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The allocation of resources in visual working memory and multiple attentional templates

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Abstract

In a visual search task, sensory input is matched to a representation of the search target in visual working memory (VWM). This representation is referred to as attentional template. We investigated the conditions that allow for more than a single attentional template. The attentional template of color targets was measured by means of the contingent attentional capture paradigm. We found that attentional templates did not differ between search with one and two memorized target colors, suggesting that dual target search allowed for multiple attentional templates. In the same paradigm, we asked participants to memorize target and distractor color with equal precision. Both were presented before the search task. An attentional template was set up for the target, but not for the distractor color, suggesting that keeping a color in VWM does not automatically result in the creation of multiple attentional templates. Importantly, the precision of recall of the distractor color was worse than the precision of recall of the target color, regardless of instructions, suggesting that participants always allocated fewer VWM resources to the distractor color. Thus, two attentional templates may be set up, but only when the two colors receive an equal amount of resources in VWM (i.e., in dual target search). In contrast, when one item is deprioritized because of task demands, it receives fewer resources in VWM and multiple attentional templates cannot be established. Thus, unequal roles in the search task prevented the simultaneous operation of multiple attentional templates in VWM.

Keywords

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

Public Significance Statement

The present study investigated basic cognitive mechanisms underlying visual search. In visual search tasks, features of the target object are matched to the visual input that arrives in our eyes. Target features are stored in working memory. In everyday life, we often search for more than a single object. For instance, we may look for the car key and the phone when we leave for work. To understand how this activity is carried out, we need to determine whether search is performed simultaneously for the two target objects, or whether we are only looking for a single object at a time. The latter possibility would show that the number of items we can search for is far smaller than the number of items that we can keep in working memory.

Introduction

Searching for an object is a frequent activity and it is common to search for more than one object at a time. The internal representation needed to guide search is referred to as attentional template (e.g., Duncan & Humphreys, 1989) or attentional control set (e.g., Folk, Remington, & Johnston, 1992). It is generally assumed that attentional templates are stored in visual working memory (VWM) and interact with perception to match visual input to a stored representation of the target. While the capacity of VWM was estimated to be on the order of four (Cowan, 2001; Luck & Vogel, 1997), there is no agreement on the number of attentional templates in VWM that can simultaneously guide search. We will describe two lines of research that arrive at different conclusions with respect to the maximal number of simultaneously active attentional templates. We suggest that differences in the allocation of resources to items held in VWM may explain the divergent results.

Dual-task paradigms: Memory-based interference from only one item

Olivers, Peters, Houtkamp, and Roelfsema (2011) proposed that only a single item from VWM can act as attentional template. The main evidence for the one-template hypothesis comes from dual task paradigms where observers were asked to maintain one stimulus in VWM while performing a search task for another stimulus. In some studies, the search task was a variant of the additional singleton paradigm by Theeuwes (1991) where participants searched for a shape target and on some trials, a color distractor was shown. Typically, reaction times (RTs) increase on distractor-present compared to distractor-absent trials, suggesting that the color distractor captured attention (for controversial discussion of this conclusion, see Awh, Belopolsky, & Theeuwes, 2012; Gaspelin & Luck, 2018; Lamy, Leber, & Egeth, 2012). The critical manipulation concerned the relation between the color of the distractor in the search task and the color stored in VWM. Interference from the color distractor was stronger when its color corresponded to the stimulus held in VWM than when its color was unrelated, a phenomenon referred to as memory-based interference. Memory-based interference suggests that contents of working memory are automatically used as attentional template. Initially, findings from experiments using this logic were inconsistent. Some studies reported memory-based interference (e.g., Olivers, Meijer, & Theeuwes, 2006) while others did not (e.g., Woodman & Luck, 2007). Studies using shape instead of color distractors were equally inconclusive, with some (e.g., Kim & Cho, 2016; Soto, Heinke, Humphreys, & Blanco, 2005), but not all (Downing & Dodds, 2004; Houtkamp & Roelfsema, 2006) reporting memory-based interference. A possible explanation for the discrepancy was offered by Olivers (2009), who observed that most studies reporting memory-based interference used fixed targets for the search task, while the others used search targets that changed from trial to trial.

A fixed target does not require updating of the target features on every trial, but it is not necessarily the same target on every trial. For instance, the fixed target in Olivers’ (2009) Experiment 5 was a shape different from all the non-targets (a singleton). Therefore, it was not necessary to store a specific shape in VWM even though the shape was not always the same. In contrast, the variable target in Olivers’ (2009) Experiment 5 was a color that changed on every trial and had to be memorized because the search display contained several colors. Fixed and variable target conditions had in common that an additional color was memorized, which is referred to as memorized color. However, only the potential distractor color was maintained in VWM in the fixed target condition, whereas target and potential distractor color were stored in VWM in the variable target condition. The question was whether a distractor in the memorized color would capture attention more than a distractor in an unrelated color. The results showed that stronger interference only occurred with fixed, but not with variable targets, suggesting that only one item in working memory can act as an attentional template. Possibly, fixed targets did not occupy space in VWM (see Carlisle, Arita, Pardo, & Woodman, 2011), allowing the memorized distractor color to play the role of attentional template. In contrast, variable targets were stored in VWM together with the memorized distractor color, relegating the memorized distractor color to the status of "accessory". According to Olivers et al. (2011), only a single item in VWM can interact with perception, whereas accessory items are stored in VWM, but do not interact with perception.

The one-template hypothesis predicts larger memory-based interference with one compared to two or more memorized colors. The reason is that a single color in VWM will automatically function as attentional template and cause memory-based interference. In contrast, when several items are maintained in VWM, none of them interacts with search. Consistent with this hypothesis, van Moorselaar, Theeuwes, and Olivers (2014) observed that memory-based interference was larger with one memorized color than with two or more. However, Hollingworth and Beck (2016) investigated search displays with two distractor colors and found that interference was larger when two distractor colors matched the memorized colors compared to only one matching color, which is consistent with the simultaneous guidance of attention by multiple VWM representations.

Dual-target search: Equal search efficiency with one and two memorized targets

While the first line of research employed dual-task paradigms (i.e., search plus memory task) and presents mixed evidence for the one-template hypothesis, the second line of research focused on multiple target search and provides solid evidence against it. The idea was to show that guidance of attention was as efficient with one as with several memorized targets. In this context, the contingent attentional capture paradigm by Folk et al. (1992) proved useful because it allows to directly measure the attentional template. In the contingent capture paradigm, participants were presented with a cue and a target display in rapid succession. Stimuli in the cue display were irrelevant, whereas stimuli in the target display required a response. In valid trials, the cue preceded the target at the same location, whereas cue and target were presented at separate locations in invalid trials. Shorter RTs on valid than invalid trials are referred to as cueing effect and suggest that attention was captured by the cue. Folk et al. (1992) showed that cueing effects are only observed when cue and target properties match. For instance, cueing effects occurred with a red cue when participants searched for a red target, but not when participants searched for a green target (Folk & Remington, 1998), suggesting that participants had established an attentional template for red that would guide attention to red cues, but not to green cues. Thus, cueing effects in the contingent capture paradigm only arise when the cue corresponds to the attentional template. Cueing effects therefore reflect features of the attentional set.

Irons, Folk, and Remington (2012) investigated whether participants can establish more than a single attentional template in the contingent capture paradigm (see also Ansorge & Horstmann, 2007; Ansorge, Horstmann, & Carbone, 2005; Worschech & Ansorge, 2012). In their experiments, participants searched for two memorized colors at the same time (for work using eye tracking, see Beck, Hollingworth, & Luck, 2012; Ort, Fahrenfort, & Olivers, 2017). Because cueing effects were observed for the two memorized target colors but not for an unrelated color, it was concluded that two attentional templates could simultaneously guide search. A conclusion that was corroborated by Grubert and Eimer (2016) who showed that the cueing effects did not differ between one and two memorized target colors. Despite the evidence in favor of multiple attentional templates (for evidence from RSVP tasks, see Moore & Weissman, 2010; Roper & Vecera, 2012), there are also doubts. For instance, Grubert and Eimer (2016) found that an electrophysiological measure of attentional selection, the N2pc, revealed attentional capture by unrelated cue colors that was not visible in behavioral measures. In a similar vein, Biderman, Biderman, Zivony, and Lamy (2017) observed that search for multiple features from different dimensions (i.e., one memorized color and one memorized shape target) was less efficient than search for a single feature, which contrasts with the equal efficiency of search for features from the same dimension (i.e., two memorized color targets).

