represent the activation levels of attentional templates before and after the operation of feedback loops triggered by the cue display. We assume the maximal initial activation of a template to be 40 and the mutual inhibition to be 25%. With multiple templates, the activation of each template is reduced by the sum of inhibition from the remaining templates. With two attentional templates, each template is inhibited by 10 (= 25% * 40) units from the other template, resulting in an initial activation of 30 (= 40 – 10). With three attentional templates, the activation is smaller because for each template, there is inhibition of 10 units from two other templates (20 = 40 – 2 * 10). If a cue matching one of the templates is presented, the corresponding attentional template is boosted by the returning bottom-up activation (10 units), which further inhibits the uncued templates. With two attentional templates, the resulting activation of the uncued template remains high (20 = 30 – 25% * 40). With three attentional templates, the resulting level of activation of uncued templates is comparable to the activation resulting from non-matching cues (7.5 = 20 – 25% * 20 – 25% * 30). The reduced activation may explain why matching/different cues behave as non-matching cues in three-color search. Note that we assume that the bottom-up activation from the cue is reduced for non-matching colors (5 rather than 10 units) because non-matching colors are not attentionally selected.

Supplementary Material

Supplementary Analysis. For brevity, analyses in the main text were carried out on the theoretically relevant difference between invalid and valid trials. For completeness, we included cue validity as a factor in the supplementary ANOVAs, which were conducted on mean individual RTs.

First, we assessed whether the difference in cueing effects for matching/same and non-matching cues differed as a function of the number of targets. Individual mean RTs were subjected to a 2 (experiment: 1, 2) × 2 (number of possible targets: 1 vs. 2/3) × 2 (cue type: matching/same =0°, non-matching=60°) × 2 (cue validity: valid, invalid). RTs were shorter with one than with two/three possible targets (483 vs. 564 ms), $F(1, 38) = 202.30$, $p < .01$, $\eta_p^2 =.842$, but this effect was smaller in Experiment 1 (484 vs. 550 ms) than in Experiment 2 (482 vs. 579 ms), $F(1, 38) = 7.62$, $p < .01$, $\eta_p^2 = .167$. In addition, RTs were shorter with matching/same than with non-matching cues (512 vs. 535 ms), $F(1, 38) = 34.89$, $p < .01$, $\eta_p^2 = .479$, but this effect was smaller with one possible target color (478 vs. 487 ms) than with two/three possible target colors (545 vs. 584 ms), $F(1, 38) = 11.49$, $p < .01$, $\eta_p^2 = .232$. RTs with valid cues were shorter than with invalid cues (520 vs. 527 ms), $F(1, 38) = 5.27$, $p = .03$, $\eta_p^2 = .122$, but there was a tendency for a larger difference in Experiment 1 (510 vs. 523 ms) than Experiment 2 (530 vs. 531 ms), $F(1, 38) = 4.00$, $p = .053$, $\eta_p^2 = .095$. In addition, the effect of cue validity was modulated by the number of possible targets, $F(1, 38) = 16.89$, $p < .01$, $\eta_p^2 = .308$. Valid cues resulted in shorter RTs than invalid cues with one target (474 vs. 492 ms), but the opposite was the case with two/three possible targets (566 vs. 562 ms). Further, the interaction of cue validity and cue type, $F(1, 38) = 170.80$, $p < .01$, $\eta_p^2 = .818$, showed that valid cues resulted in shorter RTs than invalid cues with matching cues (490 vs. 533 ms), but the opposite was true with non-matching cues (550 vs. 520 ms).

Conducting the same ANOVA on choice errors showed that fewer errors occurred with one than with two/three possible targets (10.4% vs. 14.3%), $F(1, 38) = 123.52$, $p < .01$, $\eta_p^2 = .765$, but there was a tendency for a smaller difference in Experiment 1 (7.4% vs. 15.6%) than in Experiment 2 (7.4% vs. 19.0%), $F(1, 38) = 3.73$, $p = .06$, $\eta_p^2 = .089$. Fewer errors occurred with matching/same than with non-matching cues (10.4% vs. 14.3%), $F(1, 38) = 38.28$, $p < .01$, $\eta_p^2 = .502$, but this effect was smaller with one possible target color (6.4% vs. 8.4%) than with two/three possible target colors (14.4% vs. 20.2%), $F(1, 38) = 10.92$, $p < .01$, $\eta_p^2 = .223$. The interaction of number of possible targets and cue type, $F(1, 38)$

