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Looking Sharp: Becoming a Search Template Boosts Precision and Stability in Visual
Working Memory

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Abstract

Visual working memory (VWM) plays a central role in visual cognition, and current work suggests that there is a special state in VWM for items that are the goal of visual searches. However, whether the quality of memory for target templates differs from memory for other items in VWM is currently unknown. In this study, we measured the precision and stability of memory of search templates and accessory items in order to determine whether search templates receive representational priority in VWM. Memory for search templates exhibited increased precision and probability of recall, while accessory items were remembered less often. Additionally, while memory for Templates showed benefits when instances of the Template appeared in search, this benefit was not consistently observed for Accessory items when they appeared in search. Taken together, our results show that becoming a search template can substantially affect the quality of a representation in VWM.

Visual Search; Template; Visual Attention; Working Memory

52 The source of voluntary visual attention – our ability to control what information we will
53 and will not process – has long been debated in psychology (see Awh, Belopolsky, &
54 Theeuwes, 2010). One of the main tools to investigate voluntary attention has been
55 visual search, where one attempts to determine whether a particular object is present
56 among an array of objects. To do so, one must maintain a “template”, that is, a mental
57 representation of the object that one is looking for, in order to know whether the desired
58 object is one of the many objects visible. Visual working memory (VWM), a limited
59 capacity store that maintains visual information in the service of ongoing cognitive
60 operations (see Luck, 2008 for a review), has been proposed to be the cognitive basis
61 of templates used in visual search (Desimone & Duncan, 1995). This has typically been
62 tested by measuring whether items merely stored in memory lead to attentional capture
63 towards memory-matching objects that appear in the context of a search (Soto, Hodsoll,
64 Rotshtein, & Humphreys, 2008; Olivers, Meijer, & Theeuwes, 2006; Olivers, 2009).
65 While many studies have found such memory-driven capture, in spite of the fact that
66 memory-matching objects are task-irrelevant (but see Woodman & Luck, 2007), this
67 type of attentional capture seems to only occur when templates used for the search task
68 has been practiced for several trials or more (Woodman, Luck, & Schall, 2007; Olivers,
69 2009; Carlisle, Arita, Pardo, & Woodman, 2011). Indeed, memory-driven capture also
70 tends not to occur when multiple objects are held in VWM (van Mooreselaar, Theeuwes,
71 & Olivers, 2014). These findings are consistent with the proposal that novel search
72 targets occupy a special state in VWM (Olivers, Peters, Houtkamp, & Roelfsema, 2011),
73 such that one item can serve as a template, which can interact with ongoing perceptual
74 processing, but other items held as “accessory” items that cannot interact.

75 While there is converging evidence that search templates have a special state in
76 VWM (e.g., Houtkamp & Roelfsema, 2009; Carlisle et al., 2011; Greene, Kennedy, &
77 Soto, 2015; van Moorselaar, Theeuwes, & Olivers, 2014), relatively little is known about
78 the properties of these representations. For example, Hollingworth and Hwang (2013)
79 showed that items that do not guide search need not be lower precision but simply
80 deprioritized (see also: van Moorselaar, Theeuwes, & Olivers, 2014), but this leaves
81 open the question of whether search templates have higher memory precision than
82 accessory items. Evidence from neural data shows that search templates, when
83 compared to accessory items, are associated with a sustained increase in the activity of
84 relevant visual areas and a selective, transient increase in activation of fronto-parietal
85 and visual areas when the search template, but not when accessory items, appear
86 (Peters, Roelfsema, & Goebel, 2012). Although such neural differences suggest that
87 the representation of search templates in VWM may be qualitatively different from
88 accessory items, a direct measurement of the quality of memory for templates and
89 accessory items is lacking.