The review of the literature above suggests that there is no clear answer to the question whether one or more attentional templates can guide search. Overall, there is some evidence that the number of attentional templates is limited to one in studies using dual task paradigms. In contrast, there seems less evidence for a restriction to only one target in studies using dual-target search. How can this apparent contradiction be solved? A solution to the conundrum is made difficult by the methodological differences between the two lines of research. Some research on memory-based interference avoided dimensional overlap between the memorized stimulus and the target stimulus (Kim & Cho, 2016; Olivers et al., 2006; Soto et al., 2005; Woodman & Luck, 2007) to prevent voluntary shifts of attention to the memorized stimulus. Notably, participants may attend to the memorized stimulus when it appears as a distractor in the search display to refresh VWM (Woodman & Luck, 2007). In other studies on memory-based interference, search target and memory item were drawn from the same perceptual dimension, either shape (Downing & Dodds, 2004; Houtkamp & Roelfsema, 2006) or color (Exp. 5 in Olivers, 2009). In contrast, research on dual target search in the contingent capture paradigm focused on two targets defined along the same dimension (Grubert & Eimer, 2016; Irons et al., 2012; Moore & Weissman, 2010; Roper

& Vecera, 2012), with one exception (Biderman et al., 2017). The idea of dimensional attention (Krummenacher, Müller, & Heller, 2002; Müller, Heller, & Ziegler, 1995) suggests that search is more efficient within than between perceptual dimensions, so that it matters whether the two targets are defined on the same or on different dimensions.

VWM resources and the attentional template

While these methodological issues are unresolved, we think that there are also theoretical issues regarding the nature of the attentional template and the remaining content of VWM. According to Olivers et al. (2011), VWM may contain up to four items and the attentional template is the VWM representation that interacts with perception. Although it is not explicitly stated, this approach seems most consistent with the notion that VWM has about four equal slots that store information with equal precision (Luck & Vogel, 1997; Luck & Vogel, 2013). Thus, the precision of the attentional template would be about the same as the precision of the accessory items, the only difference being that the attentional template interacts with perception whereas the accessory items do not. An alternative to slot-models posits that VWM is better conceptualized as a limited resource that can be flexibly allocated to items stored in VWM (Bays & Husain, 2008; Ma, Husain, & Bays, 2014). While the debate between proponents of these accounts is difficult to resolve because slot models may be modified to behave like resource models (Zhang & Luck, 2008), we nonetheless formulate our hypothesis with regard to resource models, mainly for ease of exposition. In particular, we suggest that differences in the VWM resources allocated to the attentional template and the accessory items may have been neglected. For instance, it seems reasonable to assume that more VWM resources were allocated to the searched-for target color in Olivers' (2009) Experiment 5 than to the memorized distractor color. Possibly, the implementation of a color as a search target is even realized as the larger allocation of resources in VWM. In contrast, there is no reason for unequal allocation of VWM resources to two equally frequent targets in dual target search. Thus, the unequal distribution of VWM resources may account for failures to observe memory-based interference in dual task paradigms, whereas the equal distribution of VWM resources may account for successful dual target search. We refer to this idea as the resource hypothesis.

To date, no evidence for the resource hypothesis is available because dual task paradigms only measured memory performance for the accessory item to ensure that participants followed the instruction to keep the item in VWM. However, it is necessary to measure the precision of VWM for the target and the accessory item to assess the resource hypothesis.

Overview of present study

Given the inconsistent literature, a portion of the present paper is devoted to empirical clarifications. First, we checked whether evidence for multiple attentional templates in the contingent capture paradigm extends to target colors that have to be stored in VWM. In previous studies, participants memorized two possible target colors that did not change across trials (i.e., fixed targets; Grubert & Eimer, 2016; Irons et al., 2012; Moore & Weissman, 2010), which allows for storage in long-term memory (see Carlisle et al., 2011). To force storage in VWM, Experiment 1 compared single and dual-target search with memorized target colors that changed from trial to trial (i.e., variable targets). Note that the target color in the search display may change randomly from trial to trial regardless of whether the memorized target was fixed or variable, because "fixed" and "variable" refers to the memorized, not the actual target color. For instance, participants may search for red and green throughout the experiment (i.e., fixed targets) or they may search for red and green on one trial, and for blue and yellow on the next (i.e., variable targets). In both cases, the color of the target in the search display may vary unpredictably (e.g., between red and green). To clarify why there was no memory-based interference with variable targets in previous studies, we asked observers to memorize the target color and the distractor color in Experiment 2. Asking participants to recall both the target and the distractor color at the end of the trial allowed us to evaluate the resource hypothesis. In Experiment 3, we addressed the alternative hypothesis that memory-based interference with variable targets was absent because memory and search targets were defined along the same dimension.

Experiment 1: Dual vs. single target search

In a variant of the contingent capture paradigm by Folk et al. (1992), observers were asked to search for a color target. To make sure that participants searched for a specific color, another letter in the target display was also colored, resulting in feature search. The memorized target colors varied unpredictably from trial to trial. In separate blocks of trials, participants memorized only a single target color (single target search) or two target colors (dual target search). We always presented two colors in the memory display at the start of the trial to assure equal stimulation (see Figure 1B). For single target search, a central letter designated the target color. To avoid spatial biases, the two colors were presented in a circular array. After a delay, the cue and target displays were shown in rapid succession. Observers were asked to indicate the orientation of the letter T in the memorized target color while ignoring the cue display. Critically, the cue color corresponded to a memorized target color on some trials but was unrelated to the memorized color(s) on other trials.

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Methods

Participants. In a previous study, we found cueing effects in a relevant color to be 87-99 ms larger than cueing effects in a neutral (irrelevant) color (Exp. 2 and Exp. 3 in Barras &

Kerzel, 2016). The partial etasquare of the respective 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. In the present experiment, ten undergraduate psychology students participated for class credit (1 man, age: *M* = 20.1 years, *SD* = 1.4). All reported normal or corrected-to-normal vision. The study was approved by the ethics committee of the Faculty of Psychology and Educational Sciences and was carried out in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki). Informed consent was given before the experiment started.

Apparatus. Stimuli were displayed on a 21-inch CRT monitor with a refresh rate of 85 Hz and a pixel resolution of 1,280 × 1,024 (horizontal × vertical), driven by an ATI Radeon HD 3450 graphics card with a colour resolution of eight bits per channel. CIE1931 chromaticity coordinates and luminance (xyY) of the monitor primaries were R = [0.63, 0.34, 18.5], G = [0.29, 0.61, 60.9], and B = [0.15, 0.07, 9.9]. Gamma corrections were applied based on the measured gamma curves of the monitor primaries. Observers viewed the screen at a distance of 70 cm. Head position was stabilized with a chin/forehead rest.

Stimuli. There was a memory, a placeholder, a cue, and a target display. The memory display consisted of a colored disk (radius of 0.6°) surrounded by a colored ring (radius of 1.2°). The placeholder display was composed of a central fixation cross (0.6° diameter) 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 1.1° and 1.4°, respectively. The linewidth was 1 pixel or 0.03°. 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 horizontal bar making up the rotated

T was 1° horizontally and vertically. The bars were 0.3° thick. Two of the Ts (target and distractor) were colored. The other letters were achromatic.

The colors were defined in CIELAB space because CIELAB is a model of colour appearance where distances approximate perceived colour differences (Fairchild, 2005). CIELAB consists of one achromatic and two chromatic axes, namely perceived lightness L*, a green-red dimension a* and a blue-yellow dimension b*. The polar coordinates of the chromatic axes (a* and b*) correspond to hue (azimuth) and chroma (radius). Hue indicates how reddish, yellowish, greenish and bluish a colour is, and chroma is a measure of perceived colorfulness (difference from grey).

The white-point of CIELAB was xyY = [0.29, 0.30, 89.27], which defines the chromatic adaptation and the maximum lightness. Stimuli were presented on an achromatic background with the chromaticities of the white-point and a lightness of L* = 55, which corresponds to a luminance of 20.5 cd/m^2. The placeholders, the achromatic cues and letters were light gray (L* = 73 or 40.3 cd/m^2). The three colors that served as cue, target and distractor colors were sampled along an isoluminant hue circle at a lightness of L* = 73. The colors had a chroma of 34. The three colors had a hue difference of 120° and were randomly determined on each trial (cf. Figure 1A). The randomisation made sure that long-term memory could not contribute to target identification and cuing effects. The large hue difference of 120° was clearly discriminable. That is, hue differences were far above hue discrimination thresholds and the three colours belonged into different categories (cf. Figure 9 in Witzel & Gegenfurtner, 2013). This way, our stimulus design avoided capture based on color similarity (Ansorge & Becker, 2014) and search biases resulting from color similarity and category membership (e.g., D'Zmura, 1991; Daoutis, Pilling, & Davies, 2006; Witzel & Gegenfurtner, 2015, 2016).

