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The Allocation of Working Memory Resources Determines the Efficiency of Attentional Templates in Single- and Dual-Target Search

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Attentional templates are representations of target features in working memory (WM). Although two attentional templates can guide visual search in dual-target search, search efficiency is reduced compared with one attentional template in single-target search. Here, we investigated whether the allocation of WM resources contributes to these differences. Participants always memorized two colors, but the use of the corresponding WM representations varied. In the blocked conditions, the two colors were either maintained as attentional templates for dual-target search or as simple WM representations for recall only. In the mixed condition, one color was maintained as an attentional template for single-target search and the other as a simple WM representation for recall only. Reaction times (RTs) were delayed and recall precision reduced with two attentional templates in the blocked condition compared with one attentional template in the mixed condition, indicating that search efficiency and WM resources decreased in dual- compared with single-target search. Moreover, the attentional template was always recalled more precisely than the simple WM representation in the mixed condition, despite lowered visual search frequency (Experiment 2) and retro-cueing (Experiment 3). Consistent with the existence of an "active" WM state, resources were strongly biased toward the attentional template in single-target search. In dual-target search, however, resources were balanced between two attentional templates and flexibly adjusted with retro-cues, as with two simple WM representations. Therefore, the allocation of WM resources goes beyond the traditional dichotomy between "active" and "accessory" WM states and explains how attentional templates guide visual search with variable efficiency.

Keywords: attentional template, resource allocation, top-down control, visual search, working memory

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We spend a large part of our daily lives looking for known objects in dense visual scenes. In some situations, we search for two objects at the same time. For instance, we may be looking for our office keys and phone on a cluttered desk before we leave for work. In these situations, visual search is guided by stored representations of object features (e.g., the shape of the office keys and the color of the phone case), which are referred to as attentional templates (Duncan & Humphreys, 1989) or attentional control sets (Folk et al., 1992). Attentional templates are activated shortly before visual search (Grubert & Eimer, 2018, 2020) to prioritize objects with corresponding attributes and to determine target-matches (Eimer, 2014). Thus, attentional templates contribute to the guidance of visual attention toward potential targets and to the decision about their goal-relevance. Consistent with prominent models of visual search (Bundesen, 1990; Desimone & Duncan, 1995; Wolfe, 1994), there is strong evidence that attentional templates are stored in working memory (WM; Carlisle et al., 2011; Woodman & Arita, 2011; Woodman et al., 2013). However, it remains poorly understood whether and how WM determines the number and efficiency of attentional templates during visual search.

Inspired by state-based models of WM (McElree, 2001; Oberauer, 2002), the single-template hypothesis (Olivers et al., 2011) considers WM to be divided into two representational states. In this view, only a single representation is maintained in an "active" state by the focus of attention, allowing it to act as an attentional template. In contrast, other representations are maintained in an "accessory" state, in which they cannot interact with visual search until they become relevant. As an alternative, the multiple-template hypothesis (Beck et al., 2012) considers that several representations can guide visual search simultaneously. That is, a small set of representations are maintained in the "active" state by a broader focus of attention (Bahle et al., 2020), which is consistent with less restrictive state-based models of WM (Cowan, 1999, 2005; Gilchrist & Cowan, 2011). Clear evidence in favor of the latter proposal stems from dual-target search (for a review, see Ort & Olivers, 2020). In these tasks, participants typically maintain

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two attentional templates (e.g., "red and blue") to search for a target that is defined by one of these features. The idea is to compare single- with dual-target search with respect to overall performance or attentional capture. In this context, behavioral (Ansorge et al., 2005; Bahle et al., 2020; Huynh Cong & Kerzel, 2020; Irons et al., 2012; Kerzel & Grubert, 2021; Kerzel & Witzel, 2019; Moore & Weissman, 2010; Roper & Vecera, 2012), electrophysiological (Berggren et al., 2020; Christie et al., 2015; Grubert & Eimer, 2015, 2016; Huynh Cong & Kerzel, 2021b), and eye-movement (Beck et al., 2012; Beck & Hollingworth, 2017) studies demonstrated that two attentional templates can guide visual search simultaneously. Importantly, however, two attentional templates may not be as efficient as one attentional template. In fact, another body of studies reported performance impairments when participants searched for two possible targets compared with a single target, whether the relevant feature was shape (Houtkamp & Roelfsema, 2009), orientation (Barrett & Zobay, 2014), color (Dombrowe et al., 2011; Grubert et al., 2016; Stroud et al., 2011), or a combination of these dimensions (Biderman et al., 2017).

Depending on the architecture of WM, two hypotheses were formulated to account for the costs associated with multiple attentional templates. From the perspective of the single-template hypothesis (Olivers et al., 2011), two attentional templates must sequentially switch between "accessory" and "active" states in WM, which impairs visual search in dual- compared with single-target search. Consistently, Ort et al. (2017) demonstrated that visual search is impaired when two attentional templates alternate from one trial to the next. Interestingly, however, the impairment was eliminated when participants could freely choose which attentional template to activate. In blocks of trials with free choice, two target colors were always presented in the search display, allowing participants to activate one of two attentional templates prior to the search displays. In blocks of trials with imposed choice, only one of the two target colors was present in the search displays, forcing participants to adjust the activation of the two attentional templates in response to the search displays. Results showed that alternating between attentional templates across trials increased the time to find the targets when the choice was imposed, but not when it was free (see also Ort et al., 2018). Therefore, switching attentional templates between "accessory" and "active" WM states impairs visual search, but only when the switch is imposed by the search task. As an alternative to this view, and consistent with the multiple-template hypothesis (Beck et al., 2012), two attentional templates may be simultaneously "active" in WM, but with different levels of activity (Bahle et al., 2020). The attentional template that guides visual search several times in a row is more activated in WM, but the activity of the other attentional template must increase when the target changes, which impairs visual search. That is, the costs in dual- compared with single-target search reflect changes in the activity levels of attentional templates, rather than switches between WM states. Although these two proposals are difficult to disentangle, the idea of activity levels (Bahle et al., 2020) is more in line with the literature showing that two attentional templates can guide visual search simultaneously. Moreover, it perfectly accounts for the observations of Ort et al. (2017) because activity levels could be modified prior to or in response to search displays, as would be the switch between "accessory" and "active" WM states. However, further elaboration is needed. For instance, it is not clear how levels of activity would operate within the focus of attention and how changes in activity could be measured independently from visual search. More important, levels of activity suggest that the "active" state is not a discrete slot in WM, but a space where representations share a continuous medium. Therefore, it seems critical to include a continuous WM process that differentiates between multiple "active" representations. To this end, the well-defined concept of WM resources may be worth considering.