90 What is not lacking is repeated demonstrations that observers are able to
91 prioritize particular representations in VWM (see Souza & Oberauer, 2016, for a recent
92 review). Such studies have relied on the retro-cuing technique, wherein a set of objects
93 are encoded into VWM, and only afterwards is one designated to be the object that will
94 be tested more often than not. When retro-cued, objects can be remembered more
95 often (Murray, Nobre, Clark, Cravo, & Stokes, 2013) and sometimes more precisely
96 (Gunseli, van Moorselaar, Meeter, & Oliver, 2015) than other items. This line of
97 research shows that substantial differences can exist between items held in VWM,

98 supporting the possibility that search templates may be remembered better than
99 accessory items.

100 It is important to note that with retro-cuing there is an obvious benefit to shifting
101 memory to the cued item, as memory for the cued items is tested more often than
102 memory for uncued items. Retro-cue benefits are larger when they more often predict
103 the tested item (Gunseli, van Moorselaar, Meeter, & Olivers, 2015), consistent with the
104 notion that participants will increasingly bias internal attention to cued items as the
105 payoff increases, assuming participants intend to minimize their performance errors.
106 This is not to say that shifts of attention are completely strategic; Berryhill et al. (2012)
107 have shown that retro-cuing effects persist when retro-cues do not predict the tested
108 item, albeit after participants had gained experience with retro-cues that were
109 completely valid. Similarly, Li and Saiki (2014) showed that a cue that loses its
110 predictive validity later in a trial nonetheless produces a retro-cue effect, albeit when
111 mixed with trials in which this cue is helpful on half of the overall trials. Our experiments
112 differ in that the cues used to indicate which item should be searched for were always at
113 chance in terms of predicting the tested item, therefore any differences between cued
114 and uncued items (or, in the present terminology, template and accessory items) cannot
115 be due to participants' intention to minimize error in memory reports, but presumably
116 instead to the need to represent templates with greater fidelity.

117 The question addressed in the current study is straightforward: does assigning
118 template status to a memory, holding constant the testing probability of template and
119 accessory items, nonetheless affect the quality of memory of the template item akin to
120 that observed in retro-cuing? Indeed, if our results do show an enhancement of memory

121 quality for templates compared to accessory items analogous to studies using retro-
122 cues (Gunseli et al., 2015; Murray et al., 2013), then this would provide converging
123 evidence for the notion that search templates require internal attention (Olivers et al.,
124 2011). Such a finding would be consistent with Souza, Rerko, and Oberauer (2015),
125 who found that memory error is lower when specific items are cued to be “refreshed”
126 during the retention interval, lending support to the notion that attention can be shifted in
127 memory even when it produces no clear performance gains. Relatedly, van Moorselaar
128 et al. (2014) showed in their final experiment that memory-driven capture selectively
129 occurred for the one item (out of two) in memory that participants expected to be tested
130 on first, even when both were ultimately tested. Indeed, memory performance was
131 better for the first item tested than the second. Both studies suggest that memory
132 resources can be unevenly distributed in VWM even when these altered distributions
133 might not be expected to reduce memory error. The goal of the present study was to
134 directly assess the quality of memory for search templates compared to accessory
135 items, with the hypothesis that assigning “search template” status to one item would
136 shift resources in VWM towards the template, improving the quality of its memory. To do
137 so, we conducted two experiments in which one of two items encoded into VWM was
138 designated a search template, and subsequently measured the quality of memory for
139 this search template, or an accessory item in VWM.

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Experiment 1

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In Experiment 1, we compared the memory for templates and accessory objects after a visual search to memory for identical objects when no search occurred to determine their relative memory quality. If objects serving as search templates indeed enter a special representational state in VWM, they should show superior memory to accessory objects.

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Method

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Participants

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Eighteen undergraduate students (5 males) participated in this experiment as partial fulfillment of course credit for a first-year Psychology course. All participants reported normal vision. Three participants were excluded due to excessive incorrect search responses, leading to fewer than 50 trials in one or more cells of the factorial design. Given that we intended to model memory performance using the Bays' three-component model (Bays, Catalao, & Husain, 2009), we excluded these participants to preclude the possibility of poor model-fitting from small number of trials. Our goal was to collect approximately 15 participants whose data could be included as it is in the typical range of the number of participants collected in experiments on memory-driven capture (e.g., Olivers, 2009).