In single target search, selection of the memorized color was accomplished by presenting the letter C or P (height of 0.31°) in the center of the memory display. The letter indicated that the to-be-memorized color was shown on the central disk (“C”) or on the peripheral ring (“P”). The letter varied randomly from trial to trial. In dual target search, both colors in the memory display had to be memorized.

Design. The conditions with one or two memorized target colors were performed on different days. The order of conditions was counter-balanced across participants. Regardless of the number of memorized target colors, we randomly selected three different colors on each trial. Two of those colors appeared simultaneously in the memory display and presentation of any of the three colors in the cue display was equally likely. The cue was a color singleton, whereas the target was shown together with a colored distractor to force feature search.

The 192 combinations of 4 cue positions, 4 target positions, 3 cue colors, 2 responses (left, right) and an additional factor with 2 levels were shown once in a block of trials. The additional factor depended on the number of targets. With one memorized target color, the additional factor determined whether the distractor color in the search display was the unrelated color from the memory display or the third color. With two memorized target colors, the additional factor determined which of the two potential target colors was shown. In this case, the distractor color in the search display was always the third color. For each number of search targets, four blocks were run, resulting in overall 1536 trials.

Procedure. A trial started with the presentation of the fixation cross for 1 s. Then, the memory display was shown for 306 ms. The memory display was followed by a blank screen for 706 ms. Then, the fixation cross reappeared together with the unfilled placeholder rings. After another 706 ms, the cue stimuli were shown for 47 ms, followed by the unfilled placeholders for 106 ms and the target stimuli for 47 ms. The resulting cue-target SOA was 153 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.

Participants started the experiment by practicing the task until they felt comfortable with it, but at least for 20 trials. Visual feedback informed participants about choice errors, anticipations (RTs < 0.2 s, which were extremely rare and will not be reported) and late trials (RTs > 1 s). Every 48 trials, visual feedback about the percentage of correct responses and the median RTs were displayed for 10 s, forcing participants to take a short break.

Results

Separate analyses of RTs and error rates showed that cueing effects were sometimes more pronounced in error rates than in RTs. Also, there were signs of speed-accuracy tradeoffs in some conditions because effects were opposite in RTs and errors. Possibly, the multi-event trial sequence favored responses at a fixed rhythm, which shifted the effects from RTs to errors in some conditions. It should be noted that there was no general speed-accuracy tradeoff because RTs and errors were in the same direction in most cases (see supplementary Table 1). To adequately mirror performance and to remove occasional effects of speed-accuracy tradeoff, we used inverse efficiency scores (IES). IES were calculated as RT / (1-PE), where PE is the proportion of choice errors (Townsend & Ashby, 1978). Similar to RTs, high IES indicate poor performance and low IES indicate good performance. For better readability, IES will be referred to as **corrected RTs** because the scores reflect RTs corrected by the proportion of errors. For instance, when the three-way ANOVA reported below was carried out separately on RTs and error rates, significant three-way interactions emerged, but these interactions were in opposite directions. Inspection of supplementary Table 1 shows that the cueing effect with two targets was smaller than with one target when RTs were considered (37 vs. 73 ms), whereas the opposite was true for percentage of choice errors (9.5% vs. 3.0%). When corrected RTs were computed, the three-way interaction disappeared, showing that it was due to speed-accuracy tradeoff in these conditions. As suggested by Lakens (2013, p. 4), we used the standard deviation of the difference to compute Cohen's *d* for the difference between means.

We considered trials not meeting the online criterion of 1 s as late and excluded these trials (1.7%) from analysis. Next, the data for each participant and condition were trimmed by removing trials with corrected RTs that were further than 2.5 standard deviations away from the respective condition mean, which amounted to 2.3% of the trials. Mean corrected RTs are shown in Figure 2. Overall, the percentage of choice errors was 1.1% (see supplementary Table 1).

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Corrected RTs. We conducted a 2 (number of memorized target colors: one, two) × 2 (cue color: matching or non-matching with respect to the memorized target colors) × 2 (cue validity: valid, invalid) repeated-measures ANOVA on the individual mean corrected RTs. Corrected RTs were shorter with one compared to two target colors (525 vs. 631 ms), *F*(1, 9) = 18.59, *p* = .002, η_p^2 = .67. The two-way interaction of cue color and validity, *F*(1, 9) = 25.85, *p* = .001, η_p^2 = .74, modulated the main effects of cue color, *F*(1, 9) = 10.51, *p* = .01, η_p^2 = .54, and cue validity, *F*(1, 9) = 17.76 *p* = .002, η_p^2 = .66. The interaction showed that valid cues led to shorter corrected RTs than invalid cues when the cue matched the memorized target color (105 ms cueing effect, 508 vs. 613 ms), *t*(9) = 6.74, *p* < .001, Cohen's *d* = 2.13, but not when the cue did not match the memorized target color (-23 ms cueing effect, 606 vs. 583 ms), *p* = .19. The absence of a three-way interaction, *p* = .58, favors the conclusion that the match of cue and target color had the same effect with one as with two memorized target colors. To further strengthen this conclusion, we compared the cueing effects with one and two memorized target colors. For matching cues, cueing effects did not differ between one and two memorized target colors (94 vs. 115 ms), *t*(10) = 1.45, *p* = .18. Similarly, there was no difference between one and two memorized target colors for non-matching cues (-27 vs. -19), *t*(10) = 0.47, *p* = .651.

Effects of color repetition. To rule out that repetition of colors between the memory, cue and target display affected cueing effects, we ran separate ANOVAs for single and dual target search. Because there was variability of the distractor color with one memorized target color, but variability of the target color with two memorized target colors, color repetitions between cue and search display differed as a function of the number of targets and separate analyses were necessary. To preview the results, none of these analyzes showed that cueing effects were modulated by color repetition.

In dual target search, the color of a cue in one of the two memorized target colors was repeated as the target color on half of the trials. On the other half of trials, the other memorized target color was shown, resulting in a change between cue and target color. In both cases, the cues were matching with respect to the memorized target colors. To evaluate effects of color repetition, individual mean corrected RTs with memory-matching cues were entered into a 2 (cue color: repetition or change in target display) × 2 (cue validity: valid, invalid) ANOVA. We confirmed the main effect of cue validity (121 ms cueing effect, 554 vs. 675 ms), *F*(1, 9) = 41.02, *p* < .001, η_p^2 = .82. Additionally, corrected RTs were

125 ms shorter when the cue color was repeated as target color than when it changed (552 vs. 677 ms), *F*(1, 9) = 73.12, $p < .001$, $\eta_p^2 = .89$. However, there was no interaction, $p = .457$, showing that the deployment of attention to cues matching one of the two possible target colors did not depend on the repetition of the cue color in the target display. These results replicate Irons et al. (2012) who also provide several possible explanations (p. 772). For instance, it may be possible that the cue shifts the corresponding attentional control set into the focus of working memory (Büsel, Pomper, & Ansorge, 2018; Moore & Weissman, 2010). However, there was no evidence that the activated set facilitated attentional guidance because cueing effects did not differ between repetitions and changes of the memory-matching color. Alternatively, shorter RTs with color repetitions may result from priming by the cue color, which facilitates the subsequent access to the same target color in working memory. Yet another account states that color repetition increased participants' confidence in judgments about the target color. Whatever the exact cause, for our present purposes, it is sufficient to conclude that color repetition did not affect attentional guidance. This conclusion is in line with electrophysiological evidence by Grubert and Eimer (2016), who showed that the cue-elicited N2pc was the same in single and dual target search. In their study, the target color on matching trials always repeated the cue color in single target search, whereas this was only the case on half of the trials in dual target search. Nonetheless, the amplitude of the N2pc was the same.