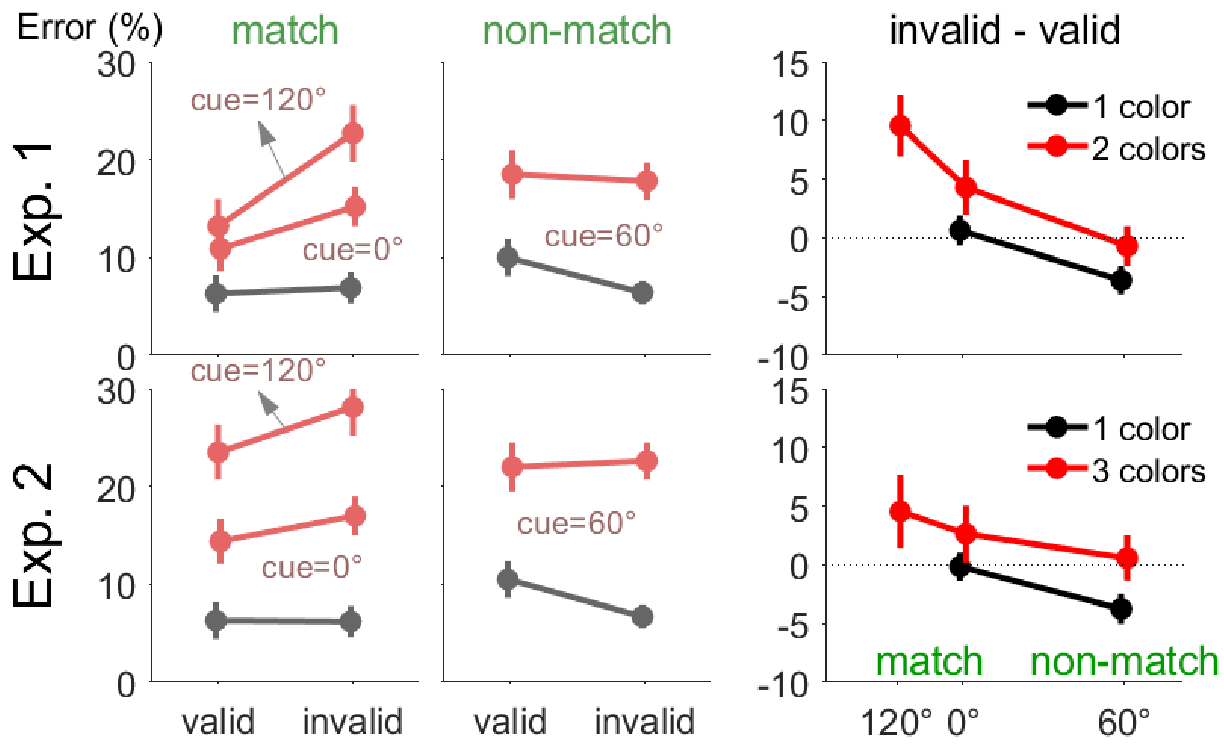
= 10.92, $p < .01$, $\eta_p^2 = .223$, indicated that the difference between matching/same and non-matching cues was smaller with one target (6.4% vs. 14.4%) than with two/three possible target colors (8.4% vs. 20.2%). The interaction of cue validity and number of possible targets, $F(1, 38) = 6.59$, $p = .01$, $\eta_p^2 = .148$, showed that valid cues resulted in more errors than invalid cues with one target (8.3% vs. 6.6%), but the opposite was the case with two/three possible targets (16.4% vs. 18.1%). The direction of this interaction is opposite to the RT results. Further, the interaction of cue type and cue validity, $F(1, 38) = 10.16$, $p < .01$, $\eta_p^2 = .211$, showed that valid cues resulted in more errors than invalid cues with matching cues (9.5% vs. 11.3%), but the opposite was true with non-matching cues (15.2% vs. 13.4%).

