Guidance of Visual Search by Negative Attentional Templates Depends on Task Demands

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Visual search for a target is faster when its features are known before the search display appears, but there is an ongoing discussion about whether knowledge of nontarget features has a similar effect. Stored target or nontarget features used to guide visual search are referred to as positive or negative attentional templates, respectively. We suggest that the inconsistent findings concerning negative attentional templates may arise from 2 methodological choices in past research. The activation of negative attentional templates was never directly assessed and the use of negative attentional templates by the participant was optional. We addressed these issues in the contingent capture paradigm, which provides a marker for the activation of attentional templates in conditions where attentional templates are optional or mandatory. If an attentional template for a color is activated, cuing effects are larger for spatial cues in a matching color than for spatial cues in a nonmatching color. The question is whether the activation of negative attentional templates results in a similar difference between matching and nonmatching colors. We found that negative attentional templates were not activated when the target could be located based on its saliency (singleton search) and the use of the negative attentional template was optional. In contrast, when the negative attentional template was necessary to locate the target (feature search), we found the expected difference between matching and nonmatching spatial cues. Thus, the activation of negative attentional templates depends on task demands. In contrast, positive attentional templates were activated irrespective of task demands.

Public Significance Statement
Visual search is facilitated when we know what to look for. For instance, if we look for our coat in a checkroom, we will be faster to find it if we can remember its color. However, it is less clear if visual search benefits from knowledge about nontarget stimuli. For instance, if we remember that we did not check a black coat, would this help us ignore the black coats in the checkroom? The present research suggests that we can, but only when the task demands make it absolutely necessary.

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

Supplemental materials: https://doi.org/10.1037/xhp0001005.supp

Major theories of visual search assume that the selection of stimuli for in-depth processing is guided by representations of target features in working memory (Bundesen, 1990; Desimone & Duncan, 1995; Eimer, 2014; Liesefeld et al., 2018; Luck et al.,

1997; Schneider, 2013; Wolfe, 2021). This representation is often called attentional template (Duncan & Humphreys, 1989) or attentional control set (Folk et al., 1992). For instance, Desimone and Duncan (1995) assumed that the competition for selection between stimuli in the receptive field of a neuron can be biased in favor of stimuli corresponding to the attentional template. Another way to guide selection is to inhibit features of nontarget stimuli (Treisman & Sato, 1990; for review, see Dent et al., 2012), but this possibility is controversial. For example, visual marking (Watson & Humphreys, 1997), negative priming (Tipper et al., 1994), or inhibition of return (Posner & Cohen, 1984) show that previously encountered nontargets are inhibited. However, these phenomena do not show that participants set up a working memory representation to inhibit nontarget stimuli because inhibitory effects may arise passively from previous exposure or selection episodes. The first study that directly addressed the question of voluntary inhibition of nontarget stimuli was provided by Arita et al. (2012). Their experiments suggested that participants were able to set up an attentional template for nontarget stimuli based on a color cue

presented at the start of a trial. The negative attentional template was thought to facilitate search by guiding attention away from nontarget stimuli, similar to a "template for rejection" (Woodman & Luck, 2007). However, as explained below, evidence in favor of negative attentional templates is inconclusive because the experimental tasks could be solved without activation of the negative template. To rule out these interpretations, we used the contingent capture paradigm, which allowed us to measure the activation of negative attentional templates more directly. Further, we compared the optional and mandatory use of negative attentional templates in two different search tasks to clarify when negative attentional templates guide visual search.

In experiments on negative attentional templates, the task of the observers was to find a target shape among similar distractor shapes. For instance, participants searched for a vertical gap among shapes with lateral gaps (Arita et al., 2012; Becker et al., 2016; Beck & Hollingworth, 2015; Berggren & Eimer, 2021; Carlisle & Nitka, 2019; Rajsic et al., 2020; Woodman & Luck, 2007). In other studies, the task was to find the letter T tilted to the left or right among other Ts that varied in length or offset (Conci et al., 2019; Reeder et al., 2017). In addition to the primary search target, participants were instructed to integrate a color into their attentional template. The color was cued before onset of the search display. A positive template cue indicated the color of potential target stimuli, whereas a negative template cue indicated the color of a subset of nontargets. It was useful to integrate either color cue into an attentional template because the number of potential target locations would be reduced. However, the use of color remained optional because participants could focus exclusively on shape. As a result, the use of template cues may be under strategic control. Consistent with strategic and not mandatory use, Beck and Hollingworth (2015) found large differences between participants. Also, there was a correlation between the use of positive and negative template cues. That is, participants who employed positive attentional templates also employed negative attentional templates. However, some participants used neither, which may explain why effects of negative template cues were sometimes elusive (Becker et al., 2016; Berggren & Eimer, 2021). Further, participants may choose to use negative attentional templates only when the expected benefits are large. Conci et al. (2019) observed that negative attentional templates were only used in difficult search tasks with high target-nontarget similarity and Arita et al. (2012) found that benefits of negative template cues only occurred when the set size was large. Thus, participants may decide whether to use negative attentional templates depending on the experimental task.

Further, there were doubts that participants actually set up a negative attentional template. One suggestion was that participants recoded the negative template cue into a positive attentional template. That is, if two colors were used in the search display and a negative template cue told participants that the target would not be in the cued color, participants may have searched for the other color instead. When the two colors are spatially separated on either side of fixation, this strategy reduces to spatial recoding (Beck & Hollingworth, 2015). For instance, if the negative template cue is red and red items in the subsequent search display are on the left side of the screen, participants may attend to items on the right side. If the colors are spatially mixed, spatial recoding is no longer possible, but it would still be possible to recode the color of the negative template cue into a positive attentional template for the other color. Some studies found that effects of negative template cues were absent with spatially mixed colors (Becker et al., 2016; Beck & Hollingworth, 2015), but other studies found these effects to be reliable (Conci et al., 2019; Reeder et al., 2017; Woodman & Luck, 2007). However, some of the latter studies allowed for color recoding at display onset because only two colors were used in the search display (Conci et al., 2019; Reeder et al., 2017). Color recoding can only be avoided if several colors are used (e.g., Experiment 3 in Woodman & Luck, 2007). A plausible hypothesis is that color recoding occurs between presentation of the negative cue and onset of the search display, but an electrophysiological marker of working memory maintenance, the CDA, was not consistent with this idea. Rather, both positive and negative template cues were maintained in working memory during the retention interval (Rajsic et al., 2020).