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Materials and Procedure

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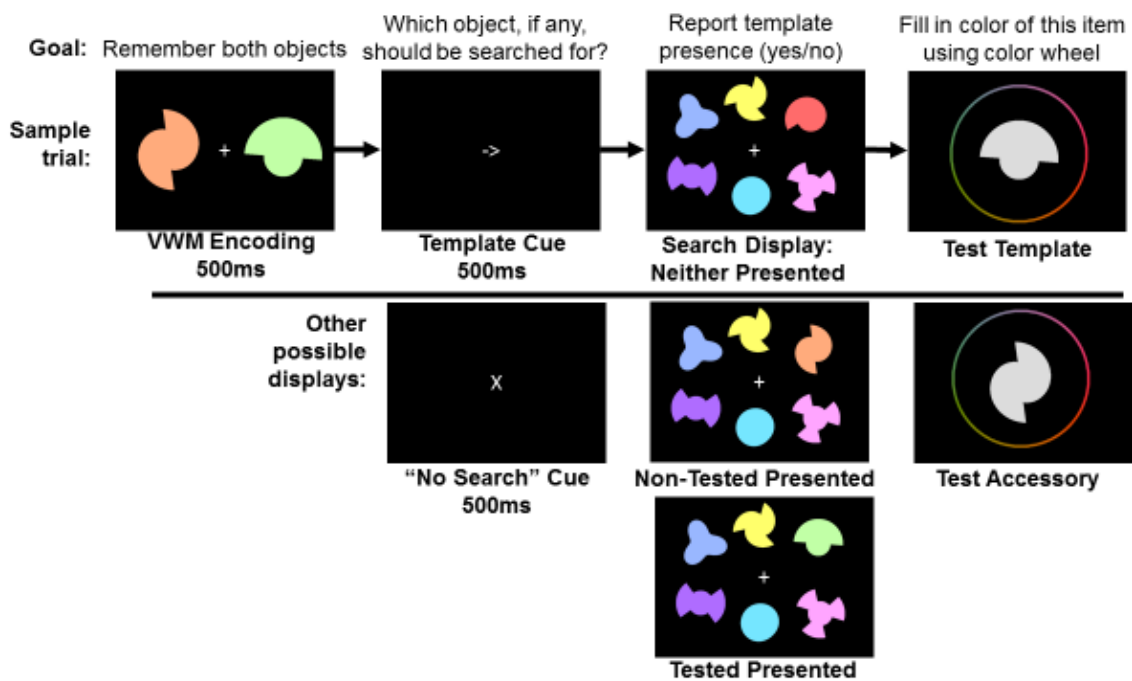
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Stimuli were created and presented using Matlab and the Psychophysics toolbox 3.0.8 (Kleiner, Brainard, & Pelli, 2007). Each participant completed 756 trials (for a sample trial, see Figure 1), over two, 1-hour sessions, broken up into blocks of 54 trials (14 blocks in total). Each trial began with 1000 ms display of a fixation cross, followed

163 by a 500 ms presentation of the memory stimuli—distinct shapes (created by
 164 modulating the radius of a circle using sine, square, or saw waves with power at 1, 2, or
 165 3 cycles within the circumference, approximately 7° in diameter; 9 different shapes in
 166 total) centered approximately 8° left and right of fixation on the horizontal meridian. The
 167 colors of the shapes were randomly selected, from a range of eight evenly-spaced
 168 angular values, with a randomly applied rotation; that is, the available color values
 169 changed, but their relative differences did not. The angular values defined colors on an
 170 imaginary circle in L*A*B color space centred on [50, 20, 35] with fixed a radius of 50.
 171



172

173 **Figure 1.** A sample trial for the experimental task. Responses for the visual search and
 174 memory tests were made using the mouse. On memory tests, the tested shape was
 175 drawn initially in gray, and after the mouse was moved to a color on the color wheel,
 176 the shape was then filled in with this color.