Recently, WM has been conceptualized as a limited resource, distributed flexibly and strategically between representations depending on their respective relevance (Bays et al., 2009; Bays & Husain, 2008; Ma et al., 2014). In addition to increasing recall precision, the allocation of WM resources may shape how representations interact with visual search. On this basis, Huynh Cong and Kerzel (2021a) proposed three principles to conceptualize the relationship between resource allocation and visual search. First, the allocation of the largest amount of WM resources to a representation is not sufficient to give this representation the status of attentional template. Simply put, a representation can be recalled with high precision but not interact with visual search (Dube et al., 2019; Dube & Al-Aidroos, 2019; Hollingworth & Hwang, 2013). Second, an attentional template receives an amount of WM resources proportional to its relevance for visual search. On the one hand, a single attentional template receives the largest amount of WM resources because it is the only relevant representation for visual search. For instance, Rajsic et al. (2017) asked participants to maintain two representations for subsequent recall. During the retention interval, a retro-cue indicated which representation would serve as the attentional template for an intervening search task. Results showed that assigning the status of attentional template to a representation increased its recall precision, regardless of the occurrence of visual search (see also Kerzel & Witzel, 2019; Rajsic & Woodman, 2020). On the other hand, two attentional templates receive an amount of WM resources that depends on their respective relevance for visual search. Therefore, two equally relevant attentional templates are recalled with similar precision (Huynh Cong & Kerzel, 2020). Third, the amount of WM resources allocated to an attentional template determines its recall precision and efficiency in guiding visual search. Consistently, previous studies showed that increasing the precision of an attentional template in WM, and presumably the amount of resources it receives, enhances attentional selection (Jenkins et al., 2018; Nako, Wu, & Eimer, 2014; Nako, Wu, Smith, et al., 2014), facilitates target recognition (Castelhano et al., 2008; Rajsic & Woodman, 2020), or both (Hout & Goldinger, 2015; Malcolm & Henderson, 2009, 2010; Schmidt & Zelinsky, 2009).

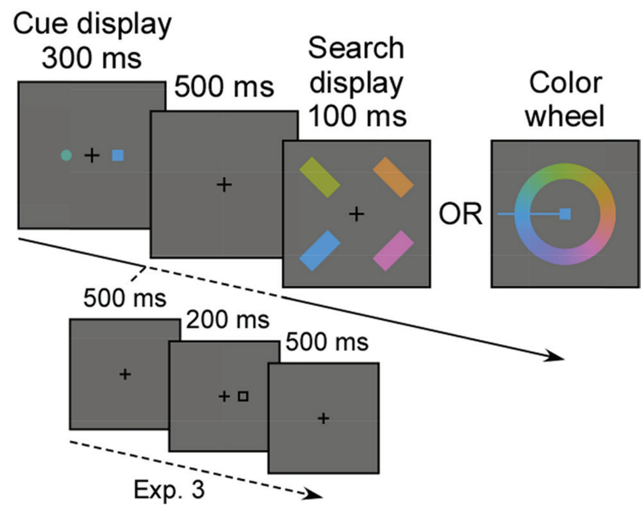
Compared with dual-state models of visual search (Bahle et al., 2020; Olivers et al., 2011), the resource hypothesis of visual search (Huynh Cong & Kerzel, 2021a) suggests that multiple attentional templates guide visual search simultaneously, but the efficiency of each attentional template may vary. Importantly, the efficiency of attentional templates in guiding visual search is predicted to go hand in hand with measures of memory performance. Thus, strong predictions about the relationship between search and memory performance can be formulated. In contrast, dual-state models of visual search (Bahle et al., 2020; Olivers et al., 2011) are limited in their predictions regarding memory performance. For instance, it may be argued that switches between WM states or changes in activity levels increases the time necessary to perform the task, without necessarily affecting the representations of attentional templates in WM. For these reasons, the resource hypothesis of visual search (Huynh Cong & Kerzel, 2021a) gives new insights into the costs associated with multiple attentional templates. In dual-target search, two equally relevant attentional templates may receive an equal share of WM resources, which is smaller than the amount of WM resources allocated to a single attentional template. As a result, two attentional templates are less efficient in guiding visual search than one attentional template, and Huynh Cong and Kerzel (2021a) predict that recall precision should also be worse for two compared with one attentional template. However, the recall precision of attentional templates has been evaluated in single- (Kerzel & Witzel, 2019; Rajsic et al., 2017; Rajsic & Woodman, 2020) and dual-target search (Huynh Cong & Kerzel, 2020) but was never directly compared between these two situations.

To fill this gap, the present study aimed at demonstrating that the allocation of WM resources determines the efficiency of attentional templates in single- and dual-target search. Based on Huynh Cong and Kerzel (2021a), we assumed that attentional templates would receive fewer WM resources in dual- than single-target search, which would generate the costs associated with multiple attentional templates. In Experiment 1, we tested this assumption by comparing search and memory performance with two attentional templates, two simple WM representations, or one attentional template and one simple WM representation. In Experiment 2, we manipulated the frequency of visual search to investigate whether the attentional template always receives the largest amount of WM resources in single-target search (Kerzel & Witzel, 2019; Rajsic et al., 2017; Rajsic & Woodman, 2020). Finally, Experiment 3 used retro-cues to evaluate whether WM resources are more flexibly allocated between two attentional templates in dual-target search (Huynh Cong & Kerzel, 2020) than between one attentional template and one simple WM representation in single-target search.

Experiment 1

Experiment 1 served to determine whether the allocation of WM resources is responsible for the costs associated with multiple attentional templates. Participants performed a search or memory task while maintaining two attentional templates, two simple WM representations, or one attentional template and one simple WM representation. Each trial began with the presentation of two colors that were shown on a disk and a square. Participants had to memorize the two colors and the associated shapes. The retention interval was followed by the search or memory task (see Figure 1). In the search task, participants had to find the bar in one of the two memorized colors and report its tilt. In the memory task, participants had to recall the color associated with the shape shown at the center of the color wheel. We ran two blocked and one mixed condition (see Table 1). In the blocked condition with two attentional templates, the search task was performed on half of the trials to induce maintenance of the two colors as attentional templates. On the other half of the trials, one of the two colors was probed in the memory task. In the blocked condition with two simple WM representations, only the memory task was run to prevent maintenance of the two colors as attentional templates. In the mixed condition, participants maintained one attentional template and one simple WM representation. To designate one color as an attentional template and the other as a simple WM representation, we used the shapes in the cue display. For instance, the square would indicate the color that could be the target in the search task, whereas the disk would indicate the color that would only be probed in the memory task. Similar to the blocked conditions, the attentional template was used for the search

Figure 1
Illustration of Stimulus Displays and Time Course in the Three Experiments



Note. The cue displays contained two colors in two shapes to be memorized for a subsequent search or memory task. In the search task, participants had to find the bar in one of the two memorized colors and reported its tilt. In the memory task, participants had to recall the color indicated by the shape at the center of a color wheel. In Experiment 3 only, the retention interval was extended to include a 75% valid retro-cue. The retro-cue indicated the shape and location of the color that would be the most relevant for the upcoming search or memory task. See the online article for the color version of this figure.

Table 1
Distribution of Trials in Experiment 1

Trial	*N* of		Attnl. Template		Simple WM Rep.	
	Attnl. Template	Simple WM Rep.	Search Task	Memory Task	Search Task	Memory Task
Blocked: Attnl. Template	2	—	50%	50%	—	—
Blocked: Simple WM Rep.	—	2	—	—	—	100%
Mixed: Attnl. Template / Simple WM Rep.	1	1	50%	25%	—	25%

Note. The WM load was always two, but the number of attentional templates and simple WM representations varied between conditions.

and memory task, whereas the simple WM representation was only probed in the memory task.

