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New Templates Interfere With Existing Templates Depending on Their Respective Priority in Visual Working Memory

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Attentional templates are stored representations of target features that guide visual search. While transiently active templates are as efficient as templates held in a sustained fashion, their simultaneous activation generates costs for the sustained template. Here, we investigated whether the quality of the memory representation determines these costs. Two possible target colors were cued before search display onset. In blocked conditions, the 2 colors either changed on every trial or were fixed throughout. In the mixed condition, 1 color was fixed, while the other varied from trial to trial. In Experiment 1, participants also reproduced 1 of the 2 target colors on a memory wheel after each search episode. The analysis of search performance replicated longer reaction times (RTs) to sustained than transient targets when template types were mixed, but no difference when they were blocked. Critically, analysis of memory judgments showed that random guesses for sustained templates increased from the blocked to the mixed condition, mirroring RTs. This suggests that newly activated transient templates retroactively interfered with already activated sustained templates, impairing their efficiency to guide attention and their stability in memory. Increasing the priority of sustained templates through maintenance constraints (Experiments 1 vs. 2) or retro-cueing (Experiment 3) reduced the associated costs. Finally, these costs were unaffected by different retention intervals (Experiment 4). We argue that retroactive interference affects the control of visual search and memory maintenance alike, but critically depends on the respective priority of representations in visual working memory.

Public Significance Statement

How do we find our wallet and key when we leave for work? When searching for known objects, we remember their respective features and match them to the visual inputs reaching our eyes. Depending on how often we have looked for these objects, corresponding features can be newly or durably stored in memory. The present study shows that new features interfere with well-known features when searching for both of them simultaneously. Under this condition, well-known features become less efficient in guiding visual search and are more often forgotten. However, our results also indicate that this interference could be reduced, if not eliminated, by manipulating the importance with which each type of feature was maintained in memory. Thus, our findings strongly suggest that searching for known objects critically depends on the relevance of their features in memory.

Keywords: visual search, attentional template, top-down control, visual working memory, retroactive interference

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A large part of our daily activities requires directing attention to goal-relevant objects. Visual search for these target objects is driven by stored representations of their known features. These attentional templates (Duncan & Humphreys, 1989) or attentional control sets (Folk, Remington, & Johnston, 1992) are activated shortly before the search task (Grubert & Eimer, 2018, 2020), and guide attention toward the locations of objects with template-matching attributes (Eimer, 2014). Most models of

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attention (Bundesen, Habekost, & Kyllingsbæk, 2005; Desimone & Duncan, 1995; Schneider, 2013; Wolfe, 2007) assume that templates are stored in visual working memory (VWM).

As VWM can hold three to four items (Cowan, 2001; Vogel, Woodman, & Luck, 2001), several attentional templates may operate at the same time. To investigate attentional guidance by multiple templates, previous studies compared single- to dual-target search with respect to overall performance or attentional capture. In this context, behavioral (Ansorge, Horstmann, & Carbone, 2005; Irons, Folk, & Remington, 2012; Kerzel & Witzel, 2019; Moore & Weissman, 2010; Roper & Vecera, 2012), electrophysiological (Christie, Livingstone, & McDonald, 2015; Grubert & Eimer, 2015, 2016), and eye movement (Beck & Hollingworth, 2017; Beck, Hollingworth, & Luck, 2012) studies showed that participants could concurrently employ two color templates. However, two simultaneous templates might not be as efficient as a single template. In fact, another body of studies reported performance impairments when participants searched for two possible targets relative to a single target, whether the relevant feature was shape (Houtkamp & Roelfsema, 2009), color (Dombrowe, Donk, & Olivers, 2011; Grubert, Carlisle, & Eimer, 2016; Stroud, Menneer, Cave, Donnelly, & Rayner, 2011), or both (Biderman, Biderman, Zivony, & Lamy, 2017).

While the debate about the efficiency of multiple templates is ongoing, the determinants of the associated costs remain poorly understood. Grubert, Carlisle, and Eimer (2016) proposed that an important factor was whether target features remained constant or changed through successive selection episodes. In fact, most studies that reported multiple template costs used two possible targets that varied between individual trials (e.g., Houtkamp & Roelfsema, 2009), involving the transient activation of templates in VWM. In contrast, most evidence for equal efficiency of two templates comes from studies that kept target features fixed across blocks of trials (e.g., Beck et al., 2012; Irons et al., 2012; Moore & Weissman, 2010). Here, corresponding templates may no longer be held in VWM, but may be transferred to a longer-term store. Consistent with theories of learning and automaticity (Anderson, 2000; Logan, 2002), long-term memory (LTM) may play a role in guiding visual search (Hutchinson & Turk-Browne, 2012; Stokes, Atherton, Patai, & Nobre, 2012; Summerfield, Lepsien, Gitelman, Mesulam, & Nobre, 2006) by taking over control of attention from VWM (Carlisle, Arita, Pardo, & Woodman, 2011; Gunseli, Olivers, & Meeter, 2016; Reinhart, Carlisle, & Woodman, 2014; Reinhart, McClenahan, & Woodman, 2016; Reinhart & Woodman, 2014; Woodman, Carlisle, & Reinhart, 2013). In that respect, Carlisle, Arita, Pardo, and Woodman (2011) used event-related potentials (ERPs) to explore the nature of memory representations controlling attention. During brief streaks of learning to search for a fixed target, they recorded the contralateral delay activity (CDA), an electrophysiological marker of storage in VWM (Luria, Balaban, Awh, & Vogel, 2016; Vogel & Machizawa, 2004). They found that the CDA decreased in amplitude across trials of searching for the same target. In fact, the CDA was reliably present only for the first four trials of each run. This suggests that within five trials, templates were no longer held in VWM, but had been transferred to LTM. Moreover, Woodman, Carlisle, and Reinhart (2013) showed that the decrease of CDA amplitude was mirrored by an increase of the anterior P170, reflecting the incremental build-up of LTM representations (Voss, Schendan, & Paller, 2010). The gradual tradeoff between the CDA and P170 amplitude as a function of target repetition confirms the progressive involvement of LTM in visual search.

Unlike LTM, VWM capacity is limited in terms of slots (Cowan, 2001; Vogel et al., 2001) or resources (Bays, Catalao, & Husain, 2009; Bays & Husain, 2008; Ma, Husain, & Bays, 2014), which leads to competitive interactions between simultaneously held representations (Oberauer, Lewandowsky, Farrell, Jarrold, & Greaves, 2012; Oberauer & Lin, 2017). On this basis, Grubert et al. (2016) hypothesized that multiple-feature search would be more impaired when guided by transiently activated templates in VWM, relative to templates held in a sustained fashion in LTM. Therefore, they compared the efficiency of multiple templates in blocks where targets varied from trial to trial, to blocks where targets remained fixed across trials. While reaction times (RTs) were delayed for variable compared with fixed target blocks, there was no corresponding delay or attenuation of N2pc components (see Kerzel & Witzel, 2019 for corresponding behavioral results). Because the N2pc is an ERP marker of template-guided attentional selection (Eimer & Kiss, 2008; Leblanc, Prime, & Jolicoeur, 2008; Lien, Ruthruff, Goodin, & Remington, 2008), these results indicate that sustained and transient templates were equally efficient in guiding attention, and that behavioral costs were generated at postattentional stages (Moore & Weissman, 2010). Consistently, the eye movement study of Goldstein and Beck (2018) demonstrated that sustained templates only improved behavioral performance by speeding template establishment and comparison processes.