In sum, the idea of negative attentional templates is plagued by two problems. First, the use of negative templates is under strategic control (i.e., it depends on task demands) and second, the observed benefits of negative template cues are open to multiple interpretations (i.e., spatial or color recoding). To solve these issues, we used the contingent capture paradigm to probe the activation of positive and negative attentional templates more directly. In addition, we changed the search task to compare optional and mandatory use of negative templates. In the contingent capture paradigm developed by Folk et al. (1992), a spatial cue precedes the search display and the match between colors of the spatial cue and the target is manipulated. For instance, Folk and Remington (1998) instructed participants to search for a red target. In the preceding display with a spatial cue, either a target-matching red cue or a nonmatching green cue was presented. The result was that spatial cues in the target-matching color captured attention, whereas spatial cues in the nonmatching color did not. Thus, the difference between target-matching and nonmatching spatial cues shows that an attentional template was activated for the target color, but not for an unrelated color (e.g., Becker et al., 2019; Burnham, 2020; Jung et al., 2021; Kerzel, 2019; Kim et al., 2019; Ruthruff et al., 2020; Schönhammer et al., 2020). Attentional capture is measured as the difference in RTs between spatial cues appearing at the target location (valid cues) and spatial cues appearing at a nontarget location (invalid cues). When RTs are shorter on trials with valid than invalid cues, the spatial cue benefits performance. Besides cuing benefits, there are also occasions where the spatial cue impairs visual search and RTs are longer on trials with valid than invalid cues. The reasons for these same location costs are controversial (Büsel et al., 2021; Carmel & Lamy, 2014, 2015; Kerzel, 2019; Huynh Cong & Kerzel, 2021; Schoeberl et al., 2020).

Importantly, we varied the task demands to clarify why evidence for negative attentional templates was sometimes elusive. Previous research has suggested that evidence for negative attentional templates was stronger when the search task was difficult (Arita et al., 2012; Conci et al., 2019). Here, we selected two search tasks with different requirements concerning the use of attentional templates (e.g., Bacon & Egeth, 1994). In singleton search, the target had a unique color among homogeneous nontargets. Therefore, the target could be located based on its saliency alone and the use of positive and negative color templates was optional. In feature search, it was necessary to know the target or distractor color because the target was not the most salient

stimulus. The use of positive and negative color templates was therefore mandatory. In Experiments 1 and 2, participants performed singleton search where the target stimulus was a color different from the nontarget color. In Experiments 3 and 4, participants performed feature search where two colored stimuli (target and distractor) were shown among otherwise gray nontarget stimuli. Concerning the difficulty of the two search tasks, previous research found that singleton and feature search have similar search times (Bacon & Egeth, 1994; Barras & Kerzel, 2016; Leber & Egeth, 2006), suggesting that the difficulty is comparable.

Experiments 1 and 2: Singleton Search

The target in Experiments 1 and 2 was a singleton color different from the uniform nontarget color. Briefly before onset of the search display, a spatial cue was presented and attentional capture was calculated as the difference between invalid and valid trials (i.e., invalid—valid). A difference larger than zero indicated cuing benefits, whereas a difference smaller than zero indicated same location costs. The color of the spatial cue either matched the target or the nontarget color. Critically, a template cue was shown about half a second before the search display. In Experiment 1, the template cue indicated the color of the nontargets and could therefore be used to activate a negative attentional template. In Experiment 2, the template cue indicated the color of the target and could

be used to activate a positive attentional template. Because neither the positive nor the negative attentional template was necessary to find the target, use of the template cue was optional. If an attentional template for color was established, we predict a difference between target-matching and nonmatching spatial cues. That is, a cuing benefit should be observed with target-matching spatial cues, whereas no cuing effect or same location costs should be observed with nonmatching spatial cues. In contrast, if no attentional template was set up, cuing benefits should be observed for target-matching and nonmatching colors alike, suggesting that participants searched for any singleton irrespective of color (Folk & Anderson, 2010; Folk & Remington, 2008). Therefore, the difference in cuing effects between target-matching and nonmatching colors is diagnostic of attentional template activation. Note that spatial cues matching the target color correspond to a positive template, whereas nonmatching spatial cues correspond to a negative template (see Figure 1A). Thus, a difference between target-matching and nonmatching spatial cues reflects different mechanisms depending on the type of template cue. With positive template cues, the difference results from attentional capture by the target-matching spatial cue, whereas with negative template cues, it results from inhibition of the nonmatching spatial cue.

Based on the literature, we may derive two predictions for the activation of negative and positive attentional templates in singleton search. Because participants were not required to use the

Figure 1
Illustration of Experimental Stimuli (Not Drawn to Scale)
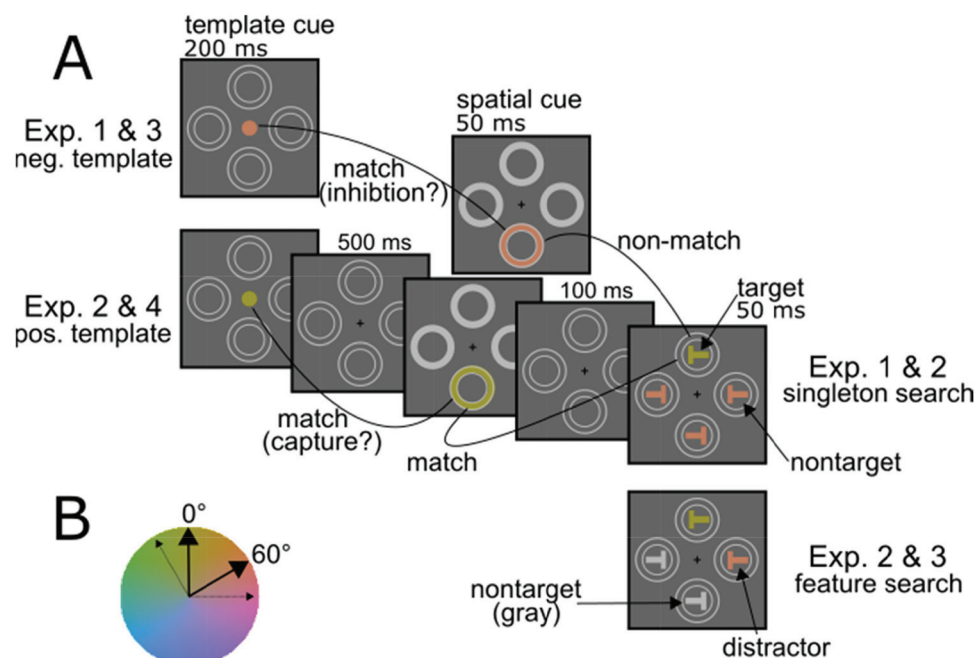
Note. Panel A shows the sequence of stimuli. Observers memorized the color shown on the template cue, which corresponded to the target or nontarget/distractor color. Briefly before the search display, the spatial cue was shown in the target-matching or nonmatching color. Results are presented in terms of the match between spatial cue and target, but note that a description in terms of the match between spatial cue and template cue is also possible. Panel B shows the CIE-lab color space with the target and distractor color shown in panel A (0° and 60°, respectively). The target color on any trial was selected to have a color difference larger than 30° from the target and distractor colors of the preceding trial. See the online article for the color version of this figure.