177

178 After the offset of the memory items, a 500 ms blank display preceded the search
179 instructions display. The instruction display, which lasted 500 ms, consisted of a left-
180 facing arrow, a right-facing arrow, or an X drawn at fixation. Participants were instructed
181 that if an arrow appeared, then they were to search for the object that had appeared on
182 that side of fixation just previously in the upcoming display. This allowed us to designate
183 one object in memory as the search template, and one object as the accessory item. If
184 an X appeared, participants were told that they did not have to respond to the upcoming
185 display, and that it would offset on its own. This allowed us to measure the baseline
186 memory for two items in VWM when no search occurred, but with identical stimulus
187 conditions during the retention interval. Each cue type (left arrow, right arrow, or an X)
188 was equiprobable.

189 Next, the search display, which consisted of six peripheral shapes evenly spaced
190 along an imaginary circle around fixation, appeared. The shapes were drawn
191 approximately 6° from fixation, and were the same size as the shapes presented in the
192 memory array (approximately 7° in diameter). These shapes were colored using the six
193 non-sampled color values from the array of values used to select the memory colors,
194 except on trials where one shape matched the memory shapes, in which case five non-
195 sampled colors were used for the non-memory-matching shapes. Participants were
196 instructed to use the computer mouse to report whether the search target was present
197 or absent on search trials. On non-search trials, the search display offset after a random
198 amount of time (drawn from a log-normal distribution with mean 0 and SD 0.5, with the
199 constraint that samples could not exceed 4000ms, producing a mean time of 1120ms

200 and *SD* of 560ms). Actual search RTs (when excluding only trials with >4000ms RTs for
201 direct comparison) had a mean of 1040ms and an average *SD* of 557ms.

202 In order to assess how visual repetition affects memory for search templates and
203 accessory items, on 2/3 of trials one of the shapes in the search display matched one of
204 the objects in VWM (see Figure 1). On half of these trials, this shape was the search
205 template (i.e., the search was target present), and on the other half, the shape was the
206 accessory item (i.e., the search was target absent). As such, stimulus repetition effects
207 could be measured independently of memory status (either template or accessory).

208 After the offset of the search array, and a 500 ms delay, the cued recall memory
209 test occurred. Memory error was measured by presenting a gray shape at fixation
210 accompanied by a peripheral color wheel. The shape matched one of the two shapes
211 presented at the beginning of the trial, and participants were instructed to report the
212 associated color for the probed shape by clicking a color on the color wheel.
213 Participants again used the computer mouse to select the color that they believed
214 belonged with the presented shape. The next trial began following this response.

215 **Results and Discussion**

216 For all analyses, trials were excluded when search RT fell below 100ms or two
217 standard deviations above a participant's search RT. Mean correct search response
218 time (RT) was affected by target presence, $F(2, 28) = 4.26$, $p = .024$, $\eta^2_p = .23$, with
219 search response times being shorter when the target was present ($M = 919$ ms, $SE =$
220 56ms), but not differing between target absent trials when the accessory object
221 appeared ($M = 991$ ms, $SE = 61$ ms) and when neither memory object appeared ($M =$
222 993ms, $SE = 61$ ms), demonstrating that participants indeed searched for the instructed

223 template. Accuracy was high, $M=94.8\%$, $SE = 1.0\%$, but a slight speed-accuracy trade-
224 off occurred, $F(2, 28) = 7.91$, $p = .002$, $\eta^2_p = .36$, such that 3% more errors occurred on
225 target present trials than target absent trials, which we attribute to the low prevalence of
226 targets (33%; Wolfe, Horowitz, Van Wert, Kenner, Place, & Kibbi, 2007).