These observations suggest that the efficiency of simultaneous templates does not depend on their sustained or transient nature. However, Berggren, Nako, and Eimer (2020) recently demonstrated that sustained templates are sometimes less efficient than transient templates. Berggren et al. (2020) compared the efficiency of both types of template when they were blocked or randomly intermixed. In the blocked condition with sustained templates, participants searched for one of two fixed target colors. In the blocked condition with transient templates, participants searched for one of two target colors that changed on every trial. They found faster RTs to fixed compared with variable targets, but no difference in the corresponding N2pc components. In line with previous observations (Goldstein & Beck, 2018; Grubert et al., 2016; Kerzel & Witzel, 2019; Moore & Weissman, 2010), sustained and transient templates were equally efficient in guiding attention when templates of the same type were activated together. In addition, Berggren et al. (2020) ran a mixed condition, where one of the two target colors changed from trial to trial, while the other remained fixed. Critically, RTs and the N2pc were delayed for fixed compared with variable targets, revealing a specific form of competition for mixed templates. When one template was transiently activated, while the other was held in a sustained fashion, the efficiency of the sustained template was impaired. According to one account, the costs associated with the sustained template are generated by its retrieval from LTM, which would involve its buffering into VWM (Cantor & Engle, 1993; Cowan, Donnell, & Saults, 2013; Fukuda & Woodman, 2017; Nairne & Neath, 2001; Reinhart & Woodman, 2014). If correct, the sustained template costs should only emerge for target features that have been transferred to LTM, which occurs after about five trials (Carlisle et al., 2011). Alternatively, the encoding of the new transient template within VWM would interfere with any other already activated template. As described in classic research on memory (e.g., Underwood, 1957), recently encoded information could generate retroactive interference effects on previous memory representations (Dewar, Cowan, & Sala, 2007; Wixted, 2004), even within VWM (Lewandowsky, Oberauer, & Brown, 2009; Mercer, 2018). The sustained template costs should thus emerge whenever there is a need to encode a new search template (i.e., from trial two onward). Consistently, Berggren et al. (2020, Experiments 2 and 3) found that the sustained template costs emerged reliably on the third trial of each run and did not increase in size for subsequent trials. They concluded that the establishment of a new search template retroactively interfered with the maintenance of an existing template, whether this template was represented in VWM or LTM.

Typically, costs of multiple templates have been investigated by focusing on the nature of target-defining features (Berggren et al., 2020; Grubert et al., 2016). However, the fidelity with which templates are represented in memory could be critical in determining their efficiency. Recently, Kerzel and Witzel (2019) used the contingent capture paradigm (Folk & Remington, 1998; Folk et al., 1992) to investigate conditions that allow for more than a single attentional template. They found similar cueing effects for one and two memorized target colors, confirming that dual target search involved no additional costs (Grubert & Eimer, 2016; Irons et al., 2012). In the same paradigm, they examined what prevents a color stored in VWM from acting as a template. To answer this question, the target and distractor colors were shown before the search display and participants were asked to memorize both with equal precision. Unlike the target color, no cueing effects were observed for the distractor color, showing that no attentional template had been set up for it. At the same time, the recall precision (*SDs*) of the distractor color was worse than the recall precision of the target color (18 vs. 23; see also Hout & Goldinger, 2015; Rajsic, Ouslis, Wilson, & Pratt, 2017; Rajsic & Woodman, 2020). Kerzel and Witzel (2019) concluded that the establishment of two attentional templates depends crucially on the allocation of equal memory resources between them. In contrast, when one representation is deprioritized because of task demands, it receives fewer resources in VWM and multiple attentional templates cannot be established. Considering VWM as a limited resource that is flexibly allocated (Bays et al., 2009; Bays & Husain, 2008; Ma et al., 2014), this account states that a representation will act as a template depending on the amount of VWM resource it receives. Critically, the allocation of VWM resource depends on the priority of representations, such that the most relevant ones receive a larger share of resources and are thus more precisely remembered (Dube & Al-Aidroos, 2019; Salahub, Lockhart, Dube, Al-Aidroos, & Emrich, 2019). This proposal allows linking the precision of attentional templates in VWM and their efficiency in guiding visual search. However, highly precise templates can also accelerate the decision about whether or not targets match. In this regard, template fidelity could facilitate target recognition, once it has been localized, rather than increase the efficiency of visual search (Rajsic & Woodman, 2020).

Based on these new perspectives, the aim of the present study was to investigate whether the fidelity of templates in memory determines their ability to guide visual search. We assumed that by acting on search efficiency (Kerzel & Witzel, 2019) and target recognition (Rajsic & Woodman, 2020), the fidelity in memory would generate the difference between sustained and transient templates (Berggren et al., 2020; Goldstein & Beck, 2018; Grubert et al., 2016; Kerzel & Witzel, 2019; Moore & Weissman, 2010). Each trial began with the presentation of two target colors. The following search display contained a target in one of the memorized target colors, among three differently colored nontargets (see Figure 1). Participants had to judge the tilt of the target item as quickly and accurately as possible. To assess template fidelity in memory, we asked participants to perform a continuous delayed-estimation task for one of the two target colors after each search episode (Experiment 1). We then compared search performance with a condition that did not involve a concurrent memory task (Experiment 2). Further, we evaluated the effects of template priority in memory using deterministic retro-cues (Experiment 3). Finally, we investigated the role of template encoding and activation by varying the time interval between cue and search displays (Experiment 4).

Experiment 1: Sustained Template Costs and Memory Performance

Experiment 1 served to replicate the results from Berggren et al. (2020) and to link them with memory performance. We compared three task conditions. In the blocked transient condition, the two possible target colors changed on every trial. In the blocked sustained condition, the two colors were fixed throughout. In the mixed condition, one color was fixed while the other changed from trial to trial. Thus, participants maintained two transient or two sustained templates in the blocked conditions, but one transient and one sustained template in the mixed condition. In addition, participants performed memory judgments after each search episode by adjusting a color wheel to one of the two possible target colors. Based on previous results (Berggren et al., 2020; Goldstein & Beck, 2018; Grubert et al., 2016; Kerzel & Witzel, 2019), we

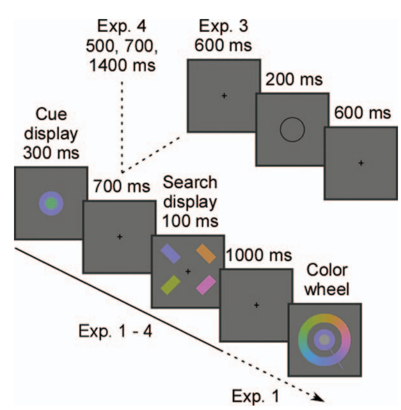

Figure 1. Illustration of stimulus displays and time course in the four experiments. Search displays contained four colored bars tilted to the left or right. Targets were defined by one of two possible colors that were indicated at the start of each trial by a concentric cue display. In Experiment 1 only, one of the two target colors was recalled on a memory wheel after each search episode. In the blocked sustained condition, target colors remained fixed throughout. In the blocked transient condition, two new target colors were cued at the start of each trial. In the mixed condition, one target color remained fixed, while the other changed on a trial-by-trial basis. See the online article for the color version of this figure.

expected RTs to be delayed to transient compared with sustained targets in blocked conditions, reflecting postattentional costs (Moore & Weissman, 2010). In contrast, RTs should be delayed to sustained compared with transient targets in the mixed condition, reflecting a specific form of competition between both types of template (Berggren et al., 2020).

The new critical question concerned memory performance. We predicted more memory errors for transient compared with sustained templates in the blocked conditions. For instance, Kerzel (2019, Experiments 2 and 3) found that the average precision recall (*SDs*) for sustained templates was between five to nine, compared with 14 (Zhang & Luck, 2008) or 18 (Kerzel & Witzel, 2019) for transient templates. As a result of the lower fidelity, postattentional costs may occur for transient compared with sustained templates. Specifically, low fidelity may delay target comparison (Goldstein & Beck, 2018) and recognition (Rajsic & Woodman, 2020). Concerning the mixed condition, the encoding of the transient template in VWM would interfere with the sustained template (Berggren et al., 2020), whether this template is held in LTM or transferred to VWM (Cantor & Engle, 1993; Cowan et al., 2013; Fukuda & Woodman, 2017; Nairne & Neath, 2001; Reinhart & Woodman, 2014). We propose that retroactive interference would impair the fidelity of the sustained template in memory and thus, its search efficiency. We expected an increase of memory errors for sustained templates in the mixed compared with the blocked conditions. Transient templates, however, should not be subject to retroactive interference since these templates are always newly encoded at each search episode. That is, memory errors should be similar in the blocked and mixed conditions.