negative template cues and previous research suggested that negative templates are only used when highly beneficial (e.g., in difficult tasks, Arita et al., 2012; Conci et al., 2019), we do not expect evidence for the activation of negative attentional templates in singleton search. In contrast, it is known that participants set up positive attentional templates even when not necessary. For instance, Folk and Remington (1998) found a difference between target-matching and nonmatching spatial cues although the target was a color singleton. Nonetheless, an important difference to previous work is that the target color changed from trial to trial in the current experiment, whereas it was fixed in previous work on singleton targets (Becker et al., 2019; Folk & Remington, 1998; Harris et al., 2019). Trial-by-trial changes ensured that template color was stored in working memory (review in Huynh Cong & Kerzel, 2021; Woodman et al., 2013) and avoided effects of intertrial repetition (Folk & Remington, 2008; Goller & Ansorge, 2015; Schoeberl et al., 2019). Therefore, it is not clear whether the activation of positive attentional templates would be observed here.

Method

Participants

In previous studies, target-matching and nonmatching spatial cues were compared in within-participant designs. However, we were interested in an interaction with one within- and one between-participants factor (i.e., color of spatial cue and type of template cue). Therefore, we could not rely on previous estimates of effect size. We decided on a sample size of 18 participants per group for Experiments 2–4. With this sample size, G*Power 3 (Faul et al., 2007) indicates a minimal $F(1, 34) = 4.1$ or $\eta_p^2 = .11$ for the mixed-factors interaction to become significant. For paired-samples t test in each group, the critical t with 18 participants is $t(17) = 1.74$ with a minimal Cohen's $d_z = .61$. Because we did not expect a difference between target-matching and nonmatching spatial cues with negative attentional templates in Experiment 1, but did not want to miss small differences, we increased the sample size to 24 in Experiment 1. This resulted in modest changes of the critical F value (from 4.1 to 4.08, η_p^2 from .11 to .09) and the critical t-value (from 1.74 to 1.71, Cohen's d_z from .61 to .52). Thus, there were 24 undergraduate psychology students in Experiment 1 (2 male; age: $M = 20.8$ years, $SD = 4.0$) and 18 in Experiment 2 (3 male; age: $M = 19.5$ years, $SD = 2.0$). 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 presented on a 22.5-in. VIEWPixx Light (VPixx Technologies Inc., Saint-Bruno, Canada) at 100 Hz and 1,920 × 1,200 pixels. Color coordinates and luminance were measured by a ColorCAL MKII colorimeter (Cambridge Research Systems, Rochester, U.K.). Viewing distance was 66 cm and a chin/forehead rest was used. The Psychtoolbox (Kleiner et al., 2007) was used to run the experiment.

Stimuli

Four placeholders and a fixation cross (.5° × .5°, linewidth .07°) were shown throughout. Placeholders resembled unfilled rings and were made up of two circles (diameters of 2.3° and 2.8°, linewidth .02°). One placeholder was shown left, right, above and below the central fixation cross (see Figure 1A). The center of each placeholder was shown at a distance of 3° from the center of the central fixation cross. The template cue was a filled circle (diameter of .4°), which replaced the fixation cross. The spatial cue was a placeholder filled with a color, while the remaining placeholders were filled with gray. The search display consisted of Ts presented in the center of the placeholders. Two Ts were tilted to the left and two to the right. The Ts were made up of two bars (1° long, linewidth .2°). The target T was a color different from the remaining nontarget Ts. The stimuli were presented against a medium gray background with xyY = (.274, .356, 29.2). The placeholders, the gray spatial cues and the gray nontarget Ts were light gray with xyY = (.274, .356, 58.7). The colors were selected in CIELAB-space (Fairchild, 2005) on an isoluminant color wheel (luminance of 58.7 cd/m² or L* = 61, saturation of 59). On each trial, we randomly selected two colors separated by a rotation of 60° on the color wheel (see Figure 1B). For clarity, the color assigned to the target was assigned a rotation of 0° and the color assigned to the nontarget a rotation of 60°. The target colors on trial n differed by at least 30° from target and nontarget colors on trial n-1, which reduced the colors available for random selection from 360° to 240°. For instance, if the colors on trial n-1 were 0° and 60°, the selection of the target color on the subsequent trials would be limited to 90°–330°. Overall, the random choice of cue and target colors made it very hard to recode the color of the negative template cue into the target color. To rule out effects of color predictability or color repetition, we ran additional analyses on trials where all colors on consecutive trials differed by at least 60°. These results are presented in the Supplemental Materials A.

Design

On each trial, there were two different colors in the search display, the target (0°) and nontarget color (60°). In Experiment 1, negative template cues were employed, which were the same color as the nontargets (60°). In Experiment 2, positive template cues were employed, which were the same color as the target (0°). In both experiments, spatial cues in a target-matching color had the same color as the target (0°), whereas spatial cues in a nonmatching color had the same color as the nontargets (60°). The results are presented in terms of the match between spatial cue and target color, because this relation did not change between Experiments 1 and 2. However, it should be noted that it is also possible to consider the relation between template and spatial cue. As shown in Figures 1A and 2, the color of the negative template cue corresponded to the nontarget color and therefore to the nonmatching spatial cues. In contrast, the color of the positive template cue corresponded to the target and therefore to the matching spatial cues. The 64 combinations resulting from crossing the spatial cue positions (left, right, top, bottom), target positions (left, right, top, bottom), spatial cue colors (target-matching = 0°, nonmatching = 60°), and response locations (left, right) were shown once in a block of trials. There were eight trial blocks for a total of 512 trials per participant and experiment.