Concerning search performance, we expected RTs to be delayed in the blocked compared with the mixed condition, indicating that two attentional templates are less efficient than a single attentional template (Barrett & Zobay, 2014; Biderman et al., 2017; Dombrowe et al., 2011; Grubert et al., 2016; Houtkamp & Roelfsema, 2009; Stroud et al., 2011). Critically, we assumed that recall precision, which indexes the allocation of WM resources (Bays et al., 2009; Bays & Husain, 2008; Ma et al., 2014) would follow the same pattern. That is, recall precision should be lower for one of two attentional templates in the blocked condition than for a single attentional template maintained with a simple WM representation in the mixed condition. Note that the WM load is the same in the blocked and mixed condition as participants always memorized two colors. However, as proposed by Huynh Cong and Kerzel (2021a), WM resources should be evenly shared between two attentional templates (Huynh Cong & Kerzel, 2020), but biased toward the attentional template when maintained with a simple WM representation (Kerzel & Witzel, 2019; Rajsic et al., 2017; Rajsic & Woodman, 2020). Finally, we expected recall precision to be similar in the two blocked conditions since there is no reason for unbalanced allocation of WM resources between two equally relevant attentional templates or simple WM representations. To estimate recall precision, we decomposed raw memory errors and used the standard deviations (*SD*s) of recall (see below). Because *SD*s are inversely related to recall precision, small *SD*s indicate precise recall and large *SD*s indicate poor recall.

Method

Participants

Twenty-four undergraduate students participated for class credit (age: M = 20.5 years, SD = 2.2; three males). Because no previous study compared the recall precision of attentional templates in single- and dual-target search, the required sample size was difficult to estimate. However, we based our estimation on Rajsic et al. (2017) to ensure that we replicated the difference in recall precision between an attentional template and a simple WM representation. Their Cohen's d_z was approximately .55, which requires a sample size of at least 22 (α = .05, power = .8) according to G*Power (Faul et al., 2007). Therefore, we aimed for a sample size of 24 participants as in similar studies (e.g., Rajsic & Woodman, 2020), which allowed us to detect differences with d_z of .52. The study was approved by the ethics committee of the Faculty of Psychology and Education 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 each experiment.

Apparatus

Stimuli were presented on a 22.5-in. LCD monitor with a refresh rate of 100 Hz and a pixel resolution of 1,920 × 1,200 (VIEWPixxLight, VPixx Technologies Inc., Saint-Bruno, Canada), driven by an AMD Radeon HD 7470 with a color resolution of eight bits per channel. CIE1931 chromaticity coordinates and luminance (xyY) of the monitor primaries were R = (.673, .309, 54.2), G = (.096, .747, 123.8), and B = (.100, .093, 19.6). Gamma curves of the monitor primaries were measured with a ColorCAL MKII colorimeter (Cambridge Research Systems, Rochester, U.K.) to perform gamma corrections. Viewing distance was maintained with a chin/forehead rest at 66 cm.

Stimuli

The experiment was run on MATLAB using the Psychtoolbox-3 (Brainard, 1997; Pelli, 1997). All stimuli were displayed on a gray background, with a light gray fixation cross (.13° × .13°). Figure 1 illustrates stimuli and time course. Each trial began with a cue display (300 ms) where one disk (radius of .25°) and one square (.45° × .45°) were shown in the two colors to memorize. The disk and square were presented randomly left and right at .5° from the fixation cross. Following a blank interstimulus interval (500 ms), the search display (100 ms) or the color wheel (until response) appeared. The search display contained four rectangular bars (.5° × .25°) tilted by 45° of rotation from vertical. The bars appeared on the diagonals through fixation at an eccentricity of 1.6°. The orientations of the bars were random with the constraint that two bars were tilted to the left and two bars tilted to the right. One of the bars was in one of the two memorized colors, whereas the others appeared in different colors. The target bar appeared at a random location but equally likely on the left and right. The color wheel had an inner and outer rim with a radius of .87° and 1.31°, respectively. At the center of the color wheel, the disk or square from the cue display was presented with an attached line cursor (.2° line width) in the currently selected color of the wheel. The interval between the response in the search display or color wheel, and the onset of the next cue display was 1,000 ms.

The colors were defined in CIELAB space because CIELAB is a model of color appearance where distances approximate perceived color differences (Fairchild, 2005). The white point of CIELAB was xyY (.280, .358, 195.3). Stimuli were presented on a gray background with a luminance of 28.6 cd/m^2 or L* = 45. The fixation cross was light gray with a luminance of 57.6 cd/m^2 or L* = 61. The six colors used in cue and search displays were sampled along an isoluminant hue circle at a lightness of L* = 61, and a chroma of 59. We selected six colors separated by a hue difference of 60°: orange (45°), amber (105°), green (165°), blue (225°), purple (285°), and pink (345°). On each trial, we jittered the rotation of all colors by the same amount, randomly between +20° and −20°. The random jitter ensured that colors were maintained in WM (Carlisle et al., 2011; Woodman et al., 2013; Woodman & Arita, 2011). The hue difference of 60° prevented search biases that result from color similarity and category membership (Witzel & Gegenfurtner, 2013, 2015). To cancel motor biases, the spatial orientation of the zero-hue angle was randomized between trials.

Procedure

Participants were instructed to memorize the two colors in the cue display together with the shape on which these colors were shown. For the search task, participants had to find the bar in one of the two memorized colors, and to report its tilt (left, right) by pressing the corresponding mouse button. They were instructed to respond as fast and accurately as possible. If a response was incorrect, early (RTs < 200 ms) or late (RTs > 1,200 ms), the corresponding visual feedback was shown. For the memory task, participants had to recall the color indicated by the shape at the center of the color wheel. They could rotate the line cursor by turning the mouse around the initial mouse position and select a color by mouse click. Participants were asked to be as precise as possible without consideration of time. They started the experiment by practicing the task until they felt comfortable with it, but at least for 40 trials. Every 64 trials, visual feedback about the percentage of correct responses, the median RTs, and the mean distance between the true and judged color were displayed during a self-terminated break of at least 5 seconds.

Design

The three conditions (blocked condition with two attentional templates, blocked condition with two simple WM representations, mixed condition with one attentional template and one simple WM representation) were run in separate blocks of 128 trials. The order of conditions was counterbalanced across participants and repeated once for a total of 256 trials per condition. In the blocked condition with two attentional templates, participants unpredictably performed the search or memory task. On trials with the search task, the search display contained one of the two memorized colors. On trials with the memory task, each color was equally likely to be probed. In the blocked condition with two simple WM representations, only the memory task was performed and each memorized color was equally likely to be probed. In the mixed condition with one attentional template and one simple WM representation, participants unpredictably performed the search or memory task. The search displays always contained the color indicated by a fixed shape in the cue display, which was the disk for half participants and the square for the other half. For the memory task, each color was equally likely to be probed.

Results

In the following analyses, we controlled the false-discovery-rate of multiple *t* tests (Benjamini & Hochberg, 1995), but we reported uncorrected *p* values for clarity. The *t* tests remained significant after correction unless otherwise noted.