In single target search, an unrelated color was presented in the memory display in addition to the to-be-memorized target color. The unrelated color could reappear in the cue display and could also be shown as a distractor in the target display. However, it was also possible that the third possible color (which was not presented in the memory display) was shown as cue or distractor. To check whether performance with non-matching cues was affected by color repetitions, we entered individual mean corrected RTs into a 2 (novelty of non-matching cue color: already presented in memory display, new in cue display) × 2 (distractor color in search display: repetition of cue color, change from cue color) × 2 (cue validity: valid, invalid). Only the effect of cue validity was significant, $F(1, 9) = 6$, $p = .037$, $\eta_p^2 = .4$, indicating longer RTs at cued than at uncued locations (-29 ms cueing effect, 551 vs 522 ms). Note that the negative cueing effect was not significant when single and dual target search were combined (see above). None of the other effects were significant, *p*s > .17, suggesting that priming or other mechanisms related to color repetition did not play a role.

Discussion

We found that cueing effects were unaffected by the number of memorized target colors. Colors that matched the attentional template resulted in cueing effects, whereas unrelated colors did not. The size of the cueing effects was similar for one and two memorized target colors. Our results provide further support for the simultaneous control of attention by multiple attentional templates (for concerns about the reliability of this finding, see Biderman et al., 2017) and rule out the possibility that target representations were offloaded from VWM to long-term memory (e.g., Carlisle et al., 2011). Because the memorized target colors changed randomly from trial to trial, participants had to load VWM on each trial. In previous studies, it was possible to offload target representations into long-term memory because the memorized target colors did not change across trials (Grubert & Eimer, 2016; Irons et al., 2012; Moore & Weissman, 2010) or only few colors were used (Roper & Vecera, 2012). Finally, there was an increase in RTs with two compared to one memorized target color. Because the cueing effects were unchanged with two memorized target colors, the cause for the overall slowing is most likely post-perceptual and not related to the attentional template. Possibly, it takes more time to match the selected input to two internal representations compared to only one (Sternberg, 1969) and the order of memory scanning may be influenced by the first-seen color. That is, shorter RTs with repetition of the cue color in the target display would result from a bias to start scanning of VWM with the cue color.

Experiment 2: Precision of color memory

Having established that attentional guidance in dual-target search is as efficient as in single-target search, we turn to the experiments using a dual task paradigm. We presented two colors in the memory display and asked observers to retain both (see Figure 1C). However, one color was the designated target color, whereas the other was the distractor color. Using the accessory color as distractor color in the search display prevented participants from searching for both colors. The key hypothesis concerned the memory performance for the target and the distractor color. According to the resource hypothesis, most VWM resources are attributed to the search target. If this was true, color judgments of the target color should always be more precise than judgments of the memorized distractor color, regardless of participants' intentions. To test for intentional control, we manipulated the type of feedback and the priority of target or distractor recall in a between-subjects design (see Table 1). While it may be possible to decrease the advantage of the target representation with better feedback and more attention to distractor judgments, the resource hypothesis predicts that it should be impossible to achieve equal or even better precision for the distractor. We had no specific predictions regarding feedback and instructions other than that better feedback and stronger incentives to pay attention to the distractor may decrease the predicted difference between target and distractor.

Methods

Participants and procedure. Fifty-two students from the same pool as above participated, resulting in about 12 participants per group. Regarding the power analysis, there were two aspects to consider. First, we tested for cueing benefits for the memorized distractor color. Because participants always had to memorize the distractor color, we may collapse across groups. With fifty-two participants, effect sizes of Cohen's *d* = 0.39 would become significant (alpha = .05, power = .8). The cueing effect in the potential target color in Experiment 1 had a Cohen's *d* of 2.13. Second, we predicted differences between target and distractor color regarding memory performance. Again, data from all groups may be collapsed to test for this difference. However, we were also interested in whether the predicted effect would disappear in any of the groups. Because the effect size of the difference in memory performance is not known, we cannot compute the sample size necessary to find a significant interaction between group and recalled stimulus (distractor or target). More important for the resource hypothesis, we conducted separate t-tests for each group to check whether the predicted difference was signficant. In this case, small sample sizes work against our hypothesis.

The apparatus, procedure and design were as in Experiment 1 with the following exceptions. On each trial, a memory and a search task were performed. In the memory task, participants were asked to retain both colors from the memory display and to recall the two colors at the end of the trial. Participants were told to be as precise as possible and that there was no time pressure for the color judgments. In the search task, participants were asked to respond as rapidly as possible to the designated target color in the search display. The target color was designated by the central disk for half of the observers and by the peripheral ring for the other half.

After a response in the search task was registered, a blank interval of 706 ms elapsed. If a response in the search task was late (RTs > 1 s) or incorrect, the trial was aborted and the corresponding visual feedback was shown. Otherwise, the color wheel for the memory task appeared. The color wheel enclosed a central disk and a peripheral ring, similar in dimensions to the memory display. Participants were asked to adjust the mouse cursor on the color wheel to each of the two memorized colors. The currently judged object (disk or ring) was colored whereas the other object was in the same light gray as the placeholders. The order of adjustment (disk first or ring first) was random. For each adjustment, the selected color was confirmed by mouse click. The adjustment of the second color was preceded by a 200 ms blank interval.

The color wheel represented an isoluminant hue circle with a chroma of 34 in CIELAB. The color wheel was 0.3° thick and the inner edge was 2.4° from fixation. To cancel motor biases, the spatial orientation of the zero hue angle was randomized between trials. By turning the mouse around the initial mouse position on the desk, participants were able to rotate the line cursor whose color matched the selected color on the wheel. The color pointed to by the line cursor was also used to draw either the central disk or the peripheral ring.

The 64 combinations of 4 cue positions, 4 target positions, 2 cue colors (target or distractor), 2 responses (left, right) were shown once in a block of trials. Participants performed three blocks for a total of 192 trials in all groups except the "with/without search" group, where they performed 256 trials. The four experimental groups differed with respect to instruction and feedback (see Table 1). These groups are referred to as "equal priority", "with/without search", "specific feedback", and "priority distractor" groups.

-- insert Table 1 about here ---

First, there were two types of feedback about the color judgments. Pooled feedback did not provide separate feedback about the recall of target and distractor colors, but only indicated the combined accuracy (median unsigned color error). Pooled feedback was given after 32 trials and the feedback remained on the screen for only 10 s. Specific feedback indicated the accuracy separately for the recall of the target and distractor color. Specific feedback was given every 16 trials and remained on the screen until participants pressed a mouse button. In all groups, feedback about the color judgments was shown together with feedback about the RT task (median RT and mean percentage correct). Participants in the “equal priority” and “with/without search” group received pooled feedback, while participants in the “specific feedback” and “priority distractor” group received specific feedback.

Second, the instruction changed between groups to test whether observers automatically prioritize the target color despite explicit instructions to do otherwise. Participants in the “equal priority”, “with/without search”, and "specific feedback" groups were told to make equally precise color judgments for the target and distractor color. Participants in the “priority distractor” group were told to use the specific feedback to achieve higher precision for the distractor than for the target color.

Third, half of the trials in the “with/without search” group were without search task to examine its effects on color memory. In trials without search, the target and distractor colors were shown in the memory display and participants prepared for search. However, cue and target displays were absent and replaced by placeholder displays. Subsequently, the placeholders continued to be shown for the mean RT from the preceding experiment (528 ms). Finally, the color judgments were collected.

Results

Two datasets were removed due to excessive errors in the search task (> 30% errors) or the color task (> 100°), leaving 13 participants in the "equal priority" group (1 man, age: *M* = 20 years, *SD* = 1.3), 13 participants in the "with/without search" group (2 men, age: *M* = 21.1 years, *SD* = 3), 12 in the "detailed feedback" group (1 man, age: *M* = 20.4 years, *SD* = 1.9), and 12 in the "priority distractor" group (1 man, age: *M* = 19.1 years, *SD* = 1.2).

Memory Error. We fit the swap model proposed by Bays, Catalao, and Husain (2009) to the memory error. The swap model provides an estimate of the standard deviation (*SD*) of the distribution of the memory error, an estimate of the guess rate, and an estimate of the probability of swapping memorized and distractor color. Fits were performed by the MemToolbox (Suchow, Brady, Fougnie, & Alvarez, 2013). Here, we focus on the precision of the memory representation, which is mostly captured by its *SD* (shown in the lower row of Figure 3). Analysis of guess rate and memory swaps are deferred to the supplementary analysis section to avoid redundancy.