Procedure

A trial started with the presentation of the template cue for 200 ms, followed by the placeholder display for 500 ms. Then, the spatial cue was presented for 50 ms, followed by the placeholder display for 100 ms and the search display for 50 ms. The placeholders were shown until a response was detected. They also remained visible during the intertrial interval of 700 ms.

Participants' task was to locate the tilted T in the singleton color and to indicate its orientation by mouse click. Left and right mouse clicks indicated targets tilted to the left and right, respectively. Participants were told to respond as rapidly and accurately as possible, while making less than 10% errors. They were informed that the spatial cue did not predict the target location and should be ignored. They were also told that the template cue at the start of a trial indicated the nontarget (Experiment 1) or target color (Experiment 2) and that they should use this information to find the target more quickly. The response window for acceptable mouse clicks was 1,250 ms after onset of the search display. Wrong mouse clicks and latencies outside the response window resulted in an immediate error message on the screen. Every 64 trials, there was a self-terminated break of at least 2,000 ms. During the break, visual feedback about the percentage of correct responses and the median (RT) was displayed. In addition, the instruction concerning the template cue was repeated. The experimental blocks were preceded by two practice blocks of 64 trials. In the first practice block, the colors were as in the experiment. In the second practice block, the selection of colors was restricted to the bluish range because they appeared more difficult to discriminate. This was done to prepare participants for variations in the difficulty of the search task, which occurred despite the equal angular differences in color space.

Bayesian Statistics

In addition to frequentist statistics, we reported Bayesian statistics for nonsignificant results. For ANOVAs, we report how much more probable the best model was compared to the models including the nonsignificant factor. For t-tests, we reported the Bayes factor H_{10}, which indicates how much more probable the alternative hypothesis H_1 is compared to the null hypothesis H_0. Bayes factors smaller than 1 favor the null hypothesis H_0 with values between $.33 - 1$ providing anecdotal evidence, values between $.1 - .33$ providing moderate evidence and values between $.03 - .1$ providing strong evidence for the null hypothesis H_0. Bayesian statistics were calculated using Jasp (JASP Team, 2021). The data are available at https://osf.io/feh9w/ and requests for the program code can be sent via e-mail to DK.

Results

We evaluated the theoretically relevant cuing effects (invalid - valid), thereby omitting the factor of cue validity, but analyses including this factor are reported in the Supplemental Materials B. Shorter RTs or fewer errors on valid than invalid trials reflect cuing benefits, and longer RTs or more errors on valid than invalid trials reflect same location costs. RTs and cuing effects are shown in Figure 2 In the analysis of cuing effects, we excluded trials with RTs outside the response window of 1,250 ms (1.0% and .4% in Experiments 1 and 2, respectively), choice errors (5.3%, 4.8%), and trials with RTs longer than 2 SDs above the respective condition mean (4.0%, 4.1%) from analysis.

Individual cuing effects were subjected to a 2 (template type: negative=Experiment 1, positive=Experiment 2) $\times$ 2 (spatial cue color: target-matching, nonmatching color) mixed-factors ANOVA and are shown in the right panels of Figure 2 The main effect of spatial cue color, $F(1, 40) = 62.19$, $p < .01$, $\eta_p^2 = .609$, was modulated by a significant interaction with template type, $F(1, 40) = 48.02$, $p < .01$, $\eta_p^2 = .546$. We followed up on the significant interaction by comparing cuing effects separately for each experiment. With a negative template cue in Experiment 1, target-matching and nonmatching colors of the spatial cue resulted in equivalent cuing benefits (37 vs. 32 ms), $t(23) = .85$, $p = .40$, Cohen's $d_z = .17$, $BF_{10} = .30$, suggesting that participants had not set up an attentional template for a specific color, but searched for any color singleton. Both cuing benefits were significantly different from zero, $t(23) > 7.5$, $ps < .01$, Cohen's $d_z > 1.5$. In contrast, with a positive template cue in Experiment 2, the cuing benefit with spatial cues in the target-matching color was larger than with spatial cues in the nonmatching color (76 vs. 3 ms), $t(17) = 8.39$, $p < .01$, Cohen's $d_z = 1.98$, suggesting that participants had set up an attentional template for the color of the positive template cue. The cuing benefit with target-matching spatial cues was significant (76 ms), $t(17) = 11.47$, $p < .01$, Cohen's $d_z = 2.7$, whereas there was no effect with nonmatching spatial cues (3 ms), $t(17) = .51$, $p = .62$, Cohen's $d_z = .12$, $BF_{10} = .27$. An account of these findings in terms of a mixture of strategies is discussed in the Supplemental Materials C.

Conducting the same mixed-factors ANOVA on choice errors confirmed these results. The main effect of spatial cue color, $F(1, 40) = 20.72$, $p < .01$, $\eta_p^2 = .341$, was modulated by a significant interaction with template type, $F(1, 40) = 5.17$, $p = .03$, $\eta_p^2 = .114$. With a negative template cue in Experiment 1, target-matching and nonmatching colors of the spatial cue resulted in equivalent cuing benefits (3.0% vs. 1.7%), $t(17) = 1.67$, $p = .11$, Cohen's $d_z = .34$, $BF_{10} = .72$, and both cuing benefits were significantly different from zero, $t(23) > 2.7$, $ps < .02$, Cohen's $d_z > .56$. With a positive template cue in Experiment 2, however, the cuing benefit with the target-matching color of the spatial cue was larger than with the nonmatching color (3.2% vs. $-.7\%$), $t(17) = 4.8$, $p < .01$, Cohen's $d_z = 1.13$. There was a cuing benefit with target-matching spatial cues (3.2%), $t(17) = 3.99$, $p < .01$, Cohen's $d_z = .94$, but not with nonmatching spatial cues $(-.7\%)$, $t(17) = .97$, $p = .35$, Cohen's $d_z = .23$, $BF_{10} = .37$.