Search Task

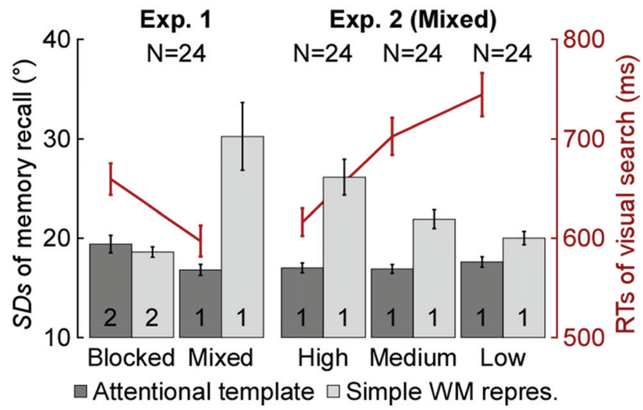
We excluded trials with RTs shorter than 200 ms or longer than 1,200 ms (3%). Then, the data for each participant and condition were trimmed by removing correct trials with RTs that were further than 2.5 *SD*s away from the respective condition mean, which amounted to 1% of the trials. Overall, the percentage of choice errors was 11%. To compare search performance in the blocked and mixed conditions, we conducted paired sample *t* tests on RTs from trials with correct responses and error rates. As shown in Figure 2 (left), RTs were delayed with two attentional templates in the blocked condition compared with one attentional template in the mixed condition (659 vs. 597 ms), $t(23) = 6.42$, $p < .001$, $d_z = 1.31$. Similarly, choice errors were more frequent in the blocked than the mixed condition (15.6% vs. 7.2%), $t(23) = 6.93$, $p < .001$, $d_z = 1.41$. Thus, two attentional templates were less efficient in guiding visual search than a single attentional template.

Memory Task

Consistent with studies that assessed the allocation of WM resources during visual search (Dube et al., 2019; Hollingworth & Hwang, 2013; Huynh Cong & Kerzel, 2020; Kerzel & Witzel, 2019; Rajsic et al., 2017; Rajsic & Woodman, 2020), we decomposed raw memory errors (i.e., degrees of distance between the true and judged colors in CIELAB space) into the three components of the swap model (Bays et al., 2009). Namely, a uniform distribution that reflects the proportion of random guesses (P_{Guess}), a von Mises distribution that reflects the proportion of responses to the nonprobed color (P_{Swap}), and a von Mises distribution that reflects the precision of responses to the probed color (P_{SD}). Although other models may better estimate recall precision and resource allocation (see van den Berg et al., 2014), P_{SD} remains relevant in this regard. As expected based on resource models of WM (Ma et al., 2014), P_{SD} has been shown to vary as a function of set size and relevance according to a power-law function (Bays et al., 2009; Dube et al., 2017; Emrich et al., 2017). Therefore, we focused the following analyses on this parameter and reported results for P_{Guess} and P_{Swap} in the online supplemental materials. Fits were performed by the MemToolbox (Suchow et al., 2013).

To evaluate recall precision, we conducted a 2 × 2 within-subjects analysis of variance (ANOVA) with the factors task Context (blocked vs. mixed) and Representation type (attentional template vs. simple WM representation) on P_{SD}. We found main effects of task Context, $F(1, 23) = 7.76$, $p = .011$, $\eta_p^2 = .252$, and Representation Type, $F(1, 23) = 12.15$, $p = .002$, $\eta_p^2 = .346$. Importantly, the theoretically relevant interaction was also significant, $F(1, 23) = 15.61$, $p = .001$, $\eta_p^2 = .404$. To follow up on this interaction, we answered our primary question about how the recall precision of attentional templates changed from single- to dual-target search. As can be seen in Figure 2 (left), *SD*s were larger when recalling attentional templates in the blocked compared with the mixed condition (19.4 vs. 16.8), $t(23) = 2.61$, $p = .016$, $d_z = .53$, indicating poorer recall precision in dual- than single-target search. Although WM

Figure 2
Standard Deviations (SDs) of Memory Recall and Reaction Times (RTs) of Visual Search in Experiments 1 and 2



Note. Small *SD*s indicate precise recall and large *SD*s indicate poor recall. Numbers on the bars indicate how many attentional templates or simple WM representations were maintained in each condition. The left panel shows *SD*s for attentional templates and simple WM representations in the blocked and mixed conditions of Experiment 1. The right panel shows *SD*s for attentional templates and simple WM representations in the high-, medium-, and low-frequency conditions of Experiment 2. For each experiment, RTs are represented by the red lines. Error bars depict one standard error of the mean. See the online article for the color version of this figure.

load was always two, fewer WM resources were allocated to an attentional template if it was maintained with another attentional template than if it was maintained with a simple WM representation. The opposite pattern was observed for the recall precision of simple WM representations. *SD*s were smaller when recalling simple WM representations in the blocked compared with the mixed condition (18.6 vs. 30.2), $t(23) = 3.54$, $p = .002$, $d_z = .72$, indicating better recall precision in the blocked than the mixed condition. Thus, more WM resources were allocated to a simple WM representation if it was maintained with another simple WM representation than if it was maintained with an attentional template. Finally, we compared attentional templates and simple WM representations in the blocked and mixed conditions. In the blocked condition, *SD*s were similar with two attentional templates and two simple WM representations (19.4 vs. 18.6), $t(23) = 1.04$, $p = .308$, $d_z = .21$. In the mixed condition, however, *SD*s were much smaller when recalling the attentional template compared with the simple WM representation (16.8 vs. 30.2), $t(23) = 3.81$, $p = .001$, $d_z = .78$, confirming that WM resources were allocated differently in single- and dual-target search.

Discussion

The allocation of WM resources may determine the efficiency of attentional templates during visual search (Huynh Cong & Kerzel, 2021a). Therefore, the reduced efficiency in dual- compared with single-target search may simply reflect that two attentional templates received fewer WM resources than one attentional template. To assess the value of this assumption, participants performed a search or memory task while maintaining two attentional templates, two simple WM representations, or one attentional template and one simple WM representation. In the search task, we replicated the costs associated with multiple attentional templates. That is, RTs were delayed and errors rates were higher with two attentional templates in the blocked condition compared with one attentional template in the mixed condition. As expected, these results corroborate the idea that attentional templates are less efficient in dual- than single-target search (Barrett & Zobay, 2014; Biderman et al., 2017; Dombrowe et al., 2011; Grubert et al., 2016; Houtkamp & Roelfsema, 2009; Stroud et al., 2011).

Importantly, the same pattern of results was found in recall precision, suggesting that the allocation of WM resources is critical in determining the efficiency of attentional templates during visual search (Huynh Cong & Kerzel, 2021a). In dual-target search, the allocation of WM resources was balanced between two equally relevant attentional templates, as evidenced by similar recall precision with two simple WM representations. In single-target search, however, WM resources were strongly biased toward the attentional template because it was recalled much more precisely than the simple WM representation maintained concurrently. Taken together, these results suggest that two attentional templates received an equal share of WM resources (Huynh Cong & Kerzel, 2020), whereas a single attentional template received the largest amount of WM resources (Kerzel & Witzel, 2019; Rajsic et al., 2017; Rajsic & Woodman, 2020). As a result, the efficiency of attentional templates was reduced in dual- compared with single-target search. Therefore, the allocation of WM resources explains how multiple attentional templates can guide visual search simultaneously and with variable efficiency, which is not possible with switches between WM states (Olivers et al., 2011) or changes in activity levels (Bahle et al., 2020).