Method

Participants. Twenty-six students participated for class credit. Two of them were excluded from analysis due to poor memory performance. One had a high-guessing rate (24%; M = 2.7%, SD = 4.5) and the other frequently responded to the nonprobed item (17%; M = 4.4%, SD = 3.5). Of the remaining 24 participants (age: M = 20.4 years, SD = 1.1, eight males), all reported normal or corrected-to-normal vision. As we introduced a different measure (i.e., memory performance), it was difficult to estimate the required sample size based on Berggren et al. (2020) who had 12 participants. However, we aimed for a sample of 24 participants, which allowed us to detect effect sizes with d_z of 0.52 (α = .05, power = .8), according to G*Power (Faul, Erdfelder, Lang, & Buchner, 2007). That is, less than half of the relevant effect size (d_z of 1.25) in Berggren et al. (2020). 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 each experiment started.

Apparatus. Stimuli were displayed on a 22.5-in. LCD monitor with a refresh rate of 100 Hz and a pixel resolution of 1,920 × 1,200 (VIEWPixx Light, VPixx Technologies Inc., Saint-Bruno, Canada), driven by an AMD Radeon HD 7470 graphics card with a color resolution of eight bits per channel. CIE1931 chromaticity coordinates and luminance (xyY) of the monitor primaries were R = (0.673, 0.309, 54.2), G = (0.096, 0.747, 123.8), and B = (0.100, 0.093, 19.6). Colors were measured with a Cambridge Research Systems ColorCAL MKII colorimeter. Gamma corrections were applied based on the measured gamma curves of the monitor primaries. Participants viewed the screen at a distance of 66 cm and their head position was stabilized with a chin/forehead rest.

Stimuli. The experiment was run on MATLAB using the Psychtoolbox-3 (Brainard, 1997; Pelli, 1997). All stimuli were shown on an achromatic background, with a light gray fixation cross (0.13° × 0.13°). Figure 1 illustrates stimuli and time course. Each trial began with a cue display (300 ms) where a central disk (radius of 0.25°) and a surrounding peripheral ring (radius of 0.5°) were presented in the two target colors. Following a blank interstimulus interval (700 ms), the search display was shown for 100 ms. The search display contained four rectangular bars (0.5° × 0.25°) 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 target colors, while the others appeared in different nontarget colors. The target location was random. After a blank interval of 1,000 ms, the color wheel appeared and stayed until a response was given. The inner and outer rims of the color wheel had a radius of 0.87° and 1.31°, respectively. The color wheel surrounded a modified version of the cue display. In this modified version, the probed object (disk or ring) and the attached line cursor (0.2° line width) were shown in the currently selected color of the color wheel, whereas the nonprobed object was in light gray and did not change its color. The interval between the color wheel offset and the cue display onset of the next trial was 1,400 ms.

The colors were defined in CIELAB space because CIELAB is a model of color appearance where distances approximate perceived color 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 color is, and chroma is a measure of perceived saturation (i.e., difference from gray). The white point of CIELAB was xyY = (0.280, 0.358, 195.3). Stimuli were presented on a gray background with a luminance of 28.6 cd/m^2 or L^* = 45. The fixation cross and the nonprobed object were light gray with a luminance of 57.6 cd/m^2 or L^* = 61. The six colors used in the cue and search displays were sampled along an isoluminant hue circle at a lightness of L^* = 61, and at 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°). The hue difference of 60° was far above hue discrimination threshold, preventing search biases resulting from color similarity and category membership (Witzel & Gegenfurtner, 2013, 2015). The color wheel represented an isoluminant hue circle with a chroma of 59. To cancel motor biases, the spatial orientation of the zero-hue angle was randomized between trials.

Procedure. Participants were instructed to memorize the colors in the cue display together with the object on which these colors were shown. For the following search task, participants had to find the bar in one of the two possible target 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 trial was aborted, and the corresponding visual feedback was shown. Otherwise, participants performed the memory task. By turning the mouse around the initial mouse position on the desk, they could rotate the line cursor to select a color on the wheel for the probed object. The selected color was confirmed 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 20 trials. Every 40 trials, visual feedback about the percentage of correct responses and the median RTs were displayed during a self-terminated break of at least 5 s.

Design. The three conditions were run in separate blocks of 80 trials. The order of conditions was counterbalanced across participants and repeated once for a total of 160 trials per condition. In the blocked transient condition, the two target colors were randomly selected on each trial with the constraint that they had to be different from the target colors on the preceding trial. In the sustained blocked condition, the two fixed target colors were selected randomly with the constraint that the color difference be larger than 60° to avoid smaller similarity between fixed compared with variable colors. In the mixed condition, one target color remained constant throughout, while the other was selected randomly from the five remaining colors. Immediate repetitions of the variable target color were not allowed. The object (disk or ring) on which the two possible target colors appeared in the cue display was randomly determined on each trial. Search displays unpredictably contained either of the two target colors and each color was equally likely to be probed in the memory task.

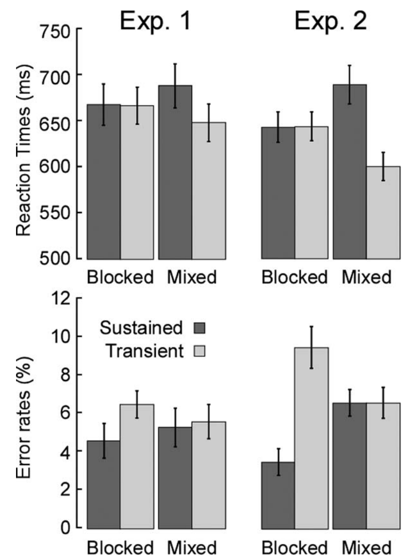

Figure 2. Reaction times (top) and error rates (bottom) measured in Experiments 1 (left) and 2 (right) in response to sustained and transient targets in the blocked and mixed conditions. Error bars depict one standard error of the mean.

Results

Search task. We excluded trials with anticipations (RTs <200 ms) or late responses (RTs >1,200 ms) from analysis (5%). 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 3% of the trials. Overall, the percentage of choice errors was 6%. RTs and error rates to sustained and transient targets in the blocked and mixed conditions are shown in Figure 2 (left). Only trials with correct responses were considered in the analysis of RTs.

We conducted a 2 × 2 within-subjects analysis of variance (ANOVA) with the factors template type (sustained vs. transient) and task context (blocked vs. mixed). There was a main effect of template type, $F(1, 23) = 4.99$, $p = .035$, $\eta_p^2 = .178$, indicating that RTs were shorter to transient than sustained targets (658 vs. 679 ms). Critically, there was a significant interaction, $F(1, 23) = 7.42$, $p = .012$, $\eta_p^2 = .244$. As shown in Figure 2 (left), there was no difference between sustained and transient targets in the blocked conditions (669 vs. 668 ms), $t(23) = 0.13$, $p = .900$, $d_z = 0.03$. In contrast, RTs were substantially delayed to sustained relative to transient targets in the mixed condition (689 vs. 649 ms), $t(23) = 2.77$, $p = .011$, $d_z = 0.57$. For error rates, only a main effect of template type was found, $F(1, 23) = 4.84$, $p = .038$, $\eta_p^2 = .174$, as choice errors were more frequent to transient than sustained targets (6.1% vs. 4.9%). The remaining effects were not significant, *p*s > .119.