227 Memory performance was first evaluated in terms of raw error, defined as the
228 precision (1/sample SD in degrees) of report errors (Figure 2a). Memory type (baseline,
229 accessory, and template; $F(2, 28) = 78.38$, $p < .001$, $\eta^2_p = .85$) and repeated exposure
230 (neither present [NP], non-tested present [NTP], and tested present [TP]; $F(2, 28) =$
231 50.13 , $p < .001$, $\eta^2_p = .78$) both affected precision (Figure 2a). The two factors also
232 interacted, $F(4, 56) = 51.07$, $p < .001$, $\eta^2_p = .78$), such that memory improved when
233 either of the two remembered items appeared in the search array, even though
234 participants were not required to attend to these items on baseline trials, $t_s > 4.38$, $p_s <$
235 $.001$. While it is intuitive that seeing a tested item during the retention interval improves
236 memory performance, it is somewhat surprising that seeing the non-tested item also
237 improves memory. One possible reason for this is that in both of these trial types fewer
238 non-remembered colors are presented, potentially reducing visual interference.
239 Alternatively, seeing either item again might reduce ambiguity regarding the specific
240 color-shape bindings being remembered, which could improve cued-recall by reducing
241 swap errors.

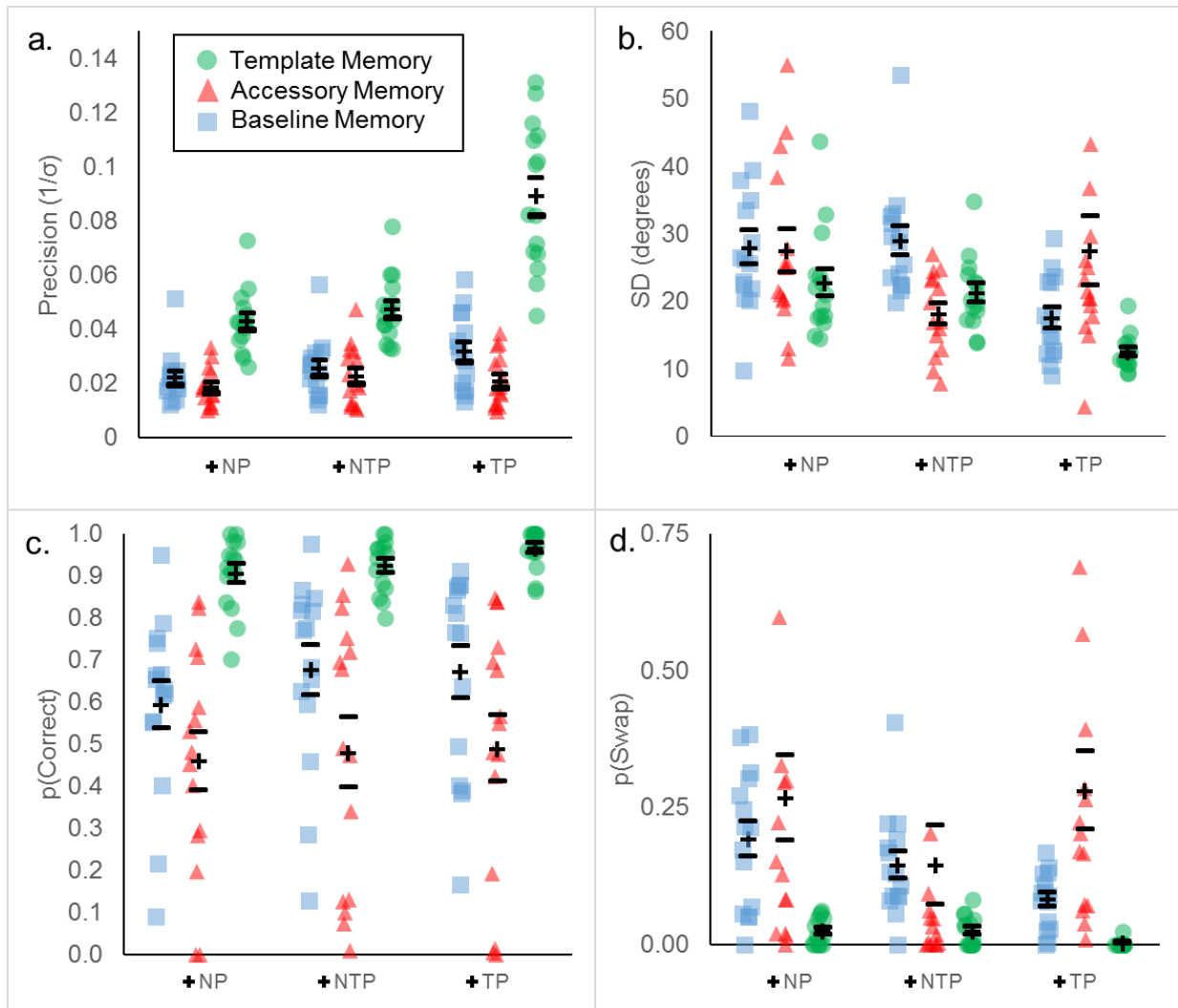
242 On the trials where one item was a search template, precision of the template
243 was better following searches where a template-matching item appeared in search
244 compared to when neither the template nor the accessory item appeared in search (i.e.,
245 tested-present [TP] vs. neither present [NP], for search templates in Figure 2), $t(14) =$