--- insert Figure 3 about here ---

We conducted a 4 (group: "equal priority", "with/without search", "specific feedback", "priority distractor") x 2 (recalled stimulus: target, distractor) x 2 (cue color: target matching, distractor matching) mixed ANOVA on the individual SDs. For the "with/without search" group, only color settings from trials with search task were included in the ANOVA. The SD was smaller for the target than for the distractor color (18.3 vs. 23.0), $F(1, 46) = 78.90$, $p < .001$, $\eta_p^2 = .63$, indicating that observers memorized targets more precisely than distractors. Critically, the SD of memory errors for targets was significantly smaller than the SD for distractors in all four groups, *t*s > 3.09, *p*s < .01, Cohen's *d* > 0.89. The interaction of group and recalled stimulus approached significance, $F(1, 15) = 2.78$, $p = .052$, $\eta_p^2 = .15$, showing that the difference between target and distractor tended to be larger in the “equal priority” and “with/without search” groups (difference of 5.1 and 7.0, respectively) than in the “specific feedback” and “priority distractor” (difference of 3.9, and 2.9, respectively) groups. Because the former groups were only given pooled feedback while the latter received specific feedback, the results suggest that detailed feedback reduced the difference between target and distractor. Because the analysis of group had an exploratory character, we ran an additional analysis where we collapsed across cue color and compared participants with pooled and specific feedback. The interaction of group and recalled stimulus reached significance, $F(1, 48) = 7.53$, $p = .009$, $\eta_p^2 = .14$, confirming a larger effect of recalled stimulus with pooled than with specific feedback (difference of 6.8 for pooled vs. 3.3 for specific feedback).

Finally, we evaluated the effect of completing the search task in the group “with/without search”. We conducted a 2 (recalled stimulus: target, distractor) × 2 (search task: present, absent) on the color deviations. There was a main effect of recalled stimulus, $F(1, 12) = 16.53$, $p = .002$, $\eta_p^2 = .58$, showing that the *SD* of the memory error was smaller for the target than for the distractor (18.1 vs. 24.4). There was a tendency for an effect of search task, $F(1, 12) = 4.36$, $p = .059$, $\eta_p^2 = .27$, and a tendency for an interaction, $F(1, 12) = 4.40$, $p = .058$, $\eta_p^2 = .27$. The interaction suggested that the difference in SD between target and distractor tended to be larger when the search task was performed (difference of 7.8) than when it was omitted (difference of 4.8). However, both differences were significantly different from zero, $t(12) = 4.48$, $p = .001$, Cohen’s $d = 1.24$, and $t(12) = 2.86$, $p = .014$, Cohen’s $d = 0.79$, respectively.

Corrected RTs in the search task. In addition to 2.2% late trials, which were detected online, we excluded 2.1% outliers in the offline analysis of corrected RTs. Overall, the percentage of choice errors was 7.3% (see supplementary Table 2). Mean corrected RTs are shown in the upper row of Figure 3.

We conducted a 2 group (feedback: pooled, specific) × 2 (cue color: target-matching, distractor-matching) × 2 (cue validity: valid, invalid) repeated-measures ANOVA on corrected RTs. The interaction of cue color and cue validity, $F(1, 48) = 75.65$, $p < .001$, $\eta_p^2 = .61$, modulated the main effect of cue validity, $F(1, 48) = 27.79$, $p < .001$, $\eta_p^2 = .37$. The interaction showed that corrected RTs were significantly shorter with valid than with invalid cues when the cue color matched the target color (76 ms cueing effect, 543 vs. 619 ms), $t(49) = 9.12$, $p < .001$, Cohen's $d = 1.29$, but not when the cue color matched the distractor color (-17 ms cueing effect, 586 vs. 569 ms), $t(49) = 2.42$, $p = .019$, Cohen's $d = 0.34$. Crucially, the interaction of cue color and validity was not further qualified by group, $p = .705$, showing that cueing effects only emerged to the target color, regardless of type of feedback. Further, corrected RTs were shorter in the group with specific than with pooled feedback (554 vs. 603 ms), $F(1, 48) = 11.3$, $p = .002$, $\eta_p^2 = .19$. Group interacted with cue color, $F(1, 48) = 5.65$, $p = .021$, $\eta_p^2 = .11$, showing that RTs with target-matching cues were longer than with distractor-matching cues when feedback was pooled (612 vs. 593 ms), but the opposite was true when feedback was separate (548 vs. 561 ms).

Discussion

We asked observers to retain two colors in VWM when performing search for one of the two colors, while the other was the distractor color. Attentional capture was only observed for cues in the target color, but not for cues in the distractor color, even though both colors had to be retained in VWM. These results are consistent with Olivers' (2009) Experiment 5 and appear to support the one-template hypothesis. If observers established an attentional template for the target color, the other items in memory (i.e., the distractor color) would not interact with perception. However, the precision of color judgments suggests that more resources were allocated to the target than to the distractor, irrespective of the execution of the search task, the nature of the feedback, or the instructed priorities. Thus, the status of the target and distractor colors in VWM was not the same and cueing effects only emerged to the color receiving the most VWM resources. In contrast, the two target colors in dual target search (Experiment 1) had the same status because they were equally relevant for the search task. Thus, the discrepancy between dual target and dual task paradigms may be resolved by saying that multiple items in VWM may be set up as attentional templates when they have equal status in VWM, but not when one is given higher priority because of task requirements.

The question arises whether memory-based capture could arise if the memorized color was not the distractor color in the search task. Possibly, participants established a template for rejection (Arita, Carlisle, & Woodman, 2012) to bias attention away from the distractor color. For instance, Arita et al. (2012) found that participants were able to speed search for a color target by using stored information about the distractor color. On the account that observers in our experiment used information about the distractor color as a template for rejection, we would have to accept that search relied on the less precise distractor representation to locate the target. This idea seems implausible, but cannot be ruled out. Further, one may wonder how memory for the distractor color compares to memory for a color that was neither distractor nor target. A "neutral" color would reveal whether there was inhibition of the distractor color, as the negative cueing effect to cues in the distractor color would suggest (-17 ms, see results). However, it is difficult to ensure that a "neutral" color is indeed neutral. If a color is not used as distractor color, participants may establish the color as search template without being reminded of this error by selecting the wrong color in the search task. Nonetheless, we admit that the current study cannot entirely rule out effects of distractor-related inhibition on memory (similar to Olivers, 2009). However, the potential role of inhibition is fully compatible with our hypothesis that only the item receiving maximal resources in VWM acts as search template. Inhibition may be one of the factors that reduce the VWM resources allocated to the distractor.

Experiment 3: Fixed targets

A possible objection to the conclusions from Experiment 2 is that memory-based interference has never been demonstrated with search and memory targets that were defined on the same perceptual dimension. Actually, previous studies failed to report memory-based interference with items from the same dimension (Downing & Dodds, 2004; Houtkamp & Roelfsema, 2006; Exp. 5 in Olivers, 2009). However, these studies used variable target colors. Therefore, we tested whether memory-based interference for same-dimension stimuli may occur with fixed targets. In Experiment 3, the fixed target was the only colored item in the search display (i.e., a singleton). The singleton color changed from trial to trial, but unlike in Experiments 1 and 2, participants did not have to remember the changing target color to perform the task. In this sense, the target was "fixed". Further, participants memorized a color at the beginning of each trial for recall at the end of the trial. We evaluated whether cues in the memorized color produced larger cueing effects than unrelated colors. Because participants performed singleton search, any cue color is expected to result in cueing effects (Folk & Anderson, 2010; Irons et al., 2012). However, memorized colors are expected to result in larger cueing effects. According to the one-template hypothesis, memory-based interferences occurs because the memorized color acts as attentional template in this situation. Similarly, according to the resource hypothesis, the only item in VWM receives the maximum resources and therefore acts as attentional template.

Methods

We suspected the effect size to be smaller in the current experiment because the color of the search target was irrelevant for the search task. We therefore increased the sample size to 17 to avoid missing the effect (2 men, age: *M* = 23.53, *SD* = 9.4). The larger sample size allowed us to detect effects sizes as small as 0.72 (Cohen's *d*). The procedure was as in Experiment 2 with the following exceptions (see Figure 1D). As before, two colors were shown in the memory display, but only one of the colors had to be memorized. The two colors in the memory display had an equal probability of being select for the cue display. In the search display, only a single colored stimulus was shown (i.e., a color singleton). Therefore, it was not necessary to know the target color in advance. The target color was always different from the two colors in the memory display.