Color wheel task. On the same trials, as for the RT analysis, we decomposed raw memory errors (i.e., degrees of distance in CIELAB-space between the true and judged color) 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 precision of responses to the probed item (P_{SD}), and a von Mises distribution that reflects the proportion of responses to the nonprobed item (P_{Swap}). Fits were performed by the MemToolbox (Suchow, Brady, Fougnie, & Alvarez, 2013).

For each parameter, we conducted a 2 × 2 × 2 within-subjects ANOVA with the factors template type (sustained vs. transient), task context (blocked vs. mixed), and probed color (color of search target vs. other color). The probed color could be the same as the color of the search target or it could be the other color from the cue display. For the precision (P_{SD}), there was a main effect of template type, $F(1, 23) = 5.81$, $p = .024$, $\eta_p^2 = .202$, indicating that *SDs* were lower for sustained than transient templates (12.2 vs. 13.5). A highly significant main effect of probed color, $F(1, 23) = 25.39$, $p < .001$, $\eta_p^2 = .525$, revealed that *SDs* were lower when the color of the search target was probed compared with when the other color was probed (12.0 vs. 13.7). Possibly, there was opportunity for perceptual resampling (Maxcey-Richard & Hollingworth, 2013; Woodman & Luck, 2007) when the probed color was the search target, which increased precision. No other effect reached significance, *p*s > .089.

Concerning the guess rates (P_{Guess}), the ANOVA revealed a significant main effect of template type, $F(1, 23) = 14.94$, $p = .001$, $\eta_p^2 = .394$, indicating that random guesses were less frequent for sustained than transient templates (1.1% vs. 2.9%). Importantly, there was a significant interaction involving template type and task context, $F(1, 23) = 10.29$, $p = .004$, $\eta_p^2 = .309$, as in the analysis of RTs. As shown in Figure 3, random guesses for sustained templates increased from the blocked to the mixed condition (0.3% vs. 1.9%), $t(23) = 2.94$, $p = .007$, $d_z = 0.60$, mirroring RTs. In contrast, guess rates for transient templates did

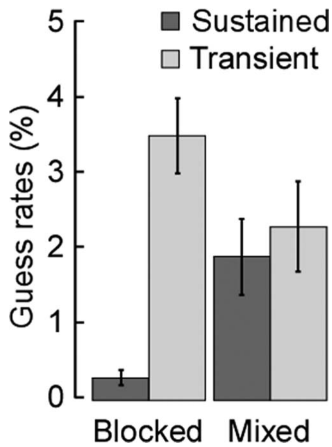

Figure 3. Guess rates measured in Experiment 1 in response to sustained and transient templates in the blocked and mixed conditions. Error bars depict one standard error of the mean.

not differ between the blocked and mixed conditions (3.5% vs. 2.3%), $t(23) = 1.54$, $p = .136$, $d_z = 0.31$. Further, there was a marginal main effect of probed color, $F(1, 23) = 4.20$, $p = .052$, $\eta_p^2 = .154$, that was modulated by an interaction with template type, $F(1, 23) = 16.08$, $p = .001$, $\eta_p^2 = .411$. For transient templates, random guesses were lower when the probed color was the color of the search target compared with when it was the other color (1.7% vs. 4.2%), $t(23) = 3.64$, $p = .001$, $d_z = 0.74$, suggesting a resampling effect. In contrast, for sustained templates, guess rates were similar when the probed color was the color of the search task or the other color (0.7% vs. 1.4%), $t(23) = 1.45$, $p = .159$, $d_z = 0.30$. The remaining effects were not significant, ps $>$ .096.

For responses to the nonprobed item (P_{Swap}), there was a main effect of template type, $F(1, 23) = 4.75$, $p = .040$, $\eta_p^2 = .171$, indicating that there was more confusion with nonprobed colors with sustained than transient templates (4.9% vs. 3.9%). A main effect of probed color, $F(1, 23) = 4.36$, $p = .048$, $\eta_p^2 = .159$, revealed that there were less responses to the nonprobed item when the probed color was the search target color instead of the other color (3.6% vs. 5.2%). The three-way interaction was marginally significant, $F(1, 23) = 4.01$, $p = .057$, $\eta_p^2 = .148$. The reduction of swap errors occurring when the probed color was also the search target color appeared in the blocked condition for sustained templates (3.6% vs. 6%), $t(23) = 2.05$, $p = .052$, $d_z = 0.42$, but in the mixed condition for transient templates (2.2% vs. 4.8%), $t(23) = 2.53$, $p = .019$, $d_z = 0.52$. No other effect reached significance, ps $>$ .475.

Discussion

To investigate the relationships between the efficiency of templates and their fidelity in memory, we asked participants to search for one of two target colors and to recall one of them after each search episode. We found that RTs did not differ between the two blocked conditions, suggesting that sustained and transient templates were equally efficient when two of the same type were activated together. Consistently, ERP (Berggren et al., 2020; Grubert et al., 2016) and eye movement (Goldstein & Beck, 2018) studies showed that sustained and transient templates did not differ in their ability to control the allocation of attention to target objects. However, these studies reported postattentional costs associated with transient templates (see also Kerzel & Witzel, 2019; Moore & Weissman, 2010), which we did not replicate. Possibly, our memory task added new constraints on the establishment of templates, causing these costs to disappear (see Experiment 2). Further, we assumed that memory performance would mirror search performance, because the fidelity of templates in memory affects search efficiency (Kerzel & Witzel, 2019) and target recognition (Rajsic & Woodman, 2020). We found that the precision of memory judgments (P_{SD}) was generally better for sustained than transient templates, as expected based on previous results (Kerzel, 2019; Kerzel & Witzel, 2019; Zhang & Luck, 2008). However, overall RTs were not shorter to sustained than transient targets. Thus, our results indicate that better precision of templates does not automatically result in higher efficiency in search tasks, as reported by previous research (Hout & Goldinger, 2015; Rajsic et al., 2017) that also controlled for perceptual resampling (Kerzel & Witzel, 2019, Experiment 2; Rajsic & Woodman, 2020, Experiment 3). However, our observations are in line with a recent study of Dube and Al-Aidroos (2019) demonstrating that the precision of representations in memory could be enhanced without affecting the ability of these representations to guide visual search (see also Hollingworth & Hwang, 2013). Consistently, there is evidence (Carlisle & Woodman, 2011; Olivers & Eimer, 2011) that remembering for search differs from remembering for recall (see General Discussion section).

In the mixed condition, one target color changed on a trial-by-trial basis, while the other remained constant throughout. As expected, we found delayed RTs to sustained relative to transient targets. In addition, guess rates increased for sustained templates from the blocked to the mixed condition, mirroring the increase in RTs. Consistently, Berggren et al. (2020) reported a corresponding delay and attenuation of the N2pc component. These results suggest that each new transient template in VWM interferes with the already activated sustained template (Berggren et al., 2020), whether this template was held in LTM or transferred to VWM (Cantor & Engle, 1993; Cowan et al., 2013; Fukuda & Woodman, 2017; Nairne & Neath, 2001; Reinhart & Woodman, 2014). The retroactive interference not only impaired the efficiency of the sustained template to guide attention, but also weakened the stability of its representation in memory. Similar to precision, however, there was no general association between search efficiency and stability in memory. In the blocked condition, guess rates were lower for sustained compared with transient templates, while RTs were equal. Conversely, in the mixed condition, RTs were delayed to sustained relative to transient targets, but guess rates were similar. Overall, the precision and guess rates suggest that there is not much association between memory and search performance, corroborating the idea of distinct processes (Carlisle & Woodman, 2011; Dube & Al-Aidroos, 2019; Hollingworth & Hwang, 2013; Olivers & Eimer, 2011). However, changes in memory performance may indicate changes in the status of the attentional template. Notably, retroactive interference degraded the sustained template in the mixed condition, which had repercussions both on memory and visual search.