246 8.21, $p < .001$, but was not affected when the accessory item appeared (i.e., non-tested
247 present [NTP[vs. NP), $t(14) = 1.61$, $p = .13$. Accessory precision, on the other hand,
248 benefitted from both the appearance of the accessory item in search (i.e., TP vs. NP for
249 accessory item memory), $t(14) = 2.52$, $p = .024$, and, arguably also, the appearance of
250 the template (i.e., NTP vs. NP), $t(14) = 1.89$, $p = .08$.

251 One potential reason for differences in memory between repeated exposure
252 conditions is differences in overall search time, given that target present searches were
253 faster than target absent searches. To test this possibility, we performed a median split
254 on search display times for no search trials, comparing subsequent memory precision.
255 Despite a large difference in display times, $M_{\text{short}} = 689\text{ms}$, $SE = 3.7\text{ms}$, $M_{\text{long}} = 1349\text{ms}$,
256 $SE = 7.2\text{ms}$, $t(14) = 92.73$, $p < .001$, memory did not differ, $M_{\text{short}} = 0.022$, $SE = 0.0025$,
257 $M_{\text{long}} = 0.026$, $SE = 0.0029$, $t(14) = 0.93$, $p = .37$. As such, differences in retention
258 duration are unlikely to account for the present findings.

259 To better understand the nature of the changes in memory quality caused by
260 searching, we applied the three-component model (Bays, Catalao, & Husain, 2009) to
261 our data, which expresses memory performance as a mixture of three types of
262 responses: correct responses (i.e., responses drawn from a distribution centered
263 around the probed object's color, with an estimated SD), swap responses (i.e.,
264 responses drawn from a distribution centred around the non-probed object's color, with
265 the same SD as correct responses), and guess responses (i.e., responses drawn from a
266 uniform distribution, where every color-response is equally likely). Data in each cell of
267 our design, for each participant, was fitted with the model, and the resulting parameter
268 estimates were analysed. The SD of correct responses for baseline VWM in the three