Further, we compared the average individual RTs between negative and positive template cues. RTs were longer with a negative than a positive template cue (554 vs. 506 ms), $t(40) = 4.51$, $p < .01$, Cohen's $d_s = 1.41$, confirming that guidance of visual search by negative attentional templates was less efficient than by positive attentional templates (Kawashima & Matsumoto, 2018; Kugler et al., 2015). Alternatively, it may be that there was general inhibition for all colors induced by the negative template cue (Reeder et al., 2018) or that trying to use a negative template slowed search. However, our experiments lacked a neutral condition so it is unclear whether the difference reflects facilitation with positive template cues or inhibition with negative template cues.

Discussion

We investigated whether participants activated negative and positive attentional templates in singleton search. In singleton search, the activation of an attentional template for a specific color is optional because the target can be located based on its saliency. We measured effects of spatial cues on search performance and

Figure 2

Reaction Time Results (in Ms) in Experiments 1–4 as a Function of Search Type (Feature, Singleton), Template Type (Negative, Positive), Validity of the Spatial Cue (Valid, Invalid), and the Relation Between the Color of the Spatial Cue and Color of the Target (Matching, Nonmatching)
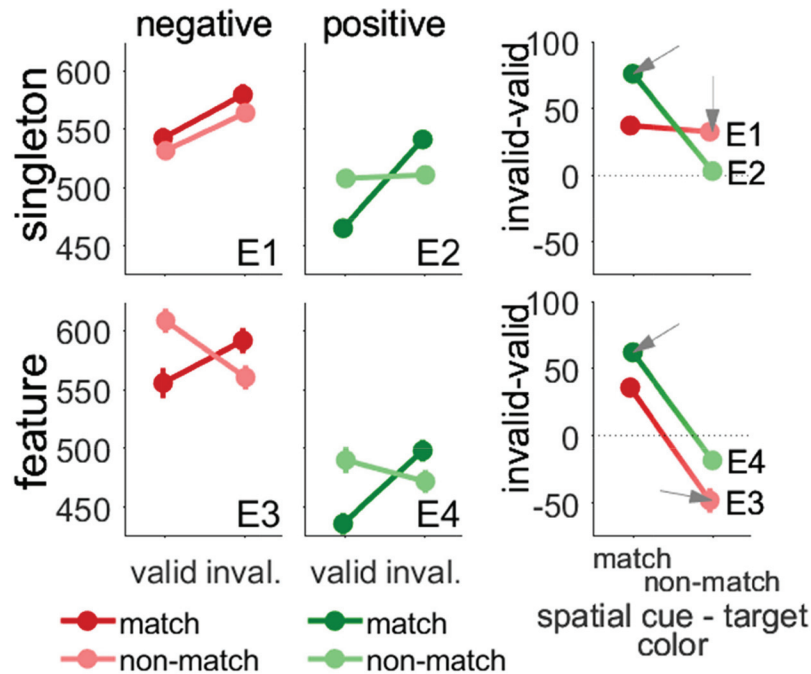
Note. Means from experiments with negative and positive template cues are in red and green, respectively. The left panels show mean reaction times. The right panels show cuing effects (invalid - valid). In the right panels, gray arrows indicate conditions where the spatial cue color matched the color of the template cue. Error bars show the standard error of the mean. See the online article for the color version of this figure.

used the difference between target-matching and nonmatching colors as a marker for the activation of attentional templates. We reasoned that if cuing effects differ between target-matching and nonmatching spatial cues, participants activated an attentional template for a specific color. If cuing effects do not differ, however, participants may have searched for any singleton color. Consistent with the activation of an attentional template for a specific color, we found differences between target-matching and nonmatching spatial cues when a positive template cue indicated the color of the target. Similar results were obtained in singleton search with a fixed color target (Becker et al., 2019; Folk & Remington, 1998; Harris et al., 2019). When a negative template cue indicated the color of the nontargets, however, there was no difference between target-matching and nonmatching spatial cues, suggesting that participants had not activated a negative template for a specific color, but searched for any color singleton. Thus, positive templates are activated even when optional, whereas negative templates are not.

Experiments 3 and 4: Feature Search

In Experiments 3 and 4, we changed the search task from singleton to feature search. In our variant of feature search, we

presented two colored stimuli among gray nontargets. One of the colored stimuli was the target and the other was the distractor. Because there were two stimuli in unique colors, participants could no longer search for a singleton, but had to search for the target color (Experiment 4) or inhibit the distractor color (Experiment 3). Thus, we expect activation of positive attentional templates in Experiment 4 and activation of negative attentional templates in Experiment 3. As in Experiments 1 and 2, the colors changed randomly from trial to trial. With negative template cues in Experiment 3, it was therefore hard to recode the distractor color shown in the template cue into the target color before onset of the search display. The reason is that the distractor and target color in the search display varied by 60° randomly in clockwise or counterclockwise direction and it is unlikely that participants had a mental representation of the color wheel to figure out the potential target colors based on the distractor color (see Figure 1B). To determine whether participants activated an attentional template corresponding to the template cue, we again relied on the difference between target-matching and nonmatching spatial cues. A difference between target-matching and nonmatching spatial cues is considered evidence for the activation of an attentional template, whereas the absence suggests that participants used some other search strategy. For instance, the negative template cue may be

recoded into the target color once the search display appears. Such a recoding strategy is not expected to affect cuing effects because the spatial cues were presented before onset of the search display.

Method

The methods were the same as in Experiments 1 and 2 except that the search display was different. Instead of uniform nontargets, we presented a distractor in the nonmatching color and two nontargets in gray. There were 18 participants in Experiment 3 (5 male; age: $M = 21.0$ years, $SD = 5.7$), and 18 in Experiment 4 (3 male; age: $M = 21.9$ years, $SD = 5.3$).

Results

In the analysis of RTs, we excluded trials with RTs outside the response window (1.1% and .2% in Experiments 3 and 4, respectively), choice errors (9.0%, 5.4%), and trials with RTs longer than 2 SDs above the respective condition mean (4.3%, 4.1%). Further, we conduced analyses to rule out position-specific color priming or color interference. To this end, we excluded invalid trials where cue and distractor appeared on the same position. The results were unchanged, which is reported in the Supplemental Materials D.