The hue angle between the memorized color and the second color in the memory display was 180°. The target color had an intermediate hue (i.e., 90° or 270° from the memorized color). The location of the to-be-memorized color in the memory display (disk or ring) was indicated by the letter C or P. Because only one color was recalled after the search task (unlike in Experiment 2, where two colors were recalled), only a single disk with 0.3° radius was shown inside the color wheel. As in Experiment 2, the color wheel surrounded the disk. The color wheel was 0.6° thick and the inner edge was 1.2° from fixation.

The 128 combinations of 4 cue positions, 4 target positions, 2 cue colors (matching or mismatching the memorized color), 2 hue angles of the target color angle (90° or 270°, which are both intermediate between 0° and 180°), and 2 responses (left, right) were shown once in a block of trials. Two blocks were run for 256 trials.

Results

Late trials amounted to 1.1% of the trials. Mean corrected RTs are shown in Figure 4. Overall, the percentage of choice errors was 4.5% (see supplementary Table 3).

--- insert Figure 4 about here ---

Memory Error. We compared the SD of the memory error for memory-matching and non-matching cue colors. The SD tended to be smaller when the cues matched the memorized color than when they were non-matching (17.2 vs. 18.2), $t(16) = 1.78$, $p = .093$, Cohen’s $d = 0.43$.

Corrected RTs in search task. We conducted a 2 (cue color: memory-matching or non-matching) × 2 (cue validity: valid, invalid) ANOVA on the individual mean corrected RTs. The interaction of cue color and cue validity, $F(1, 16) = 8.59$, $p = .01$, $\eta_p^2 = .35$, modulated the main effects of cue color, $F(1, 16) = 5.19$, $p = .037$, $\eta_p^2 = .25$, and cue validity, $F(1, 16) = 53.27$, $p < .001$, $\eta_p^2 = .77$. The interaction indicated that the cueing effect was larger with cues matching the memorized color (100 ms cueing effect, 489 vs. 590 ms), than with non-matching cues (66 ms cueing effect, 492 vs. 558 ms). By paired t-test, the former, $t(16) = 6.67$, $p < .001$, Cohen's $d = 1.52$, and latter cueing effect, $t(16) = 6.55$, $p < .001$, Cohen's $d = 1.49$, were significantly different from zero.

Discussion

We observed stronger interference from cue colors matching the memorized color than from unrelated cue colors. Both the memorized and the unrelated color were shown in the memory display, which rules out priming as an explanation for the results. Presumably, the memorized color acted as attentional template because participants did not have to maintain a competing target representation in VWM. Rather, observers searched for a color singleton, which is known to result in cueing effects by any cue color (Folk & Anderson, 2010; Irons et al., 2012). However, keeping one color in VWM automatically established this color as search template, which resulted in stronger cueing effects for memory-matching colors. Because the search and memory targets were defined on the same perceptual dimension, we can rule out the possibility that memory-based interference depends on cross-dimensional stimuli.

General Discussion

The present experiments contribute to the ongoing discussion on whether a single or multiple attentional templates can simultaneously control attention. Research from dual target search provided evidence in favor of attentional guidance by two search templates, but it was not clear whether the attentional templates were actually stored in VWM because the memorized target colors did not change across trials. Experiment 1 avoided contributions from long-term memory by changing the memorized target colors from trial to trial. Consistent with the previous literature, we observed evidence in favor of multiple attentional templates operating at the same time. That is, regardless of whether observers searched for one or two memorized target colors, cueing effects occurred to colors matching the attentional template, whereas cueing effects were absent to unrelated colors. In the following experiments, we investigated the conditions under which colors stored in memory result in cueing effects. As in the dual-target condition of Experiment 1, two colors were stored in VWM in Experiment 2, but the two colors played unequal roles in the search task. One color was the search target and the other was the distractor color. We found no cueing effects to the distractor color, suggesting that no attentional template was formed for the distractor color, which supports the idea that only a single attentional template can be formed. At the same time, we observed that the distractor color was recalled less precisely than the target color, regardless of observer intentions or execution of the search task

(FOOTNOTE 1). Thus, more VWM resources were attributed to the target item than to the distractor. The unequal allocation of VWM resources may explain why one color acted as attentional template and caused cueing effects whereas the other was "accessory" and did not result in cueing effects.

In sum, we think that the dual-task paradigm in Experiment 2 does not provide conclusive evidence against multiple attentional templates because participants were unable to assign equal status to the target and distractor colors. The VWM representation of the target color was always given higher priority in VWM compared to the distractor color. Experiment 3 ruled out that using the same perceptual dimension for target and accessory stimulus prevented cueing effects for accessory stimuli. When we used fixed (singleton) targets, it was neither necessary nor possible to store the target features in VWM. We found that cueing effects increased for cues in the memorized color, showing that the content of VWM operates as attentional template when there is no competition with other items in VWM. Taken together, the results suggest that a memorized color may act as attentional template, but only when it is assigned more or equal VWM resources compared to the remaining items. This is the case when only a single item has to be memorized. When two items have to be memorized with equal status (e.g., in dual target search), multiple attentional sets may be established. In contrast, when one item has a higher priority because of task demands (i.e., target vs. distractor), only a single attentional template can be established.

Our conclusions are consistent with recent studies by Rajsic, Ouslis, Wilson, and Pratt (2017) and Hollingworth and Hwang (2013) in which retro-cueing procedures were used. Rajsic et al. (2017) presented two objects in the memory display and asked observers to retain both. A retro-cue informed observers about which of the two objects was the target in a subsequent search task. Rajsic et al. (2017) found that the color of the search target was better retained than the color of the other object in the memory display. Similar to our "with/without search" condition in Experiment 2, memory for the search target was better even when the search was not performed, consistent with the typical retro-cueing benefit (Souza & Oberauer, 2016). Further, Hollingworth and Hwang (2013) examined memory-based interference from a color that was initially retained, but not retro-cued for later recall. They observed that the uncued item did not produce more interference than an unrelated color, even though the precision of memory performance was similar to the item that was retro-cued for later recall. Thus, the deprioritized item in VWM did not interact with perception to produce larger interference compared to unrelated colors. Their idea of inactive items in VWM is close to our idea that items receiving fewer resources do not interact with perception. In contrast to experiments with retro-cues, however, our experiments have the advantage that they allow for direct measurements of the attentional template and that they are directly comparable to studies that provided evidence for multiple attentional templates (i.e., dual target search in the contingent capture paradigm). Because the attentional template may be set up in 200 ms or less (Vickery, King, & Jiang, 2005; Wolfe, Horowitz, Kenner, Hyle, & Vasan, 2004), the presentation time of 300 ms for our memory display and the delay until target onset of 1.4 s provided ample time to set the priorities for the target and memorized color in Experiment 2. The fact that the distractor color received fewer VWM resources and was "inactive" was therefore not due to time constraints. Rather, it may reflect the obligatory distribution of VWM resources between target and distractor in visual search tasks.

Further, our conclusion that variable targets prevent another item in VWM to act as attentional template appears inconsistent with a recent study by Foerster and Schneider

(2018). They demonstrated that memory-based interference does occur with variable targets, albeit with methods different from those used in the present and previous studies. In their experiments, one of four everyday target objects was presented in the memory display. After a retention delay, the target and a distractor object appeared in the saccade display and participants had to make a saccade to the memorized target object. The target object was shown in a task-irrelevant color in the memory display. Critically, this color either matched or did not match the target color in the subsequent saccade display. When the color was non-matching, the distractor object in the saccade display could be drawn in the target color from the previous memory display. The results showed that saccades went more frequently to the distractor object when it shared the original target color than when it was shown in an unrelated color. Because the identity of the target object varied randomly from trial to trial, these results seem at odds with previous studies who failed to find memory-based interference with variable targets (Downing & Dodds, 2004; Houtkamp & Roelfsema, 2006; Exp. 5 in Olivers, 2009). Possibly, there is an effect of dimensional overlap. When accessory item and attentional template are both color-defined, as in our experiments, memory-based interference may be absent. In contrast, when the attentional template is shape-defined and the accessory item is color-defined (as in Foerster & Schneider, 2018), memory-based interference may be present. According to Foerster and Schneider, participants integrate search-relevant and irrelevant features into an object (e.g., a red cup), arguing for object-based VWM templates. In contrast, it was not possible to create object-based representations in our study because color was the only attribute. While the difference between object-based vs. feature-based memory may be a possible explanation for the discrepancy, a large number of alternatives remain (e.g., saccadic error rates instead of cueing effects, search set of 2 vs. 4, etc.).