269 repeated exposure conditions (neither present, non-tested present, tested present) was
270 28° ($SE = 2.5^\circ$), 29° ($SE = 2.1^\circ$), and 18° ($SE = 1.6^\circ$), respectively, and estimated
271 $p(\text{Correct})$ for baseline VWM in the three repeated exposure conditions was .59 ($SE =$
272 $.06$), .68 ($SE = .06$), and .67 ($SE = .06$), respectively. SD of correct responses was
273 determined by memory type, $F(2, 28) = 6.19$, $p = .006$, $\eta^2_p = .31$, repeated exposure,
274 $F(2, 28) = 4.42$, $p = .022$, $\eta^2_p = .24$, and their interaction, $F(4, 56) = 6.39$, $p < .001$, $\eta^2_p =$
275 $.31$ (Figure 2b). However, the probability of a correct response was only affected by
276 memory type, $F(2, 28) = 31.37$, $p < .001$, $\eta^2_p = .69$, with no interaction with repeated
277 exposure, $F(4, 56) = 0.98$, $p = .43$, $\eta^2_p = .07$, but a marginal main effect of repeated
278 exposure, $F(2, 28) = 3.02$, $p = .065$, $\eta^2_p = .18$ (Figure 2c). Critically, the SD of correct
279 responses was lower for templates even when no memory-matching object appeared in
280 search, $t(14) = 2.09$, $p = .055$. Repeated-exposure had opposite effects for accessory
281 items and search templates; templates had lower SD on target present trials compared
282 to none-present, target absent trials, $t(14) = 6.35$, $p < .001$, and accessory-item present,
283 target absent trials, $t(14) = 9.00$, $p < .001$. Accessory items, however, showed no SD
284 reduction when the accessory item appeared in search (i.e., TP vs. baseline for
285 Accessory items), $t(14) = 0.01$, $p = .99$, $\eta^2_p = .001$. Instead, their SD was lower when
286 the template appeared in search (i.e., NTP vs. baseline), $t(14) = 2.68$, $p = .02$.



287

288 **Figure 2.** The effects of memory type (squares: baseline, triangles: accessory Items,
 289 circles: search templates) and repeated exposure (x-axis: NP; neither present; NTP;
 290 non-tested present; TP: tested present) on memory performance. Panel A depicts raw
 291 memory precision ($1/\sigma$ in degrees), panel B depicts estimated memory SD, panel C
 292 depicts estimated p(Correct), and panel d depicts estimated p(Swap). Mean values are
 293 depicted with "+" markers, with "-" markers depicting the mean +/- 1 SE; square,
 294 triangle, and circle markers depict individual participants' mean values, with random x
 295 jitter added to reduce occlusion.

296

297 An analysis of the probability of swap errors (Figure 2d) revealed a main effect of
298 memory type, $F(1, 14) = 7.13$, $p = .003$, $\eta^2_p = .34$, with a large difference in the
299 probability of a swap errors between template-tested trials and accessory-tested trials,
300 $F(1, 14) = 8.86$, $p = .01$, $\eta^2_p = .39$. This shows that true “swaps” were not occurring, and
301 participants were likely reporting the only color they knew (the template color) when the
302 accessory item was tested. Since, this would imply that the accessory color was
303 unavailable, instead of truly swapped with the template color, then these excess swap
304 responses on accessory-tested trials are better considered as guesses – trials in which
305 the accessory color was unknown. Thus, we conclude that, in our task, both swap and
306 guess responses reflected a loss of information about the tested item. The estimated
307 $p(\text{Swap})$ for baseline VWM in each repeated exposure condition was .19 ($SE = .04$), .15
308 ($SE = .03$), .09 ($SE = .01$), respectively.

309 Finally, we analysed search performance as a function of subsequent memory
310 quality. In order to equate the number of trials, we performed a median split on mean
311 squared memory error for both template and accessory memories, thus comparing
312 search when memory was “good” to when it was “bad”. Search was faster overall when
313 memories were recalled with less error, $F(1, 14) = 14.83$, $p = .002$, $\eta^2_p = .51$, $M_{\text{good}} =$
314 938ms , $SE_{\text{good}} = 54\text{ms}$, $M_{\text{bad}} = 998\text{ms}$, $SE_{\text{bad}} = 60\text{ms}$. In addition, searches were faster
315 when the template was tested, which reflects a larger contribution of the memory quality
316 of templates to search speed; trials with good template memory showed faster search
317 than trials with good accessory memory, $t(14) = 3.66$, $p = .003$, but no such difference
318 occurred when memory was bad, $t(14) = 0.38$, $p = .71$. No interactions were found
319 between memory quality and search conditions (template present, accessory present,
320 neither present), $F_s < 0.98$, $p_s > .38$, corroborating the conclusion that, when a template
321 is held in VWM, accessory items do not interfere with search (Woodman, Carlisle, &
322 Reinhart, 2013; Hollingworth & Hwang, 2013).