Finally, we investigated the effects of two nuisance variables. First, we considered the possibility of perceptual resampling when the target color in the search task was probed in the memory task. We found that resampling increased the recall precision regardless of template type. In contrast, resampling reduced guess rates for transient templates only, suggesting that transient templates were less stable in memory than sustained templates. Second, we addressed differences between central and peripheral cue colors. Preliminary results had shown that participants performed poorly in the memory task when the two cue colors were presented on opposite lateral positions. Similar to Kerzel and Witzel (2019), we thus presented the cue colors on a central disk surrounded by a peripheral ring. However, concentric cue displays may induce perceptual or attentional biases in favor of the central or peripheral color. To examine these biases, we performed additional analyses on search and memory performance, which we report in the online supplemental materials. In short, we found that performance was worse when the central rather than the peripheral cue color became the search target or was probed in the memory task. Importantly, however, the ANOVAs showed that neither nuisance variable modulated the theoretically relevant two-way interactions of template type and task context.

Experiment 2: Sustained Template Costs Without Memory Task

In the mixed condition, RTs were delayed to sustained compared with transient targets ($M = 689$ vs. 649 ms; $d_z = 0.57$), but not as much as in Berggren et al. (2020; $M = 654$ vs. 590 ms; $d_z = 1.25$). Moreover, there was no RT difference between sustained and transient targets in the blocked conditions ($M = 669$ vs. 668 ms; $d_z = 0.03$), as would be expected on the basis of postattentional costs (Berggren et al., 2020; Goldstein & Beck, 2018; Grubert et al., 2016; Kerzel & Witzel, 2019; Moore & Weissman, 2010). Possibly, our memory task constrained the establishment and maintenance of templates. In the blocked conditions, transient templates may be encoded more precisely than in a search-only task context, accelerating target recognition (Rajsic & Woodman, 2020) and eliminating postattentional costs. In the mixed condition, the maintenance of both templates for later recall may balance their priority to some degree. As a result, sustained and transient templates became closer in efficiency compared with a search-only task context. Thus, our concomitant memory task may be responsible for the reduced RT difference between template types. To test these assumptions, we repeated Experiment 1, but without the color judgment. If the concurrent memory task was indeed responsible for the results of Experiment 1, its absence should generate results more similar to Berggren et al. (2020).

Method

Participants. A second group of 24 students took part in Experiment 2 (age: $M = 20.3$ years, $SD = 1.1$; five males). All reported normal or corrected-to-normal vision.

Stimuli and procedure. These were identical to Experiment 1, but without the color wheel (see Figure 1). Trials ended when participants responded to the search target. The interval between the search display offset and the next cue display onset remained 1,400 ms.

Results

As in Experiment 1, we excluded anticipated and late trials (4%) and correct trials with outlier RTs (3%). Overall, the percentage of choice errors was 7%. Figure 2 (right) shows RTs and error rates to sustained and transient targets in the blocked and mixed conditions.

To compare Experiments 1 and 2, mean individual RTs from trials with correct responses were entered into a 2 × 2 × 2 mixed ANOVA with the factors template type (sustained vs. transient), task context (blocked vs. mixed), and experiment (1 vs. 2). We replicated a significant main effect of template type, $F(1, 46) = 22.79$, $p < .001$, $\eta_p^2 = .331$, and a significant interaction between template type and task context, $F(1, 46) = 29.66$, $p < .001$, $\eta_p^2 = .392$. Critically, however, there was a significant three-way interaction between template type, task context, and experiment, $F(1, 46) = 4.58$, $p = .038$, $\eta_p^2 = .091$. In the blocked conditions, RTs were similar to sustained and transient targets, regardless of experiment (difference of 1 ms in both experiments), $t(46) = 0.13$, $p = .894$, $d_s = 0.01$. In contrast, the RT difference between sustained and transient targets in the mixed condition was smaller in Experiment 1 than in Experiment 2 (difference of 40 vs. 89 ms), $t(46) = 2.19$, $p = .034$, $d_s = 0.63$. Finally, there was no main effect of experiment, $F(1, 46) = 0.86$, $p = .358$, $\eta_p^2 = .018$, indicating that RTs were similar between Experiments 1 and 2 (669 vs. 644 ms). None of the remaining effects were significant, $ps > .088$.

For error rates, we replicated a significant main effect of template type, $F(1, 46) = 25.77$, $p < .001$, $\eta_p^2 = .359$, that was modulated by an interaction with task context, $F(1, 46) = 23.19$, $p < .001$, $\eta_p^2 = .335$, and an interaction with experiment, $F(1, 46) = 5.09$, $p = .029$, $\eta_p^2 = .100$. However, the three-way interaction between template type, task context, and experiment was also significant, $F(1, 46) = 8.04$, $p = .007$, $\eta_p^2 = .149$. The difference of choice errors between sustained and transient targets in the blocked conditions was smaller in Experiment 1 than in Experiment 2 (difference of 1.9% vs. 6.0%), $t(46) = 3.63$, $p = .001$, $d_s = 1.05$. In contrast, in the mixed condition, there was no difference between sustained and transient targets, regardless of experiment (difference smaller than 1% in both experiments), $t(46) = 0.33$, $p = .743$, $d_s = 0.10$. No other effect reached significance, $ps > .272$.

The separate analyses of RTs and error rates showed signs of speed–accuracy trade-off. For instance, RTs were longest to sustained targets in the mixed condition, but error rates were highest to transient targets in the blocked condition. To remove occasional effects of speed–accuracy trade-off, we calculated inverse efficiency scores (Townsend & Ashby, 1978) for Experiments 1 and 2. Inverse efficiency scores will be referred to as corrected RTs and correspond to RTs divided by (1 − error rates). Conducting the same ANOVA as above, we replicated a significant main effect of template type, $F(1, 46) = 6.04$, $p = .018$, $\eta_p^2 = .116$, a significant interaction between template type and task context, $F(1, 46) = 35.63$, $p < .001$, $\eta_p^2 = .437$, and a significant three-way interaction between template type, task context, and experiment, $F(1, 46) = 7.33$, $p = .009$, $\eta_p^2 = .138$. As in the analysis of uncorrected RTs, there was no difference between sustained and transient targets in the blocked conditions of Experiment 1 (703 vs. 716 ms), $t(23) = 1.30$, $p = .207$, $d_z = 0.27$. In contrast, corrected

RTs were longer to transient than sustained targets in the blocked conditions of Experiment 2 (716 vs. 669 ms), $t(23) = 3.37$, $p = .003$, $d_z = 0.69$, which is consistent with the presence of postattentional costs. In addition, we replicated the reduced difference between sustained and transient targets in the mixed condition of Experiment 1 compared with Experiment 2 (difference of 42 vs. 98 ms), $t(46) = 1.96$, $p = .056$, $d_s = 0.57$. No other effect reached significance, $ps > .521$.

Discussion

In Experiment 2, we investigated effects of the memory task in Experiment 1 by asking participants to only perform the search task. Using uncorrected RTs, we found no difference between sustained and transient templates in the blocked conditions of both experiments. However, when we corrected for speed–accuracy trade-off, the results of Experiment 2 replicated the postattentional costs associated with transient templates in a search-only task context (Berggren et al., 2020; Goldstein & Beck, 2018; Grubert et al., 2016; Kerzel & Witzel, 2019; Moore & Weissman, 2010). Conversely, in Experiment 1, transient templates may have been encoded more precisely in preparation for the memory task, accelerating target recognition (Rajsic & Woodman, 2020) and eliminating postattentional costs.