Second, we compared cueing effects with matching/different, matching/same and non-matching cues in two- and three-color search. Matching cues could either be in the same color as the actual target (matching/same=0°) or in the other possible target color (matching/different=120°). Non-matching cues were in the distractor color (non-matching=60°). Individual cueing effects were subjected to a 2 (experiment: 1, 2) × 3 (cue type: matching/different=120°, matching/same=0°, non-matching=60°) × 2 (cue validity: valid, invalid) mixed-factors ANOVA. The three-way interaction of experiment, matching cue type and cue validity, $F(2, 76) = 3.31$, $p = .042$, $\eta_p^2 = .08$, modulated the main effects of cue type, $F(2, 76) = 36.48$, $p < .01$, $\eta_p^2 = .49$, the interaction of cue type and cue validity, $F(2, 76) = 17.60$, $p < .01$, $\eta_p^2 = .317$, and the interaction of cue validity and experiment, $F(2, 76) = 11.92$, $p < .01$, $\eta_p^2 = .239$. We followed up on the significant three-way interaction by running separate ANOVAs for each experiment.

We first conducted a 2 (cue type: matching/different, matching/same) x 2 (cue validity: valid, invalid) ANOVA on conditions with multiple possible target colors, separately for each experiment. In Experiment 1, the main effects of cue type, $F(1, 19) = 25.29$, $p < .01$, $\eta_p^2 = .571$, and the main effect of cue validity, $F(1, 19) = 14.76$, $p < .01$, $\eta_p^2 = .437$, were not qualified by a two-way interaction, $p = .91$, showing that the effect of cue validity was similar for matching/different cues (588 vs. 623 ms) and matching/same cues (514 vs. 551 ms). In Experiment 2, the same ANOVA yielded a main effect of cue type, $F(1, 19) = 22.81$, $p < .01$, $\eta_p^2 = .546$, and a significant interaction, $F(1, 19) = 10.34$, $p < .01$, $\eta_p^2 = .352$, showing that RTs were longer on valid than invalid trials for matching/different cues (656 vs. 624 ms), but shorter for matching/same cues (548 vs. 568 ms).

Further, we conducted a 2 (cue type: matching/different, non-matching) x 2 (cue validity: valid, invalid) ANOVA on conditions with multiple possible target colors, separately for each experiment. In Experiment 1, the main effect of cue type, $F(1, 19) = 19.87$, $p < .01$, $\eta_p^2 = .511$, was qualified by a significant interaction, $F(1, 19) = 11.05$, $p < .01$, $\eta_p^2 = .368$, showing that RTs were shorter on valid than invalid trials with matching/different cues (588 vs. 623 ms), but longer for non-matching cues (581 vs. 553 ms). In Experiment 2, the main effects of cue type, $F(1, 19) = 8.85$, $p < .01$, $\eta_p^2 = .318$, and cue validity, $F(1, 19) = 22.49$, $p < .01$, $\eta_p^2 = .542$, were not qualified by a two-way interaction, $p = .34$, showing that RTs were longer on valid than invalid trials with matching/different (656 vs. 624 ms) and with non-matching cues (624 vs. 577 ms).

Conducting the same 2 (experiment: 1, 2) × 3 (cue type: matching/different=120°, matching/same=0°, non-matching=60°) × 2 (cue validity: valid, invalid) mixed-factors ANOVA on choice errors yielded a main effect of cue type, $F(2, 76) = 22.06$, $p < .01$, $\eta_p^2 = .367$, showing that fewer errors occurred with matching/same (14.4%) than with matching/different (21.9%) and non-matching (20.2%) cues. The main effect of cue validity, $F(1, 38) = 9.15$, $p < .01$, $\eta_p^2 = .194$, showed that fewer errors occurred with valid than invalid cues (17.1% vs. 20.6%). The interaction of cue type and cue validity, $F(2, 76) = 5.49$, $p < .01$, $\eta_p^2 = .126$, showed that fewer errors occurred with valid than invalid cues for matching/different (18.3% vs. 25.4%) and matching/same cues (12.6% vs. 16.1%), but were about equal for non-matching cues (20.2% vs. 20.2%). The three-way interaction was not significant, $F(2, 76) = 1.07$, $p = .35$, $\eta_p^2 = .027$.



Supplementary Figure. Choice errors in Experiments 1 and 2. The left and center column show the mean error percentages. The right column shows the difference between invalid and valid trials (cueing effects). Error bars show the standard error of the mean.