Experiment 2

Consistent with previous studies (Kerzel & Witzel, 2019; Rajsic et al., 2017; Rajsic & Woodman, 2020), we showed that the attentional template was recalled much more precisely than the simple WM representation in the mixed condition. According to Huynh Cong and Kerzel (2021a), the attentional template received the largest amount of WM resources because it was the only relevant representation for visual search. However, an alternative explanation would be that the attentional template was more frequently used. That is, the attentional template was used in all search trials and in half of the memory trials in the mixed condition of Experiment 1, which amounted to 75% of trials (see Table 1). To rule out this possibility, we manipulated the frequency of visual search in Experiment 2. Three conditions were compared in a between-subjects design to avoid the carry-over of strategies. In the high-frequency condition, we replicated the mixed condition of Experiment 1. The attentional template was used for search on 50% of trials and was recalled on another 25% of trials, whereas the simple WM representation was recalled on the remaining 25% of trials. In the medium-frequency condition, the attentional template was used for search on 25% of trials and was recalled on another 25% of trials, whereas the simple WM representation was recalled on 50% of trials. Finally, in the low-frequency condition, the attentional template was used for search on 12.5% of trials and was recalled on another 12.5% of trials, while the simple WM representation was recalled on 75% of trials. If a single attentional template always receives the largest amount of WM resources because of its status in visual search (Huynh Cong & Kerzel, 2021a), recall precision should always be better with an attentional template compared with a simple WM representation. In contrast, if WM resources are allocated only according to the frequency of visual search, we would expect recall precision to be better with the attentional template than the simple WM representation in the high-frequency condition, but worse in the low-frequency condition.

Method

Participants

A first group of 25 undergraduate students performed the high-frequency condition (age: $M = 19.4$ years, $SD = 1.3$; six males), a second group of 24 performed the medium-frequency condition (age: $M = 19.9$ years, $SD = 1.6$; four males), and a third group of 24 performed the low-frequency condition (age: $M = 19.8$ years, $SD = 1.7$; two males). One participant was excluded from the high-frequency condition due to high error rates (23%) compared with the remaining sample ($M = 8.3\%$, $SD = 3.5$).

Stimuli and Procedure

These were identical to Experiment 1 with the following exceptions. We only presented the mixed condition and manipulated the frequency of visual search in three conditions (high-, medium-, and low-frequency condition). The conditions are explained in the introduction and were performed by different groups of participants.

Each group of participants performed six blocks of 128 trials for a total of 768 trials.

Results

Search Task

Overall, the percentages of choice errors were 8%, 8%, and 11% in the high-, medium-, and low-frequency conditions, respectively. As in Experiment 1, we excluded trials with RTs shorter than 200 ms or longer than 1,200 ms (4%, 6%, 6%), and trials with outlier RTs (3%, 3%, 2%). To compare search performance in the three groups, we conducted one-way ANOVAs on RTs from trials with correct responses and error rates. As shown in Figure 2 (right), RTs increased as the frequency of visual search decreased, $F(2, 69) = 12.62$, $p < .001$, $\eta_p^2 = .268$. Between-subjects comparisons revealed that RTs were shorter in the high-frequency condition compared with the medium-frequency condition (616 vs. 702 ms), $t(46) = 3.68$, $p = .001$, $d_s = 1.06$. However, the difference between the medium- and low-frequency conditions did not reach significance (702 vs. 744 ms), $t(46) = 1.49$, $p = .142$, $d_s = .43$. For error rates, the effect of visual search frequency approached significance, $F(2, 69) = 3.05$, $p = .054$, $\eta_p^2 = .081$, but none of the between-subjects comparisons were significant, $ps > .058$.

Memory Task

To evaluate recall precision, P_{SD} was entered into a 2 × 3 mixed ANOVA with the factors Representation type (attentional template vs. simple WM representation) and Frequency of Visual Search (high, medium, low). We found main effects of Representation Type, $F(1, 69) = 64.00$, $p < .001$, $\eta_p^2 = .481$, and Frequency of Visual Search, $F(2, 69) = 3.83$, $p = .026$, $\eta_p^2 = .100$. Critically, the interaction between these two factors was significant, $F(2, 69) = 8.34$, $p = .001$, $\eta_p^2 = .195$, showing that the advantage of the attentional template over the simple WM representation declined as the frequency of visual search decreased. However, as shown in Figure 2 (right), within-subjects comparisons revealed that *SD*s for the attentional template were significantly smaller than *SD*s for the simple WM representation in all conditions: the high-frequency condition (17.0 vs. 26.1), $t(23) = 5.70$, $p < .001$, $d_z = 1.16$, the medium-frequency condition (16.9 vs. 21.9), $t(23) = 4.66$, $p < .001$, $d_z = .95$, and the low-frequency condition (17.6 vs. 20.0), $t(23) = 3.26$, $p = .003$, $d_z = .67$. Further, one-way ANOVAs showed that *SD*s for the attentional template did not change across frequency of visual search, $F(2, 69) = .68$, $p = .508$, $\eta_p^2 = .019$. In contrast, *SD*s for the simple WM representation became smaller as the frequency of visual search decreased, $F(2, 69) = 6.41$, $p = .003$, $\eta_p^2 = .157$.

Discussion

According to Huynh Cong and Kerzel (2021a), an attentional template should always receive the largest amount of WM resources in single-target search because it is the only relevant representation for visual search. Although previous studies supported this assumption (Kerzel & Witzel, 2019; Rajsic et al., 2017; Rajsic & Woodman, 2020), it has not been tested whether this is the case when visual search is rarely performed. Here, participants maintained a simple WM representation with an attentional template that was used for visual search with high (i.e., 50% of trials), medium (i.e., 25%), or low (i.e., 12.5%) frequency. In each condition, *SD*s in the memory task indicated that the attentional template was recalled more precisely than the simple WM representation. Moreover, the recall precision of the attentional template remained unchanged across the three conditions, suggesting that it was always maximal. These results indicate that an attentional template receives the largest amount of WM resources in single-target search, regardless of visual search frequency. Therefore, WM resources seem to be strongly biased toward the attentional template because of its status in visual search (Huynh Cong & Kerzel, 2021a).

Although Huynh Cong and Kerzel (2021a) correctly predicted that the attentional template would always be recalled with the highest precision, the fact that its recall precision did not change is unexpected for two reasons. First, the recall precision of the simple WM representation improved across conditions. If WM resources are limited, allocating more WM resources to the simple WM representation should occur at the expense of the attentional template. Second, RTs decreased when the frequency of visual search was high. If the search efficiency of attentional templates only depended on WM resources, RTs and recall precision should always match. These points are further considered in the General Discussion.

Experiment 3

Results from the mixed condition support the conclusion that an attentional template always receives the largest amount of WM resources in single-target search (Kerzel & Witzel, 2019; Rajsic et al., 2017; Rajsic & Woodman, 2020). In dual-target search, however, the allocation of WM resources is flexibly adjusted and balanced (Huynh Cong & Kerzel, 2020). In this situation, two attentional templates may receive an amount of WM resources that depends on their respective relevance for visual search (Huynh Cong & Kerzel, 2021a). To test this hypothesis, Experiment 3 used 75% valid retro-cues that indicated during maintenance which attentional template or simple WM representation would be the most relevant for the upcoming search or memory task (see Figure 1). Retro-cues are expected to modify the initial allocation of WM resources in ways that create a bias toward the cued representation.