Overall, our experiments examined why it is possible to set up two colors as attentional templates in dual target search, while interference from items in VWM is limited to only one color, even when two colors are stored in memory. We suggest that only colors receiving maximal VWM resources will result in an attentional template and interact with perception. When one color receives less VWM resources because of task requirements, it will not interact with perception, even when it is stored in VWM.

Footnote

Footnote 1. Because better memory for the target than for the distractor color was observed even when the search task was not executed, we may rule out that refreshing accounted for the difference. Refreshing was not possible without search display. In addition, refreshing was in principle possible for both the target and the distractor, because both were always present in the search display.

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Table 1. Differences between the four groups in Experiment 2.

group label	feedback	priority	search task
equal priority	pooled	equal	always
with/without search	pooled	equal	50% of trials
specific feedback	specific	equal	always
priority distractor	specific	distractor	always

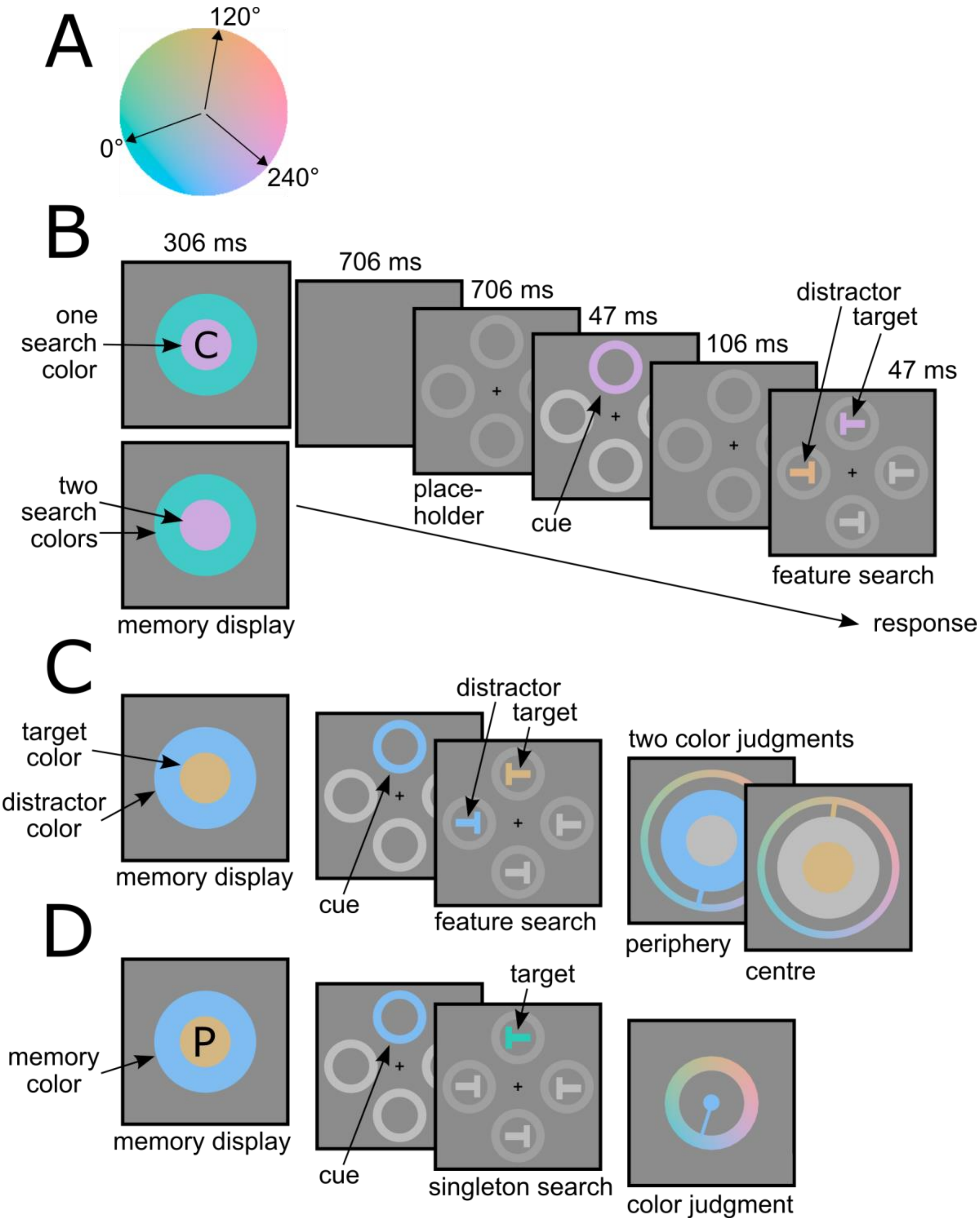

Figure 1. Illustration of experimental stimuli (not drawn to scale). Panel A illustrates CIELAB color space. Chroma increases from the center to the periphery of the disk. The azimuth corresponds to the hue. Arrows illustrate hue differences of 120°. Panel B shows the sequence of events in Experiment 1, where observers searched for one or two colors. With

only one target, the central letter indicated the location of the target color (C for central disk and P for peripheral ring). Panel C shows the dual task paradigm in Experiment 2. Observers memorized the two colors shown in the memory display. One was the target color and the other was the distractor color in the upcoming feature search task. For half of the participants, the central disk indicated the target color (as shown in panel C). For the other half, it was the peripheral disk. Panel D shows singleton search in Experiment 3 where the designated color from the memory display had to be retained while participants searched for a color singleton. The color wheel in Experiment 2 (panel C) surrounded a disk and a ring because observers were asked to recall the color of both the disk and the ring (corresponding to target and distractor color in the memory display). In Experiment 3 (panel D), the color wheel surrounded a single disk because only a single color was recalled. Note that placeholders in the experiments were composed of two unfilled circles. The dark gray rings in the figures were used for clarity.

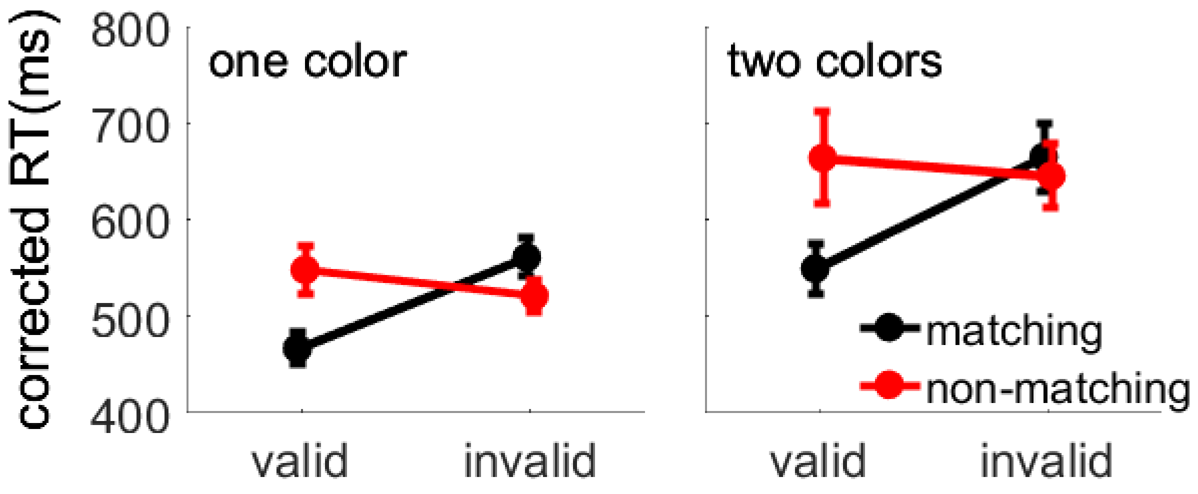

Figure 2. Results from Experiment 1. Mean corrected reaction times (RTs) are shown as a function of the number of memorized search targets, cue validity, and match between the cue and memorized target color. Error bars show the standard error of the mean.