Individual cuing effects were subjected to a 2 (template type: negative=Experiment 3, positive=Experiment 4) × 2 (spatial cue color: target-matching, nonmatching) mixed-factors ANOVA and are shown in the right panels of Figure 2 There was a main effect of spatial cue color, $F(1, 34) = 171.53$, $p < .01$, $\eta_p^2 = .835$, indicating that there were cuing benefits with the target-matching spatial cue color (49 ms), but same location costs with the nonmatching color (−33 ms). Further, cuing effects were overall smaller with negative attentional templates in Experiment 3 than with positive attentional templates in Experiment 4 (−6 vs. 22 ms), as evidenced by a significant main effect of template type, $F(1, 34) = 17.70$, $p < .01$, $\eta_p^2 = .329$. With negative attentional templates in Experiment 3, there were cuing benefits with spatial cues in a target-matching color (36 ms), $t(17) = 5.01$, $p < .01$, Cohen's $d_z = 1.18$, but same location costs with spatial cues in a nonmatching color (−48 ms), $t(17) = 5.27$, $p < .01$, Cohen's $d_z = 1.24$. Similarly, with positive attentional templates in Experiment 4, there were cuing benefits with spatial cues in a target-matching color (62 ms), $t(17) = 15.74$, $p < .01$, Cohen's $d_z = 3.71$, but same location costs with spatial cues in a nonmatching color (−18 ms), $t(17) = 3.87$, $p < .01$, Cohen's $d_z = .91$. Critically, the interaction between template type and spatial cue color was not significant, $F(1, 34) = .09$, $p = .769$, $\eta_p^2 = .003$, showing that the difference between target-matching and nonmatching colors was similar for negative and positive template cues. In the Bayesian repeated measures ANOVA, the best model with two main effects was 3.11 times more likely than the model with two main effects and the interaction. These results suggest that attentional templates were activated in both cases.

Conducting the same mixed ANOVA on choice errors confirmed these results. The main effect of spatial cue color, $F(1, 34) = 14.5$, $p < .01$, $\eta_p^2 = .299$, showed that there were cuing benefits with the target-matching color of the spatial cue (1.8%), but same location costs with the nonmatching color (−2.6%). Cuing effects were overall smaller with negative template cues in Experiment 3 than with positive template cues in Experiment 4 (−1.3% vs. .5%), $F(1,$ 34) = 6.07, $p = .02$, $\eta_p^2 = .151$. As for RTs, there was no interaction between template type and spatial cue color, $F(1, 34) = .07$, $p = .792$, $\eta_p^2 = .002$. In the Bayesian repeated measures ANOVA, the best model with one main effect was 4.00 times more likely than a model with two main effects and interaction.

In addition, we compared the individual average RTs between negative and positive template cues. RTs were longer with negative than positive template cues (579 vs. 474 ms), $t(34) = 7.68$, $p < .01$, Cohen's $d_s = 2.56$, confirming that guidance of visual search by negative attentional templates was less efficient than by positive attentional templates. In order to evaluate the difficulty of the search tasks comprehensively across Experiments 1–4, we conducted a 2 (template type: negative, positive) × 2 (search type: singleton, feature) between-participants ANOVA on individual average RTs. RTs were longer with negative than positive template cues (567 vs. 490 ms), $F(1, 74) = 80.07$, $p < .01$, $\eta_p^2 = .52$, mirroring the results of the individual t-tests reported above. While the main effect of search type did not reach significance, $F(1, 74) = .19$, $p = .66$, $\eta_p^2 = .003$, $BF_{10} < .01$, there was a significant interaction of template type and search type, $F(1, 74) = 11.10$, $p < .01$, $\eta_p^2 = .13$. With negative template cues, RTs tended to be shorter in singleton than feature search (Exp. 1 = 554 ms vs. Exp. 3 = 579 ms), $t(40) = 1.94$, $p = .06$, Cohen's $d_s = .61$, $BF_{10} = 1.33$, whereas with positive template cues, RTs were significantly longer in singleton than feature search (Exp. 2 = 506 ms vs. Exp. 4 = 474 ms), $t(34) = 2.92$, $p < .01$, Cohen's $d_s = .97$.

Discussion

We investigated the activation of negative and positive attentional templates in feature search. Because the target was not salient, it was necessary to use the template cue to perform the task. We found cuing benefits for spatial cues in the target-matching color and same location costs for spatial cues in the nonmatching color. Differences between target-matching and nonmatching colors were observed for negative and positive template cues, suggesting that participants activated attentional templates for a specific color in both cases. Because the magnitude of the difference between target-matching and nonmatching colors was similar, we conclude that the selectivity of negative and positive templates was comparable. However, cuing benefits were smaller (36 vs. 62 ms) and same location costs were larger (−48 vs. −18 ms) with negative compared to positive template cues. In particular, same location costs for the nonmatching (distractor) color increased with the negative template cue, suggesting that the negative attentional template resulted in inhibition of the respective color. Further, with negative template cues, cuing benefits for the target-matching cue color were reduced, but larger than zero. It is unlikely that participants had recoded the negative template cue into a positive attentional template as the choice of target and distractor colors was random. Rather, the cuing benefit for the target-matching color may result from an unselective attentional template for colored stimuli. In support of this idea, the size of the cuing benefit with target-matching colors was comparable in the experiments with negative template cues (Exp. 1 = 37 vs. Exp. 3 = 36 ms).

Further, there was little evidence that feature search in Experiments 3 and 4 was more difficult than singleton search in Experiments 1 and 2. With negative template cues, RTs were only 30 ms longer in feature than singleton search and this difference did not

reach significance. With positive template cues, there was a difference in the opposite direction. That is, RTs were shorter in feature than singleton search, which is unexpected as the selection of the targets in singleton search did not need an attentional template and could be based on saliency alone. However, a similar advantage of feature over singleton search has been reported in other search tasks (Barras & Kerzel, 2016).