We compared the blocked and mixed conditions (see Experiment 1) in a between-subjects design to have enough trials with invalid retro-cues for analysis. One group of participants performed the blocked condition, in which two attentional templates or two simple WM representations were maintained. Another group of participants performed the mixed condition, in which one attentional template and one simple WM representation were maintained. We expected recall precision to be better with valid than invalid retro-cues, replicating the retro-cue effect (Landman et al., 2003; Nobre et al., 2007). However, the retro-cue effect should be larger with two attentional templates in the blocked condition compared with a single attentional template maintained with a simple WM representation in the mixed condition. The reason is that WM resources should be flexibly allocated between two attentional templates in dual-target search. In single-target search, however, WM resources should be strongly biased toward the attentional template, leaving no opportunity for retro-cues to overcome this bias. Critically, since the allocation of WM resources may determine the efficiency of attentional templates (Huynh Cong & Kerzel, 2021a), we expected RTs to be shorter with valid compared with invalid retro-cues. Similar to recall precision, however, the retro-cue effect on RTs should be larger in the blocked than the mixed condition.

Method

Participants

A first group of 24 undergraduate students performed the blocked condition (age: M = 20.0 years, SD = 1.1; three males), whereas a second group of 24 participants performed the mixed condition (age: M = 20.0 years, SD = 1.5; one male).

Stimuli and Procedure

These were identical to Experiment 1 with the following exceptions. A retro-cue was presented between the cue and search display, separated by 500-ms blank interstimulus intervals to guarantee its full use and to avoid the time range of iconic memory (Irwin & Thomas, 2008). The retro-cue (200 ms) was a black outline (.2° line width) of the lateral disk or square from the cue display (see Figure 1). On 75% of trials, the retro-cue correctly indicated the shape and location of the relevant color for the upcoming search or memory task. On 25% of trials, the retro-cue indicated the shape and location of the irrelevant color for the upcoming search or memory task. To have at least 48 trials with invalid retro-cues in each condition, two independent groups of participants performed the blocked and mixed conditions. In the first group, the blocked conditions with two attentional templates or two simple WM representations were run in separate blocks of 128 trials. The order of the two blocked conditions was counterbalanced across participants and repeated three times for a total of 384 trials per type of representation. In the second group, the mixed condition was run in six blocks of 128 trials for a total of 768 trials.

Note that trials in the mixed condition were distributed as in Experiment 1 where the attentional template was used more frequently than the simple WM representation (see Table 1). However, Experiment 2 showed that recall precision was always better for the attentional template compared with the simple WM representation, regardless of visual search frequency. In addition, the validity of the retro-cue was explicitly announced to participants to promote its strategic use, whereas the frequency of use of the attentional template and the simple WM representation was completely unknown to them.

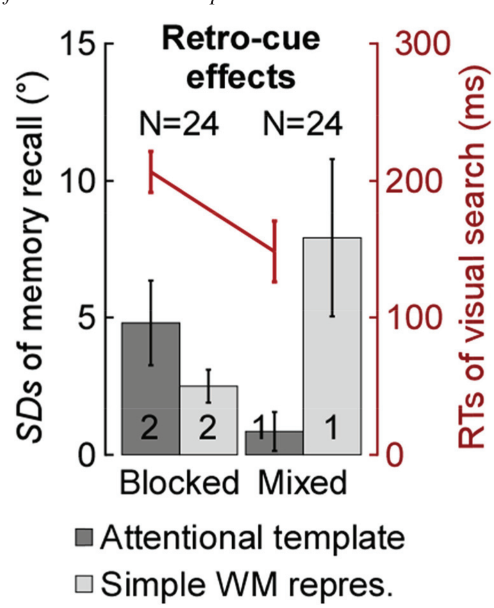
Results

Search Task

Overall, the percentage of choice errors was 12% in the blocked condition and 7% in the mixed condition. As in previous experiments, we excluded trials with RTs shorter than 200 ms or longer than 1,200 ms (5%, 3%), and trials with outlier RTs (less than 1% in both conditions). RTs from trials with correct responses were entered into a 2 × 2 mixed ANOVA with the factors task Context (blocked vs. mixed) and Retro-cue (valid vs. invalid). We found main effects of task Context, $F(1, 46) = 6.16$, $p = .017$, $\eta_p^2 = .118$, and Retro-cue, $F(1, 46) = 175.13$, $p < .001$, $\eta_p^2 = .792$. Critically, the interaction between these two factors was also significant, $F(1, 46) = 4.55$, $p = .038$, $\eta_p^2 = .090$. Consistent with the retro-cue effect, RTs were shorter with valid than invalid retro-cues in the blocked (619 vs. 825 ms), $t(23) = 13.73$, $p < .001$, $d_z = 2.80$, and the mixed condition (591 vs. 739 ms), $t(23) = 6.70$, $p < .001$, $d_z = 1.37$. As shown in Figure 3, however, a between-subjects comparison revealed that the retro-cue effect (i.e., invalid—valid retro-cues) was larger in dual-target search (blocked condition) compared with singlet-target search (mixed condition, 206 vs. 148 ms), $t(46) = 2.13$, $p = .038$, $d_s = .62$. Thus, the underlying allocation of WM resources may be more flexible with two attentional templates compared with a single attentional template maintained with a simple WM representation. Concerning error rates, the ANOVA also revealed a main effect of task Context, $F(1, 46) = 17.44$, $p < .001$, $\eta_p^2 = .275$, a main effect of Retro-cue, $F(1, 46) = 144.01$, $p < .001$, $\eta_p^2 = .713$, and a significant two-way interaction, $F(1, 46) = 10.40$, $p = .002$, $\eta_p^2 = .184$. Similar to RTs, choice errors were reduced with valid compared with invalid retro-cues in the blocked (7.2% vs. 27.4%), $t(23) = 9.70$, $p < .001$, $d_z = 1.98$, and the mixed condition (4.6% vs. 15.4%), $t(23) = 5.34$, $p < .001$, $d_z = 1.09$. Moreover, the retro-cue effect was also larger with two attentional templates in the blocked condition compared with a single attentional template in the mixed condition (20.2% vs. 10.8%), $t(46) = 3.23$, $p = .002$, $d_s = .93$.

Figure 3

Retro-Cue Effects (i.e., Invalid—Valid Retro-Cues) Computed on Standard Deviations (SDs) of Memory Recall and Reaction Times (RTs) of Visual Search in Experiment 3



Note. Numbers on the bars indicate how many attentional templates or simple WM representations were maintained in each condition. For *SD*s, retro-cue effects are shown for attentional templates and simple WM representations in the blocked and mixed conditions. For RTs, retro-cue effects are represented by the red lines. Error bars depict one standard error of the mean. See the online article for the color version of this figure.

Memory Task

Recall precision was evaluated by entering P_{SD} into a 2 × 2 × 2 mixed ANOVA with the factors task Context (blocked vs. mixed), Representation type (attentional template vs. simple WM representation), and Retro-cue (valid vs. invalid). We found main effects of Representation Type, $F(1, 46) = 7.01$, $p = .011$, $\eta_p^2 = .132$, and Retro-cue, $F(1, 46) = 20.50$, $p < .001$, $\eta_p^2 = .308$. In addition, the two-way interaction between task Context and Representation Type, $F(1, 46) = 16.59$, $p < .001$, $\eta_p^2 = .265$, was significant, as well as the three-way interaction, $F(1, 46) = 8.33$, $p = .006$, $\eta_p^2 = .153$. The two-way interaction replicated results of Experiment 1 in a between-subjects design. That is, *SD*s were larger when recalling attentional templates in the blocked compared with the mixed condition (19.8 vs. 17.5), $t(46) = 2.03$, $p = .048$, $d_s = .59$, but the opposite was true for simple WM representations, which had smaller *SD*s in the blocked compared with the mixed condition (18.5 vs. 23.6), $t(46) = 2.71$, $p = .009$, $d_s = .78$.