Further, the sustained template costs in the mixed condition were increased in Experiment 2 compared with Experiment 1. We found this increase to be significant with RTs and close to significance with corrected RTs ($p = .056$), suggesting that speed–accuracy trade-off played only a minor role in this effect. Consistent with our predictions, these results indicate that the presence of a concomitant memory task in Experiment 1 added constraints on the maintenance of the two templates. As both templates were equally likely to be probed after each search episode, the priority in memory, and therefore the allocation of VWM resource (Dube & Al-Aidroos, 2019; Kerzel & Witzel, 2019; Salahub et al., 2019), was more balanced. As a result, retroactive interference was attenuated, and the efficiency of sustained and transient templates became more similar than in a search-only task context. Critically, flexible and strategic prioritization of stored representations is characteristic of limited-capacity VWM (Oberauer, 2002, 2019; Oberauer & Hein, 2012). The fact that we observed such an effect on the sustained template, normally represented in unlimited-capacity LTM (e.g., Carlisle et al., 2011), suggests that this template was transferred to VWM to be accessed consciously (Cantor & Engle, 1993; Cowan et al., 2013; Fukuda & Woodman, 2017; Nairne & Neath, 2001; Reinhart & Woodman, 2014). Thus, the sustained template costs appear to depend on characteristics that are associated with maintaining and processing information in VWM.

Finally, as templates may be set up in 200 ms or less (Vickery, King, & Jiang, 2005; Wolfe, Horowitz, Kenner, Hyle, & Vasan, 2004), the cue presentation time of 300 ms and the delay of 700 ms until the search display provided ample time to establish the templates and to adjust priorities. The differences between sustained and transient templates were therefore not due to time constraints. Moreover, the increase of these differences from Experiment 1 to Experiment 2 was not generated by task difficulty because overall uncorrected RTs, error rates, and corrected RTs were similar in both experiments.

Experiment 3: Sustained Template Costs and VWM Prioritization

The comparison of Experiments 1 and 2 demonstrated that the sustained template costs were attenuated by maintaining both template types with equal priority in VWM. To further explore the modulatory effects of VWM prioritization, Experiment 3 used a retro-cueing procedure (Landman, Spekreijse, & Lamme, 2003; Nobre, Griffin, & Rao, 2008). Typically, retro-cues are spatial cues presented during the retention interval to guide attentional selection of contents within VWM (Souza & Oberauer, 2016). By tagging one VWM representation as the most relevant for the upcoming task, retro-cues strengthen it (Souza, Rerko, & Oberauer, 2015) and protect it from visual interferences (Matsukura, Luck, & Vecera, 2007).

Because probabilistic retro-cues are not sufficient to give the template status to a VWM representation (Dube & Al-Aidroos, 2019; Dube, Lumsden, & Al-Aidroos, 2019; Hollingworth & Hwang, 2013), we used deterministic retro-cues. That is, retro-cues always indicated correctly which of the two colors would be the upcoming target color. As the sustained template costs were attenuated under conditions of balanced priority in VWM (Experiments 1 vs. 2), the full prioritization of the sustained template should make these costs disappear. The reason is that the sustained template would be selectively attended in VWM to receive the largest part of VWM resources (Dube & Al-Aidroos, 2019; Kerzel & Witzel, 2019; Salahub et al., 2019) and to be shielded against interference (Matsukura et al., 2007; Souza et al., 2015). In contrast, the persistence of the sustained template costs despite the retro-cueing would indicate that it does not entirely depend on VWM processes, such as prioritization. Possibly, the sustained template would not be completely represented in VWM (Cantor & Engle, 1993; Cowan et al., 2013; Fukuda & Woodman, 2017; Nairne & Neath, 2001; Reinhart & Woodman, 2014), limiting the maximal priority it could receive. Alternatively, the retroactive interference may have critically impaired the sustained template, leading to permanent difficulty of access (Dewar et al., 2007; Wixted, 2004).

Method

Participants. A group of 25 students participated in Experiment 3. One participant was excluded due to low accuracy (82%) compared with the remaining sample ($M = 94.1\%$; $SD = 3.5$). The final sample size was therefore 24 participants (age: $M = 19.9$ years; $SD = 1.4$; eight males). All participants reported normal or corrected-to-normal vision.

Stimuli and procedure. These were identical to Experiment 2, with the exception that a retro-cue could be presented after the cue display (see Figure 1). As their separation must be at least 500 ms to guarantee full use of the retro-cue (Souza & Oberauer, 2016) and to avoid the time range of iconic memory (Irwin & Thomas, 2008), we used a 600 ms blank interstimulus interval. The retro-cue (200 ms) consisted of a black circle (0.2° line width) that enclosed the outer rim of either the disk or ring from the cue display, but neither disk or ring were shown. As we opted for a deterministic retro-cue, it always correctly predicted which of the two cued colors would be the target color. After another blank interstimulus interval of 600 ms, the search display was presented for 100 ms. The total retention interval was 1,400 ms, which was filled with a matching blank interstimulus interval in blocks where the retro-cue was absent. For six blocks of 80 trials each, we only tested the mixed condition as described in Experiment 1. Retro-cue present and absent blocks alternated, and the order was counterbalanced across participants.

Results

As in previous experiments, we excluded early and late trials (3%) and correct responses with outlier RTs (3%). Overall, the percentage of choice errors was 5%. Figure 4 (left) shows RTs to sustained and transient targets in the presence and absence of the retro-cue.

We conducted a 2 × 2 within-subjects ANOVA with the factors template type (sustained vs. transient) and retro-cue (present vs. absent). There was a main effect of template type, $F(1, 23) = 43.12$, $p < .001$, $\eta_p^2 = .652$, indicating that RTs were shorter to transient than sustained targets (568 vs. 610 ms). A highly significant main effect of retro-cue, $F(1, 23) = 150.22$, $p < .001$, $\eta_p^2 = .867$, reflected shorter RTs in the presence than in the absence of the retro-cue (530 vs. 648 ms). Critically, there was a significant interaction between both factors, $F(1, 23) = 49.91$, $p < .001$, $\eta_p^2 = .685$. As shown in Figure 4 (left), delayed RTs to sustained compared with transient targets were observed when the retro-cue was absent (690 vs. 606 ms), $t(23) = 7.19$, $p < .001$, $d_z = 1.47$, but not when it was present (530 vs. 530 ms), $t(23) < 0.01$, $p = 1$, $d_z < 0.01$. For error rates, the ANOVA revealed a marginal effect of template type, $F(1, 23) = 3.94$, $p = .059$, $\eta_p^2 = .146$, as choice errors tended to be more frequent to sustained than transient targets (5.0% vs. 4.2%). A significant main effect of retro-cue, $F(1, 23) = 4.80$, $p < .039$, $\eta_p^2 = .173$, indicated that choice errors were more frequent when the retro-cue was absent than present (5.5% vs. 3.8%). The interaction between both factors was not significant, $F(1, 23) = 0.97$, $p = .334$, $\eta_p^2 = .041$.

Discussion

As expected, adding a deterministic retro-cue during the retention interval eliminated the sustained template costs. That is, sustained and transient templates became equally efficient in guiding attention when participants could selectively attend to the relevant template before onset of the search display. This observation confirms that the competition between both template types (Berggren et al., 2020) can be modulated by processes that are specific to VWM. Particularly, the full prioritization of the relevant template gave it the largest part of VWM resources (Dube & Al-Aidroos, 2019; Kerzel & Witzel, 2019; Salahub et al., 2019) and protected it against interference (Matsukura et al., 2007; Souza et al., 2015). These retro-cueing benefits accelerated search times for transient templates (76 ms), but even more for sustained templates (160 ms), corroborating the idea that sustained templates were shielded from additional retroactive interference effects. Finally, the fact that the priority of sustained templates could be flexibly adjusted to affect online task performance confirms that these templates were indeed represented in VWM (Cantor & Engle, 1993; Cowan et al., 2013; Fukuda & Woodman, 2017; Nairne & Neath, 2001; Reinhart & Woodman, 2014).