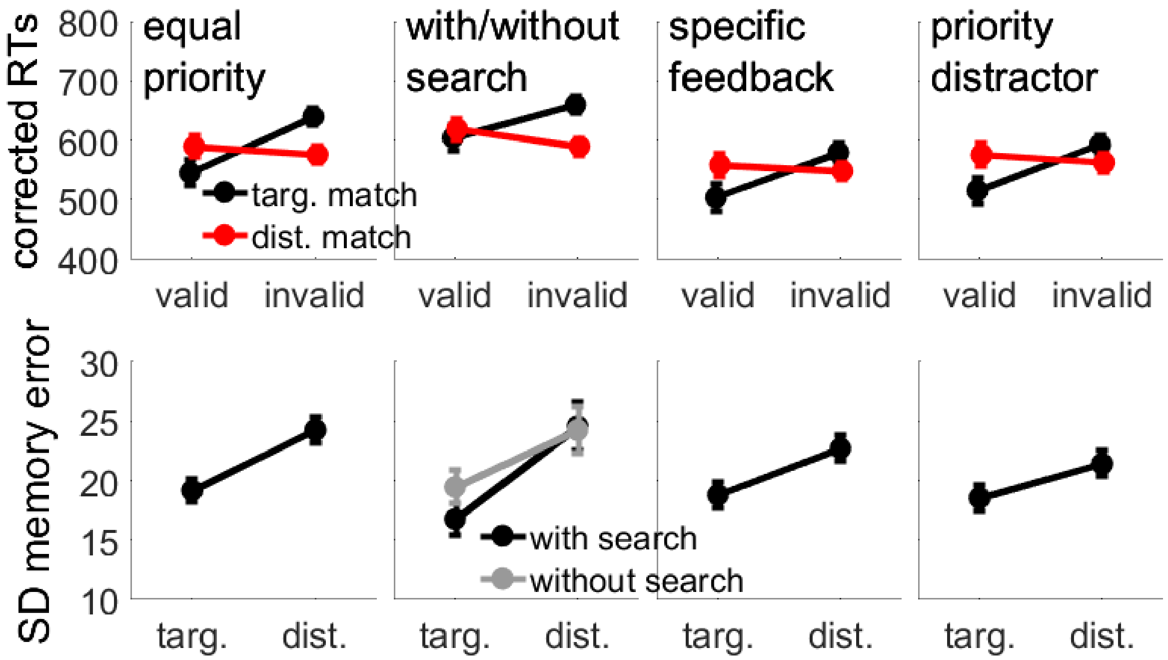

Figure 3. Results from Experiment 2. The four columns show data from the four experimental groups. The upper row shows the corrected reaction times (RTs, in ms) as a function of cue validity and cue color. The cue color matched either the target or the distractor color. The lower column shows the standard deviation (SD) of the distribution of the memory error for the target and the distractor color (in °). Error bars represent the standard error of the mean.

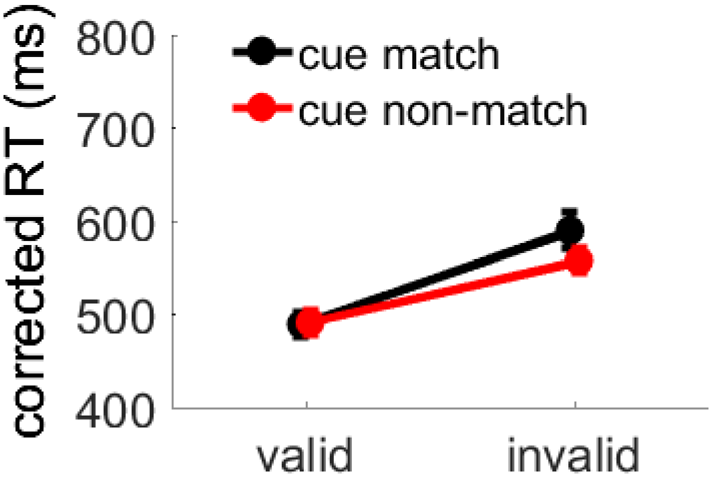

Figure 4. Results from Experiment 3. Mean corrected RTs are shown as a function of cue validity and the match between the memorized color and the cue color.

Supplementary Table 1. Mean reaction times (RT, in ms) and percentage of errors (PE) in Experiment 1 as a function of number of memorized search targets, match between cue and memorized target color, and cue validity. The difference between invalid and valid conditions is indicated as cueing effect (CE).

# colors	cue match	valid	RT	CE(RT)	PE	CE(PE)
1	yes	yes	444	73	4.7	3.0
		no	516		7.7	
	no	yes	501	-17	7.9	-1.0
		no	484		6.9	
2	yes	yes	498	37	8.4	9.5
		no	536		17.9	
	no	yes	532	-9	17.7	-0.2
		no	524		17.5	

Supplementary Table 2. Mean reaction times (RT, in ms) and percentage of errors (PE) in Experiment 2 as a function of feedback group, cue color (target-matching, distractor-matching), and cue validity. The difference between invalid and valid conditions is indicated as cueing effect (CE).

feedback	cue match	valid	RT	CE(RT)	PE	CE(PE)
pooled	target	yes	527	45	7.6	4.1
		no	572		11.7	
	distractor	yes	552	-14	8.3	-0.7
		no	538		7.6	
specific	target	yes	480	68	5.2	1.1
		no	548		6.3	
	distractor	yes	533	-13	5.6	0.3
		no	520		5.9	

Supplementary Table 3. Mean reaction times (RT, in ms) and percentage of errors (PE) in Experiment 3 as a function of match between cue and memorized color, and cue validity. The difference between invalid and valid conditions is indicated as cueing effect (CE).

cue match	valid	RT	CE(RT)	PE	CE(PE)
yes	yes	479	62	2.0	5.7
	no	541		7.7	
no	yes	475	53	3.1	2.0
	no	529		5.1	

Supplementary Analysis

We provide supplementary analysis of the guess rate and swap rate parameters derived from the model of Bays et al. (2009). The results of these analyses are consistent with the conclusions from the analysis of standard deviation reported in the main text. Most importantly, we found both guess rates and swap rates to be higher for the distractor than for the target in Experiment 2.

Experiment 2

We conducted a 4 (group: “equal priority”, “with/without search”, “specific feedback”, “priority distractor”) x 2 (recalled stimulus: target, distractor) x 2 (cue color: target matching, distractor matching) mixed ANOVA on individual guess rates. For the “with/without search” group, only color settings from trials with search task were included in the ANOVA. The guess rate was lower for the target than for the distractor color (.033 vs .078), $F(1, 46) = 18.31$, $p < .001$, $\eta_p^2 = .29$, indicating that observers memorized targets better than distractors. The effect of cue color approached significance, $F(1, 46) = 3.10$, $p = .085$, $\eta_p^2 = .06$, showing that the guess rated tended to be higher with same than with different cues (0.063 vs. 0.047). None of the other effects reached significance, *p*s > .571.

We repeated the same ANOVA on individual swap rates. The probability of swapping was smaller for targets than for distractors (.018 vs. .068), $F(1, 46) = 26.92$, $p < .001$, $\eta_p^2 = .369$. The interaction of cue color and experiment, $F(3, 46) = 3.71$, $p = .018$, $\eta_p^2 = .195$, showed that swap rate decreased when the cue color was the same as the target color in the "with/without search" and "priority distractor" groups (decrease of .022 and .005, respectively), but increased in the "equal priority" and "specific feedback" groups (increase of .012 and .006, respectively). The interaction of recalled stimulus and cue color approached significance, $F(3, 46) = 3.02$, $p = .089$, $\eta_p^2 = .06$, showing that matching cue colors decreased the swap rates for the target (.016 for matching and .021 for non-matching cue colors), whereas the opposite was the case for the distractor (.072 for matching and .64 for non-matching cue colors).

Further, we evaluated the effect of completing the search task in the group "with/without search". We conducted a 2 (recalled stimulus: target, distractor) × 2 (search task: present, absent) on the guess rate, but no significant main effect or interaction was observed, *p*s > .248. We repeated this analysis on swap rates. Swap rates were lower for the target than for the distractor (.017 vs .076), *F*(1, 12) = 8.23, *p* = .014, η_p^2 = .41. The interaction of recalled stimulus and search task, *F*(1, 12) = 5.44, *p* = .038, η_p^2 = .31, showed that swap rates increased for the target when the search task was absent (.014 vs .020), whereas it decreased for the distractor (.091 vs .061).

Experiment 3

We compared the guess and the swap rate in the color adjustment task for memory-matching and non-matching cue colors. The guess rate was smaller when the cues matched the memorized color than when they were non-matching (.040 vs .068), *t*(16) = 2.33, *p* = .033, Cohen's *d* = 0.56, whereas the swap rate did not differ (.002 in both conditions), *p* = .676.