To answer our primary question, we untangled the three-way interaction by computing the retro-cue effect (i.e., invalid—valid retro-cues) for each condition. The respective means are shown in Figure 3. We conducted a new 2 × 2 mixed ANOVA with the factors task Context (blocked vs. mixed) and Representation type (attentional template vs. simple WM representation) on these values. Neither the main effect of task Context, $F(1, 46) = .16$, $p = .695$, $\eta_p^2 = .003$, nor the main effect of Representation Type, $F(1, 46) = 2.07$, $p = .157$, $\eta_p^2 = .043$, reached significance. Importantly, the interaction between these two factors was significant, $F(1, 46) = 8.33$, $p = .006$, $\eta_p^2 = .153$. The retro-cue effect was larger with attentional templates in the blocked than in the mixed condition (4.8 vs. .9), $t(46) = 2.34$, $p = .024$, $d_s = .68$, indicating that WM resources were more flexibly allocated to one of two attentional templates than to a single attentional template maintained with a simple WM representation. In contrast, the retro-cue effect was smaller with simple WM representations in the blocked than in the mixed condition (2.5 vs. 7.9), but this effect did not reach significance, $t(46) = 1.83$, $p = .074$, $d_s = .53$. Moreover, we compared the retro-cue effects between attentional templates and simple WM representations separately for the blocked and mixed conditions. In the blocked condition, the retro-cue effect was not different between two attentional templates and two simple WM representations (4.8 vs. 2.5), $t(23) = 1.54$, $p = .137$, $d_z = .31$, reflecting that WM resources were allocated with similar flexibility. Conversely, the retro-cue effect was much smaller with the attentional template compared with the simple WM representation in the mixed condition (.9 vs. 7.9), $t(23) = 2.45$, $p = .022$, $d_z = .50$, indicating that the allocation of WM resources was less flexible with the attentional template compared with the simple WM representation. In fact, WM resources were allocated with reduced flexibility in this case because the attentional template always received the largest share, leaving no opportunity for retro-cues to overcome this bias. That is, the attentional template was recalled more precisely than the simple WM representation in the mixed condition, whether the retro-cue was valid (17.1 vs. 19.7), $t(23) = 3.76$, $p = .001$, $d_z = .77$, or invalid (17.9 vs. 27.5), $t(23) = 3.21$, $p = .004$, $d_z = .66$. No other effect reached significance, $ps > 157$.

Discussion

Contrary to single-target search, the allocation of WM resources is flexibly adjusted and balanced in dual-target search (Huynh Cong & Kerzel, 2020), suggesting that two attentional templates receive an amount of WM resources that depends on their respective relevance for visual search (Huynh Cong & Kerzel, 2021a). To assess the value of this assumption, we used 75% valid retro-cues that indicated which attentional template or simple WM representation would be the most relevant for the upcoming search or memory task. Consistent with the retro-cue effect (Landman et al., 2003; Nobre et al., 2007), attentional templates were recalled more precisely with valid than invalid retro-cues. Importantly, however, the retro-cue effect was larger with two attentional templates in the blocked condition compared with a single attentional template maintained with a simple WM representation in the mixed condition. Thus, the allocation of WM resources was more flexible in dual- than single-target search. In dual-target search, retro-cues indicated the most relevant attentional template, which received more WM resources than the other attentional template. In fact, WM resources were allocated with the same flexibility between two attentional templates as between two simple WM representations since the corresponding retro-cue effect was of similar magnitude. In single-target search, however, the allocation of WM resources was less flexible. That is, the retro-cue effect was reduced with the attentional template compared with the simple WM representation because the attentional template was always recalled more precisely, confirming that the allocation of WM resources was strongly biased toward the attentional template (Kerzel & Witzel, 2019; Rajsic et al., 2017; Rajsic & Woodman, 2020). Taken together, these results indicate that WM resources were flexibly allocated in dual-target search, but severely constrained in single-target search.

Importantly, search performance closely mirrored the recall precision of attentional templates. That is, RTs were shortened and error rates were lowered with valid than invalid retro-cues, replicating the retro-cue effect. Similar to *SD*s, however, the retro-cue effect on RTs and error rates was larger with two attentional templates in the blocked condition compared with a single attentional template in the mixed condition. Therefore, the flexibility of resource allocation was directly reflected in the efficiency of attentional templates in single- and dual-target search (Huynh Cong & Kerzel, 2021a).

General Discussion

In three experiments, we investigated whether the allocation of WM resources determines the efficiency of attentional templates in single- and dual-target search. Based on Huynh Cong and Kerzel (2021a), we assumed that attentional templates would receive fewer WM resources in dual- than single-target search, which would generate the costs associated with multiple attentional templates. Participants performed a search or memory task while maintaining two attentional templates, two simple WM representations, or one attentional template and one simple WM representation. In Experiment 1, we replicated the costs associated with multiple attentional templates and demonstrated that the allocation of WM resources was critically involved. Thus, RTs were delayed and error rates increased with two attentional templates compared with one attentional template, corroborating the idea that dual-target search is less efficient than single-target search (Barrett & Zobay, 2014; Biderman et al., 2017; Dombrowe et al., 2011; Grubert et al., 2016; Houtkamp & Roelfsema, 2009; Stroud et al., 2011). Importantly, the same pattern of results was found on recall precision. Despite equal WM load, recall precision was lower (i.e., *SD*s were larger) with one of two attentional templates compared with a single attentional template maintained with a simple WM representation. Consistent with the resource hypothesis of visual search (Huynh Cong & Kerzel, 2021a), fewer WM resources were available for attentional templates in dual- than single-target search, which reduced their efficiency during visual search. Moreover, comparisons of recall precision between attentional templates and simple WM representations confirmed that WM resources were allocated differently in single- and dual target search. On the one hand, the attentional template was recalled much more precisely than the simple WM representation in single-target search (Experiment 1), regardless of visual search frequency (Experiment 2) and retro-cue validity (Experiment 3). That is, the attentional template always received the largest amount of WM resources (Kerzel & Witzel, 2019; Rajsic et al., 2017; Rajsic & Woodman, 2020) because it was the only relevant representation for visual search (Huynh Cong & Kerzel, 2021a). On the other hand, two attentional templates were recalled as precisely as two simple WM representations (Experiment 1) and benefited similarly from retro-cues in dual-target search (Experiment 3). Thus, the allocation of WM resources was flexibly adjusted and balanced between two attentional templates depending on their respective relevance for visual search (Huynh Cong & Kerzel, 2020, 2021a). Taken together, these results suggest that two attentional templates receive an equal share of WM resources in dual-target search, while an attentional template receives the largest amount of WM resources when maintained with a simple WM representation in single-target search. As a result, attentional templates are more efficient in single- than dual-target search.