A possible objection to our conclusion is that participants may have used the retro-cue to remove the noncued template from memory. That is, our results would only reflect the benefit of maintaining a single template, whether in LTM or VWM. While we cannot rule out this possibility based on our data, there is a consensus that the removal hypothesis cannot fully account for retro-cue effects (Souza & Oberauer, 2016). For instance, Dube, Lumsden, and Al-Aidroos (2019) showed that cued representations were recalled with similar precision with probabilistic and deterministic retro-cues, suggesting that memory resources were shared equally under both conditions (see also van Moorselaar, Theeuwes, & Olivers, 2014, Experiment 4). Moreover, the retro-cueing benefits have also been observed at low levels of cue reliability where the removal of noncued items is not advantageous (Souza & Oberauer, 2016). Therefore, the elimination of the sustained template costs is more likely caused by the prioritization of the sustained template in VWM rather than by the removal of the transient template.

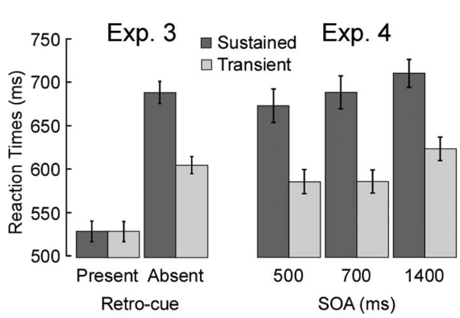

Figure 4. Reaction times measured in response to sustained and transient targets in Experiment 3 (left) with the presence and absence of a retro-cue, and in Experiment 4 (right) with SOAs of 500 ms, 700 ms, and 1,400 ms. Error bars depict one standard error of the mean.

Experiment 4: Time Course of Sustained Template Costs

The previous experiments confirmed that the guidance of attention was specifically impaired for sustained templates when concurrently held with transiently activated templates. At the same time, sustained templates were less stable in memory (Experiment 1). Consistent with Berggren et al. (2020), transient templates retroactively interfered with sustained templates. To decide whether this interference was generated by the encoding or the activation of transient templates in VWM, we manipulated the stimulus onset asynchronies (SOAs) between cue and search displays in Experiment 4.

Retroactive interference is known to decrease as a function of the temporal separation between the encoding of new contents and the manipulation of previous representations (Wixted, 2004). Similarly, the temporal separation between the encoding of transient templates and the activation of sustained templates for visual search may reduce the inference. Therefore, the sustained template costs are expected to decrease as more time passes between cue and search displays. Alternatively, transient templates may interfere with sustained templates when both are activated in preparation for visual search. Grubert and Eimer (2018, 2020) showed that both types of template were activated shortly before search onset. Because the activation of the two templates will overlap, at least shortly before search onset, the time interval between encoding and search should not matter.

Method

Participants. A fourth group of 25 students participated in Experiment 4. One participant was excluded due to low accuracy (79%) compared with the remaining participants ($M = 91.6\%$; $SD = 5.0$). The final sample size was therefore 24 (age: $M = 19.7$ years; $SD = 1.4$; three males). All reported normal or corrected-to-normal vision.

Stimuli and procedure. These were identical to Experiment 2, with the following exceptions (see Figure 1). The SOA between cue and search displays was either 500 ms, 700 ms, or 1,400 ms. Each SOA was run in separate blocks of 80 trials. Two blocks were run for each SOA and the order of blocks was counterbalanced across participants. Moreover, we only tested the mixed condition (as in Experiment 3).

Results

We excluded trials with anticipated and late responses (4%) and correct trials with outlier RTs (3%). Overall, the percentage of choice errors was 7%. Figure 4 (right) shows RTs to sustained and transient targets with the 500 ms, 700 ms, and 1,400 ms SOAs.

We conducted a 2 × 3 within-subjects ANOVA with the factors template type (sustained vs. transient) and SOA (500 ms, 700 ms, 1,400 ms) on RTs with correct responses. There was a main effect of template type, $F(1, 23) = 93.47$, $p < .001$, $\eta_p^2 = .806$, indicating that RTs were shorter to transient than sustained targets (600 vs. 695 ms). The ANOVA also revealed a significant main effect of SOA, $F(1, 23) = 9.46$, $p < .001$, $\eta_p^2 = .291$, which reflected an increase of RTs at the longest time interval. There was no difference between the 500 ms and 700 ms SOAs (631 vs. 644 ms), $t(23) = 1.55$, $p = .136$, $d_z = 0.32$, but a significant RT increase between 700 ms and 1,400 ms SOAs (644 vs. 668 ms), $t(23) = 2.92$, $p = .008$, $d_z = 0.60$. Critically, the interaction between both factors was not significant, $F(1, 23) = 2.11$, $p = .132$, $\eta_p^2 = .084$. Note that the trend for an interaction seen in Figure 4 (right) did not reflect the predicted decrease of the sustained template costs with longer SOAs. Rather, costs tended to be greater with an SOA of 700 ms compared with SOAs of 500 ms and 1,400 ms (111 vs. 87 and 87 ms, respectively). For error rates, no effect reached significance, $ps > .335$.

Discussion

To further investigate whether the encoding or the activation of transient templates interferes with sustained templates, we manipulated the SOA between cue and search displays. According to the encoding account, the interference was expected to decrease when the encoding of transient templates at cue onset was temporally separated from the activation of sustained templates before search onset. In contrast, the activation account predicted no effect of SOA because interference resulted from the overlapping activation of the two templates before search. We found that the sustained template costs were identical across SOAs, which favors the activation account. However, our conclusion rests on a null result and requires further confirmation. For instance, our SOAs were much shorter than in Grubert and Eimer (2018; 500–1,400 vs. 1,000–2,600 ms), which means that the exact time course of template activation for our SOAs still needs to be determined. Moreover, results are also compatible with another account. A transient template may be continuously refreshed in VWM between its encoding and the onset of visual search, which may cause retroactive interference. For instance, it has been demonstrated that mentally effortful tasks are able to generate retroactive interference effects, regardless of their similarity to the to-be-remembered stimuli (Dewar et al., 2007). As interference from continuous refreshing is independent of SOA, it cannot be formally distinguished from the activation account.

General Discussion

Previous research has shown that two simultaneously active templates can guide visual search for two target colors (Beck & Hollingworth, 2017; Grubert & Eimer, 2016; Irons et al., 2012; Kerzel & Witzel, 2019), but not as efficiently as for a single color (Dombrowe et al., 2011; Stroud et al., 2011). These attentional costs do not depend on whether templates are transiently activated or held in a sustained fashion (Goldstein & Beck, 2018; Grubert et al., 2016; Kerzel & Witzel, 2019; Moore & Weissman, 2010). However, the efficiency of a sustained template is specifically impaired when maintained concurrently with a transient template (Berggren et al., 2020). Consistently, in the blocked conditions, we found either no uncorrected RT difference between both types of template (Experiment 1), or delayed corrected RTs to transient targets, reflecting postattentional costs (Experiment 2). In contrast, in the mixed condition, RTs were always delayed to sustained compared with transient targets. These sustained template costs decreased with a concomitant memory task (Experiment 1) compared with a search-only task context (Experiment 2), disappeared with deterministic retro-cues during the retention interval (Experiment 3), and were unaffected by different time intervals between cue and search displays (Experiment 4). These observations confirm that the attentional costs associated with multiple templates do not depend on the type of template per se. Instead, it suggests that a specific form of competition exists between two different template types, which affects the efficiency of the sustained template to guide attentional selection.