General Discussion

Negative attentional templates may facilitate search by guiding attention away from nontarget stimuli. We investigated whether negative attentional templates can be set up in the contingent capture paradigm. Previous research faced the problem that the facilitation observed with negative template cues was open to alternative interpretations. For instance, participants may have recoded the location of stimuli in the negative template color into the location of potential target stimuli (Becker et al., 2016; Beck & Hollingworth, 2015). Another problem was that the use of negative color templates was optional as the primary search task concerned shape. Thus, use of negative templates was under strategic control (Beck & Hollingworth, 2015) and participants may have decided to use negative templates only when the task was difficult (Arita et al., 2012; Conci et al., 2019). We addressed these problems by employing the contingent capture paradigm. In the contingent capture paradigm, spatial cues precede the target, which avoids potential effects of color recoding at the onset of the search display. If participants activate an attentional template for the target color, then spatial cues in a target-matching color will result in cuing benefits, whereas spatial cues in nonmatching colors have either no effect or result in same location costs. Thus, the difference between target-matching and nonmatching colors allowed us to test for the activation of negative attentional templates. In Experiments 1 and 3, we compared target-matching and nonmatching colors when a negative template cue informed the participants about the color of nontarget/distractor stimuli. A difference between target-matching and nonmatching colors was only observed when use of the negative template cue was mandatory, but not when it was optional. Use of the template cue was optional in the singleton search task of Experiment 1 because the target could be located based on its saliency alone. In contrast, its use was mandatory in the feature search task of Experiment 3 because there were two colored stimuli of equal saliency and either the target or distractor color had to be known to locate the target. While the use of negative template cues depended on task requirements, the use of positive template cues did not. Differences between target-matching and nonmatching colors were observed in singleton search (Experiment 2) and in feature search (Experiment 4). It may appear that feature search was more difficult than singleton search, but RTs provide little evidence for this view. With negative attentional templates, there was only a small and unreliable difference in overall RTs, and with positive attentional templates, there was a difference in the wrong direction. Thus, the critical question is whether the use of negative attentional templates is mandatory and not whether the task is difficult. Possibly, difficult tasks strongly encourage the use of negative attentional templates, similar to their mandatory use, which may explain why effects of negative attentional templates are easier to find in difficult search tasks (Arita et al., 2012; Conci et al., 2019).

Relation to Search-And-Destroy Theory

In related research, it was proposed that facilitation of search by negative attentional templates, as observed originally by Arita et al. (2012), may be the result of extended practice. Search-and-destroy theory (Moher & Egeth, 2012) holds that stimuli in the color of the negative template cues are initially attended, which results in (RT) costs, before they can be avoided, which results in RT benefits. Evidence for the initial capture of attention is mixed. While results from a dot probe task (Moher & Egeth, 2012) and eye movement recordings (Beck et al., 2018) support the initial capture of attention, an electrophysiological marker of attentional selectivity, the N2pc component (Eimer, 1996; Luck & Hillyard, 1994), provided no evidence for attentional capture by stimuli in the color of the negative template cue (Berggren & Eimer, 2021; but see Donohue et al., 2018). Also, the behavioral effects of negative template cues were sometimes elusive (Stilwell & Vecera, 2019; Williams et al., 2020) unless the negative template cue was fixed in blocks of trials (Stilwell & Vecera, 2019). Consistently, search-and-destroy theory holds that negative attentional templates may only facilitate search after extensive practice with the same color (Cunningham & Egeth, 2016). However, the repeated exposure of stimuli in the negative cue color may result in passive habituation (Turatto et al., 2018; Won & Geng, 2020), which casts doubt on the voluntary use of negative attentional templates (see also Stilwell & Vecera, 2019). The results of the present study do not provide further evidence for search-and-destroy theory because we found that participants established negative attentional templates despite trial-to-trial changes of the negative template cue (similar to Arita et al., 2012; Conci et al., 2019; Reeder et al., 2017). In addition, search and destroy theory predicts cuing benefits with spatial cues in the color of the negative template cue because to-be-ignored stimuli are supposed to capture attention unless they are frequently repeated. However, we found cuing costs for spatial cues in the color of the negative template cue, which suggests that participants were able to inhibit the color of the negative template cue despite trial-to-trial changes. Again, the reason for this apparent discrepancy may be that the use of the negative attentional template in research on search-and-destroy theory was optional given that the primary task was to find one of two target letters.

Caveats

In our experiments, displays with the template cue, the spatial cue, and the target contained colored stimuli. Therefore, it may be possible that color priming occurred between successive displays (e.g., Ásgeirsson & Kristjánsson, 2011; Maljkovic & Nakayama, 1994). However, investigations of intertrial transitions have provided little evidence for effects of color priming in the contingent capture paradigm (Goller & Ansorge, 2015; Schoeberl et al., 2019). The major argument against a role of priming in the current experiments is that color priming was similar in Experiments 1 and 3 because the colors were identical, yet the results differed strongly. Thus, color priming played only a minor role. Another issue concerns the timing of the template cue in the current study, which was unusually short. Tanda and Kawahara (2019) argued that the template cue needs to lead the search display by more than 2,400 ms to allow for the creation of negative templates. However, their study did no provide a direct comparison between different time intervals.

Tanda and Kawahara only noted that the effect of the negative template cue was not significant with 1,000 ms cue lead time, whereas it was significant with 2,400 ms cue lead time. More robust evidence is required to conclude that cue lead time has to be this long. In particular, the creation of positive templates only requires about 200 ms (Vickery et al., 2005; Wolfe et al., 2004). It is therefore surprising that negative templates would require more than 10 times as much time. The cue lead time of 500 ms used in the current study appears more plausible. However, more research on this topic is required. Finally, the current study has provided evidence for the activation of negative templates, but it did not provide evidence that negative template cues facilitated search. The reason for this limitation is that our main dependent variable was the difference between cued and uncued target locations, which indicates whether target or nontarget features were activated or inhibited in a spatially global manner (Eimer, 2014; Leonard et al., 2015). In contrast, our experiments were not designed to measure search times per se. For instance, the number of stimuli in the search display was small and we did not include a neutral template cue without information about target or nontarget features. Previous research compared neutral to negative template cues to evaluate whether search was facilitated (see Carlisle, 2019). Thus, we conclude that negative templates were activated, but we cannot conclude that this activation facilitated search.