The Role of WM Resources in Visual Search

Consistent with prominent models of visual search (Bundesen, 1990; Desimone & Duncan, 1995; Wolfe, 1994), strong evidence indicates that attentional templates are maintained in WM (Carlisle et al., 2011; Woodman et al., 2013; Woodman & Arita, 2011). Therefore, it has become necessary to consider the architecture of WM and its processes when investigating template-guided visual search. In that sense, state-based models of WM (Cowan, 1999, 2005; Gilchrist & Cowan, 2011; McElree, 2001; Oberauer, 2002) have had considerable influence on the interpretation of search performance over the past years. Based on these models, the single-template hypothesis proposed that only one attentional template is maintained in an "active" WM state by the focus of attention (Olivers et al., 2011), whereas the multiple-template hypothesis considers that several attentional templates are "active" in WM (Beck et al., 2012), involving a broader focus of attention (Bahle et al., 2020). Although these two hypotheses proved useful, both revealed their limits in explaining how multiple attentional templates can guide visual search with variable efficiency. From the perspective of the single-template hypothesis (Olivers et al., 2011), the efficiency of attentional templates depends on the sequential switch between "accessory" and "active" WM states (Ort et al., 2017, 2018). However, the necessity to sequentially switch between WM states is called into question by numerous studies showing that more than one representation can be "active" at a time (Ansorge et al., 2005; Bahle et al., 2020; Beck et al., 2012; Beck & Hollingworth, 2017; Berggren et al., 2020; Christie et al., 2015; Grubert & Eimer, 2015, 2016; Huynh Cong & Kerzel, 2020, 2021b; Irons et al., 2012; Kerzel & Grubert, 2021; Kerzel & Witzel, 2019; Moore & Weissman, 2010; Roper & Vecera, 2012). From the perspective of the multiple-template hypothesis (Beck et al., 2012), several attentional templates are simultaneously "active" in WM, but changes in activity determine their efficiency during visual search (Bahle et al., 2020). Although this assumption is consistent with observations showing that multiple "active" representations interact with visual search, it is not clear how levels of activity operate in WM and how changes in activity can be measured independently from visual search. Further, levels of activity suggest that the "active" state is not a discrete slot in WM, but a space where representations share a continuous medium. Therefore, it is critical to consider continuous WM processes that differentiate between multiple "active" representations.

In the present study, we argue that the allocation of WM resources is a promising candidate in this regard. Based on resource models of WM (Bays et al., 2009; Bays & Husain, 2008; Ma et al., 2014) and studies that investigated visual search from this perspective (Dube et al., 2019; Dube & Al-Aidroos, 2019; Hollingworth & Hwang, 2013; Huynh Cong & Kerzel, 2020, 2021b; Kerzel & Witzel, 2019; Rajsic et al., 2017; Rajsic & Woodman, 2020), Huynh Cong and Kerzel (2021a) recently conceptualized the relationships between resource allocation and visual search. One of the central points of this new framework is that the allocation of WM resources determines the efficiency of attentional templates during visual search. Consistently, Experiment 1 demonstrated that two attentional templates were less efficient than a single attentional template because they each received a smaller amount of WM resources. In a similar vein, Experiment 3 showed that retro-cues increased the amount of WM resources allocated to one of two attentional templates, which improved visual search. Thus, the resource hypothesis of visual search (Huynh Cong & Kerzel, 2021a) is in line with the idea that multiple attentional templates can guide visual search (Beck et al., 2012) and explains how their respective efficiency in guiding visual search can be variable, which is not possible with switches between WM states (Olivers et al., 2011) or changes in activity levels (Bahle et al., 2020).

The Interaction Between WM Resources and States

Importantly, however, Huynh Cong and Kerzel's (2021a) proposal remains compatible with the existence of an "active" state in WM. First, the framework acknowledges that representations can be recalled with high precision without interacting with visual search (Dube et al., 2019; Dube & Al-Aidroos, 2019; Hollingworth & Hwang, 2013), suggesting that another WM process, such as an "active" WM state, determines the status of attentional template. Second, the allocation WM resources is assumed to depend on the relevance of attentional templates for visual search, which may be consistent with an "active" state in WM. In three experiments, we observed that an attentional template always receives the largest amount of WM resources in single-target search, regardless of the frequency of visual search and the validity of retro-cues. In line with the literature (Kerzel & Witzel, 2019; Rajsic et al., 2017; Rajsic & Woodman, 2020), WM resources were strongly biased toward the attentional template with no possibility to reallocate WM resources to the simple WM representation. Thus, it is likely that the attentional template and the simple WM representation were maintained in distinct WM states, preventing the flexible allocation and reallocation of WM resources. In dual-target search, however, the allocation of WM resources was balanced between two attentional templates and could be adjusted with retro-cues, as with two simple WM representations. That is, WM resources were as flexibly allocated and reallocated between two attentional templates (Huynh Cong & Kerzel, 2020) as between two simple WM representations, suggesting that representations of the same type were maintained in the same WM state.

Open Questions

Although the results of the present study are generally predicted by the resource hypothesis of visual search (Huynh Cong & Kerzel, 2021a) and support this view, some important questions remain open.

First, our data cannot definitely rule out an architecture of WM where only one attentional template is "active" at a time (Olivers et al., 2011). For instance, it may be argued that one of two attentional templates is activated in dual-target search and that a switch of attentional templates occurs when the target does not correspond to the activated attentional template (Ort et al., 2017, 2018). As a result, search efficiency is impaired in dual- compared with single-target search. Although a growing body of studies indicates that multiple attentional templates can guide visual search simultaneously (Ansorge et al., 2005; Bahle et al., 2020; Beck et al., 2012; Beck & Hollingworth, 2017; Berggren et al., 2020; Christie et al., 2015; Grubert & Eimer, 2015, 2016; Huynh Cong & Kerzel, 2020, 2021b; Irons et al., 2012; Kerzel & Grubert, 2021; Kerzel & Witzel, 2019; Moore & Weissman, 2010; Roper & Vecera, 2012), further research is necessary to confirm that this is the case in our design.

Second, one result appears incompatible with Huynh Cong and Kerzel (2021a) proposal. In Experiment 2, the recall precision of the attentional template was always maximal, which is surprising because the recall precision of the simple WM representation improved at the same time. Because WM resources are limited, we would expect that an increase in the recall precision of the simple WM representation occurs at the expense of the attentional template. Interestingly, however, state-based models of visual search would predict pretty much the same, whether the focus of attention contains a single or multiple "active" representations. In both cases, the simple WM representation entering the focus of attention should at least partially deactivate the attentional template and reduce its recall precision. Therefore, additional work is necessary to understand why the recall precision of the attentional template was not affected by search and probing probabilities. Finally, another related issue is that RTs did not fully mirror the recall precision of the attentional template in Experiment 2, as would be expected if search efficiency only depended on WM resources. A possible explanation is that WM resources improved attentional guidance, but not subsequent recognition and decision processes. Thus, the attentional template may have received the largest amount of WM resources, which guaranteed efficient guidance of visual attention, but target recognition and decision may have been slowed when visual search was less frequent. However, effects of task probabilities in Experiment 2 need to be clarified before firm conclusions can be drawn.

Conclusion

Overall, we demonstrated that the allocation of WM resources determines the efficiency of attentional templates in single- and dual-target search. In dual-target search, two attentional templates receive an equal share of WM resources as they are equally relevant for visual search. In single-target search, however, an attentional template maintained with a simple WM representation always receives the largest amount of WM resources since it is the only relevant representation for visual search. As a result, the efficiency of attentional templates is reduced in dual- compared with single-target search. On this basis, we argue that theoretical advances in the WM literature, such as the emergence of the resource concept, is critical to fully understand visual search guided by multiple attentional templates.

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