Based on studies that linked template-guided visual search with the fidelity in memory (Hout & Goldinger, 2015; Kerzel & Witzel, 2019; Rajsic et al., 2017; Rajsic & Woodman, 2020), we investigated the competition between sustained and transient templates in terms of memory performance (Experiment 1). We found that overall recall precision was higher for sustained than transient templates, without any corresponding RT difference. There was no general association between search efficiency and stability in memory either. In the blocked conditions, guess rates were high for transient templates and almost absent for sustained templates, while RTs were equal. Conversely, in the mixed condition, RTs were delayed to sustained relative to transient targets, but guess rates were similar. Taken together, these results strongly suggest that the precision and stability of templates in memory play a limited role on attentional and postattentional stages of visual search. Consistently, previous research has demonstrated that enhancing the precision of representations in memory did not automatically affect their ability to guide visual search (Dube & Al-Aidroos, 2019; Hollingworth & Hwang, 2013). Possibly, attentional templates are part of VWM, but involve additional processes that are functionally different from VWM maintenance and activation (Olivers & Eimer, 2011), such as executive control (Carlisle & Woodman, 2011). Alternatively, distinct mechanisms of prioritization may exist in VWM (Dube & Al-Aidroos, 2019). Representations would be prioritized for search as templates, or for recall as memory items. While our study was not designed to decide between these proposals, one aspect of our data is not consistent with the assumption of Dube and Al-Aidroos (2019). That is, the comparison between Experiments 1 and 2 showed that manipulating the priority for recall affected the search efficiency of templates, suggesting that the priority for search and for recall are directly linked (see below for more details).

However, memory performance may still indicate changes in the status of a template that also determines search performance. We found that guess rates increased from the blocked to the mixed condition for sustained templates, thus mirroring the increase in RTs. In contrast, guess rates were equal for transient templates between blocked and mixed conditions. This pattern of behavioral results was similar to the ERPs results of Berggren et al. (2020) who found a delay and attenuation of the N2pc components to sustained targets in the mixed relative to the blocked condition, but no difference for transient targets. This suggests that the competition between sustained and transient templates affected both visual search (Berggren et al., 2020) and memory maintenance (Dewar et al., 2007; Lewandowsky et al., 2009; Mercer, 2018; Wixted, 2004). Taken together, our results show an interesting dissociation between representations in memory and the efficiency of attentional templates, while highlighting the similarities of control mechanisms between attention and memory. That is, memory performance seems generally unrelated to search performance, but interference effects are reflected in both memory and search performance.

Sustained Template Costs and Retroactive Interference

Consistent with most models of attention (Bundesen et al., 2005; Desimone & Duncan, 1995; Schneider, 2013; Wolfe, 2007), searching for variable targets involves the transient activation of new templates in VWM. In VWM, these templates compete (Oberauer et al., 2012; Oberauer & Lin, 2017) for limited slots (Cowan, 2001; Vogel et al., 2001) or resources (Bays et al., 2009; Bays & Husain, 2008; Ma et al., 2014). As a function of target repetition, corresponding templates can be transferred to LTM (Carlisle et al., 2011; Gunseli et al., 2016; Reinhart et al., 2014; Reinhart et al., 2016; Reinhart & Woodman, 2014; Woodman et al., 2013). These templates are stored in a sustained and passive fashion in LTM, allowing an effortless and robust access through time (Anderson, 2000; Logan, 2002). Despite these qualitative differences, both VWM and LTM representations are subject to retroactive interference effects (Dewar et al., 2007; Lewandowsky et al., 2009; Mercer, 2018; Wixted, 2004). On this basis, Berggren et al. (2020) asserted that each new transient template in VWM would interfere with any other already activated template. Consistently, we demonstrated that this retroactive interference not only impaired the efficiency of the sustained template to guide attentional selection, but also weakened the stability of its representation in memory (cf. guess rates in Experiment 1). Importantly, this effect was only present in the mixed condition, demonstrating its retroactive nature. Moreover, Experiment 4 showed that the retroactive interference did not depend on retention intervals. That is, the sustained template costs were similar across different time intervals between cue and search displays. Possibly, the interference occurred when sustained and transient templates were simultaneously activated in preparation for visual search. However, this conclusion requires further investigation, notably because our results could also reflect interference from continuous refreshing of the transient template.

Modulatory Effect of VWM Prioritization

Interestingly, when Grubert and Eimer (2018) observed that sustained templates were transiently activated and deactivated, they concluded that "it appears implausible to assume that target templates were held in a different more permanent long-term memory store" (p. 9537). While it seems indeed incoherent with the control of attention by representations maintained either in LTM or VWM, it is in line with proposals of flexible transfer between these stores. To be accessed consciously and to affect online task performance, sustained templates would be retrieved from LTM and buffered within VWM (Cantor & Engle, 1993; Cowan et al., 2013; Fukuda & Woodman, 2017; Nairne & Neath, 2001; Reinhart & Woodman, 2014). While this transfer is not responsible for the sustained template costs (Berggren et al., 2020), it exposed the sustained template to characteristics that are associated with maintaining and processing information in VWM. Particularly, we showed that manipulating the priority of the sustained template in VWM could attenuate retroactive interference effects. That is, the concomitant memory task reduced the sustained template costs (Experiments 1 vs. 2) and deterministic retro-cues made it disappear (Experiment 3). The memory task added constraints on the maintenance of the two templates, as both had to be recalled with equal probability after each search episode. Under this condition of equal priority, VWM resources would be shared evenly between both templates (Dube & Al-Aidroos, 2019; Kerzel & Witzel, 2019; Salahub et al., 2019), leading them to become closer in efficiency. In the same vein, retro-cues guided the attentional selection within VWM to the relevant template for the search task. That is, the sustained template was fully prioritized and protected from interference (Matsukura et al., 2007; Souza et al., 2015), leading this template to be as efficient as the transient template. Together, the comparison between Experiments 1 and 2, as well as Experiment 3, demonstrated that the efficiency of the sustained template can be shielded against retroactive interference effects by increasing its priority in VWM. That is, our results indicate that search efficiency is better predicted by the respective priority of two simultaneously active templates than by the exact precision and stability of these templates. In the case where two templates of the same type are concurrently activated, the priority is balanced, leading to similar search efficiency. In contrast, when maintaining different types of template concurrently, the retroactive interference may be associated with higher priority for the transient template. Consequently, rebalancing the priority decreases the interference and fully prioritizing the sustained template eliminates it. For the most part, this proposal is in line with the resource account of Kerzel and Witzel (2019). However, it does not consider the exact precision of templates to be associated with search efficiency because templates need processes that go beyond memory maintenance (Carlisle & Woodman, 2011; Dube & Al-Aidroos, 2019; Hollingworth & Hwang, 2013; Olivers & Eimer, 2011).

Our conclusion about the transfer of the sustained template from LTM and its flexible prioritization in VWM is also consistent with another class of theories. Particularly, the embedded-processes theory of Cowan (1999) and related models (McElree, 2001; Oberauer, 2002) propose that VWM comprises an active portion of LTM in which the focus of attention selects the relevant information one at time to potentially guide attention (Olivers, Peters, Houtkamp, & Roelfsema, 2011). While these models do not expect equal efficiency between two simultaneously held templates (but see Bahle, Thayer, Mordkoff, & Hollingworth, 2020), they correctly predict that manipulating the focus of attention, and thus the priority in VWM, would modulate the competition between sustained and transient templates. This suggests an interesting avenue for future research in which the links between search efficiency and template priority could serve to probe the architecture of VWM.

Overall, the present study demonstrated that newly activated templates interfere in a retroactive fashion with previously activated, sustained templates. Search efficiency and stability in memory were both impaired for sustained templates, indicating similar effects on visual search and memory maintenance. However, while memory performance may reflect changes in the status of a template that also determine search performance, our results suggest that search and memory performance are generally unrelated. Instead, the respective priority of each template in VWM appears to strongly affect search performance, as changes in priority could reduce, if not eliminate, the retroactive interference and the associated costs.

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