Underlying Mechanism

We found that differences between target-matching and nonmatching cue colors were similar with negative and positive attentional templates in features search. In addition, cuing effects were reduced with negative template cues. What are the mechanisms explaining these results? Major theories of visual attention have proposed multiple mechanisms underlying the enhanced processing of attended stimuli (e.g., sensory enhancement or noise reduction, for review see Carrasco, 2011), but less is known about how inhibition of nontarget stimuli is achieved. One recent proposition was that processing of salient nontarget stimuli is suppressed below the baseline processing of inconspicuous nontarget stimuli (Gaspelin et al., 2015). While there is some support for attentional suppression from single-cell recordings (Cosman et al., 2018), behavioral and electrophysiological evidence is ambiguous (Kerzel et al., 2021). For instance, Gaspelin et al. (2015) interleaved a letter identification task with a variant of the additional singleton paradigm and observed that letter identification was worse at the location of the salient distractor compared to inconspicuous nontargets. Because search performance in this variant of the additional singleton paradigm was better in the presence than in the absence of the salient distractor, Gaspelin et al., concluded that the suppression of the salient distractor below baseline accounted for the improved search performance. However, Lien et al. (2021) observed that below-baseline performance in the search task occurred even for nonsalient nontargets, which contradicts the idea that the effect arises from suppression of salient distractor stimuli. Further, it was proposed that an electrophysiological component associated with attentional suppression, the P_D component (Hickey et al., 2009), occurred in response to a salient distractor that was successfully suppressed (Gaspelin & Luck, 2018). However, closer examination revealed that the P_D was followed by an electrophysiological marker of attentional selection, the N2pc component, which is incompatible with the idea that the distractor was successfully suppressed (Kerzel & Burra, 2020; but see Drisdelle & Eimer, 2021).

While the discussion about attentional suppression is ongoing, electrophysiological investigations using the contingent capture paradigm have measured responses to both the cue and the target display. In both cases, there was little evidence for attentional suppression. Event-related responses to the cue display showed that spatial cues in the target-matching color elicit an N2pc, suggesting that attention was deployed to the cue, whereas there was no N2pc to spatial cues in the nonmatching color (Eimer & Kiss, 2008; Lien et al., 2008, 2010). Concerning search tasks where nonmatching spatial cues produced same-location costs, recent studies found no evidence for attentional suppression of the cue as indexed by a P_D (Kerzel & Huynh Cong, 2021; Schönhammer et al., 2020). Thus, the worse performance at the cued location (i.e., same-location costs) was not caused by attentional suppression of the spatial cue. Rather, Kerzel and Huynh Cong (2021) found that spatial cues resulting in same-location costs reduced subsequent signal enhancement for stimuli at the cued location. Signal enhancement at the cued location is indexed by the CP component (Livingstone et al., 2017). In search tasks resulting in same-location costs, the CP was reduced at the location of nonmatching compared to target-matching spatial cues. Thus, same-location costs resulted primarily from changes in the processing of the search display, notably from the reduced enhancement of stimuli at the cued location.

Applied to negative attentional templates in the current experiments, we suggest that two distinct and successive processes may underlie attentional selectivity with negative attentional templates in Experiment 3. First, participants may have searched for color singletons in an unselective manner, which resulted in attentional selection of spatial cues in both the target-matching and nonmatching color. Thus, unselective deployment of attention to spatial cues may explain why there were cuing benefits with spatial cues in the target-matching color. It is unlikely that these cuing benefits resulted from template-guided selection of the target-matching spatial cue because the target color was unknown. Second, negative templates may have changed processing of the subsequent target display. That is, signal enhancement at the cued location may have been selectively inhibited if the spatial cue was in the color of the negative template. The inhibition of signal enhancement may explain why there were pronounced same location costs for nonmatching spatial cues with negative templates (see also Kerzel & Huynh Cong, 2021). Thus, we suggest that negative templates are implemented as a two-stage process where spatial cues are initially attended independently of their color, but subsequent inhibition reduces the signal enhancement at the location of spatial cues in the color of the negative template. The separation between initial capture and subsequent enhancement is similar to the idea that attention is initially captured and only in some conditions engaged (Zivony & Lamy, 2018). While further electrophysiological work is necessary to validate these ideas, our main conclusion remains that differences between target-matching and nonmatching spatial cues show that negative attentional templates can be activated when needed.

Object Updating and Same Location Costs

While we refer to reduced signal enhancement to explain the same-location costs with negative template cues, same-location

costs were also observed with positive template cues in Experiment 4. We think that reductions of signal enhancement account for both occurrences of same-location costs. However, other accounts have been proposed. Initially, same-location costs were attributed to inhibition of nonmatching or nontarget colors (Eimer & Kiss, 2010; Lamy et al., 2004). It is assumed that inhibition can only be applied if the nontarget color is known beforehand. However, same location costs also occurred when the colors changed randomly and were not known before onset of the search display (Carmel & Lamy, 2014). As an alternative to inhibition, it was proposed that same location costs arise from object updating. In this account, spatial cue and target are part of the same object file (Carmel & Lamy, 2014, 2015). On valid trials with target-matching spatial cues, cue and target are the same color, which yields a continuous object. On valid trials with nonmatching spatial cues, however, the color changes between spatial cue and target. The necessary updating of the object file may take time and explain why RTs were longer on valid than invalid trials (see also Büsel et al., 2021; Schoeberl et al., 2020). Importantly, the object-updating account reflects bottom-up characteristics of the stimulus. However, we find increased same-location costs resulting from changes in the instruction. Same location costs were more pronounced with a negative compared to a positive template cue. As the template cue was shown 500 ms before in the center of the display, it is unlikely that it changed the perceptual characteristics of the cue-target display (i.e., the object files). Rather, the task requirements affected same location costs. Nonetheless, a contribution of object-file updating to same-location costs cannot be ruled out.

Conclusions

We investigated the use of negative attentional templates in the contingent capture paradigm. Negative attentional templates indicate the color of nontarget or distractor stimuli and it is debated whether they can be activated. One problem of previous research was that use of negative color templates was optional because the primary search task was based on shape. Here, we used the contingent capture paradigm to assess whether negative attentional templates can be activated to guide visual search. We found no evidence for the activation of negative attentional templates when their use was optional (singleton search). When use of the negative attentional template was mandatory (feature search), however, we found strong evidence that participants activated a negative attentional template. We propose that negative attentional templates are implemented by two successive processes. Participants may initially search for any colored stimulus and then inhibit the usual enhancement of signals at the location of the spatial cue. Our results clarify that inconsistencies in the previous literature may be due to task requirements. Easy tasks with optional use of negative template cues may result in little support for negative attentional templates, whereas difficult tasks where use of the negative attentional template acquires a mandatory character may provide more robust support.

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