323 Experiment 2

324 Experiment 1 showed that objects represented in VWM that become search
325 templates are remembered both more often and with greater precision. However, it is
326 not clear whether the change in memory states occurs in anticipation of search or
327 during the search itself. To resolve this ambiguity, we ran a second experiment where
328 participants were again told which of two remembered items needed to be search for,
329 but included trials where no search occurred. If changes in memory states occur when a
330 representation is selected for use as a search template, then we should observe
331 differences between templates and accessory items even when no search is performed.

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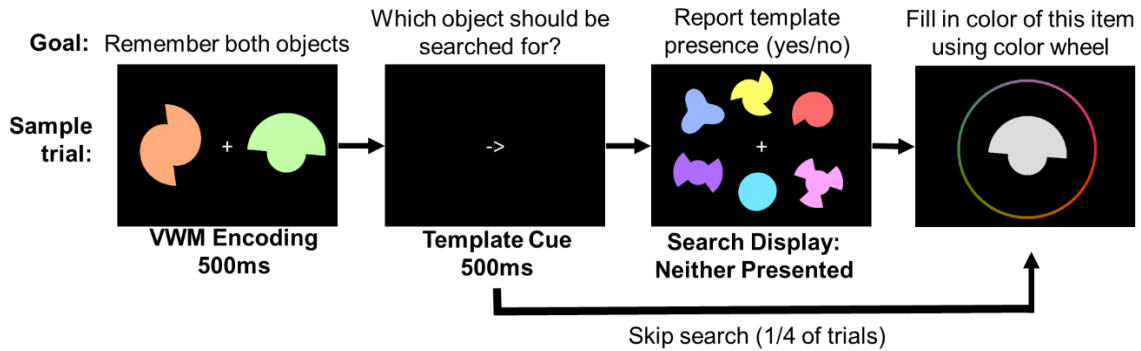
Methods

333 Participants

334 Twenty-four undergraduate students, enrolled in a first-year Psychology course at the
335 University of Toronto, were recruited as participants in Experiment 2. All provided
336 informed consent before participating, and none had participated in Experiment 1.

337 Materials and Procedure

338 Stimuli and Procedure were identical to Experiment 1 with the following exceptions.
339 First, participants completed only a single, one-hour session consisting of 288 trials.
340 This reduction in trial numbers was motivated by exploratory analysis of data from
341 Experiment 1, which showed that the model-fitted memory data did not appreciably
342 differ when only the first of the two sessions for each participant was analysed. Second,
343 the trials with “no search” cues (X's) from Experiment 1 were removed. Instead, four
344 possible trial types followed a search cue (an arrow pointing left or right). No search
345 trials occurred when, 500ms after the offset of the search cue, the memory probe
346 display was presented. These trials occurred on 1/4 of all trials. On the remaining 3/4 of
347 trials, the search display was presented with neither of the memory items present, with
348 the accessory item present, or with the template item present. A schematic of the
349 possible events in a given trial for Experiment 2 is depicted in Figure 3.



350

351 **Figure 3.** A schematic of events in Experiment 2. Not depicted are the 1000ms fixation
 352 period at the beginning of each trial, the 500ms interstimulus interval between the offset
 353 of the template cue and the search display, and the 500ms interstimulus interval
 354 between the offset of the search array and the memory probe, all of which consisted of
 355 a fixation mark on a blank screen.

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Results and Discussion

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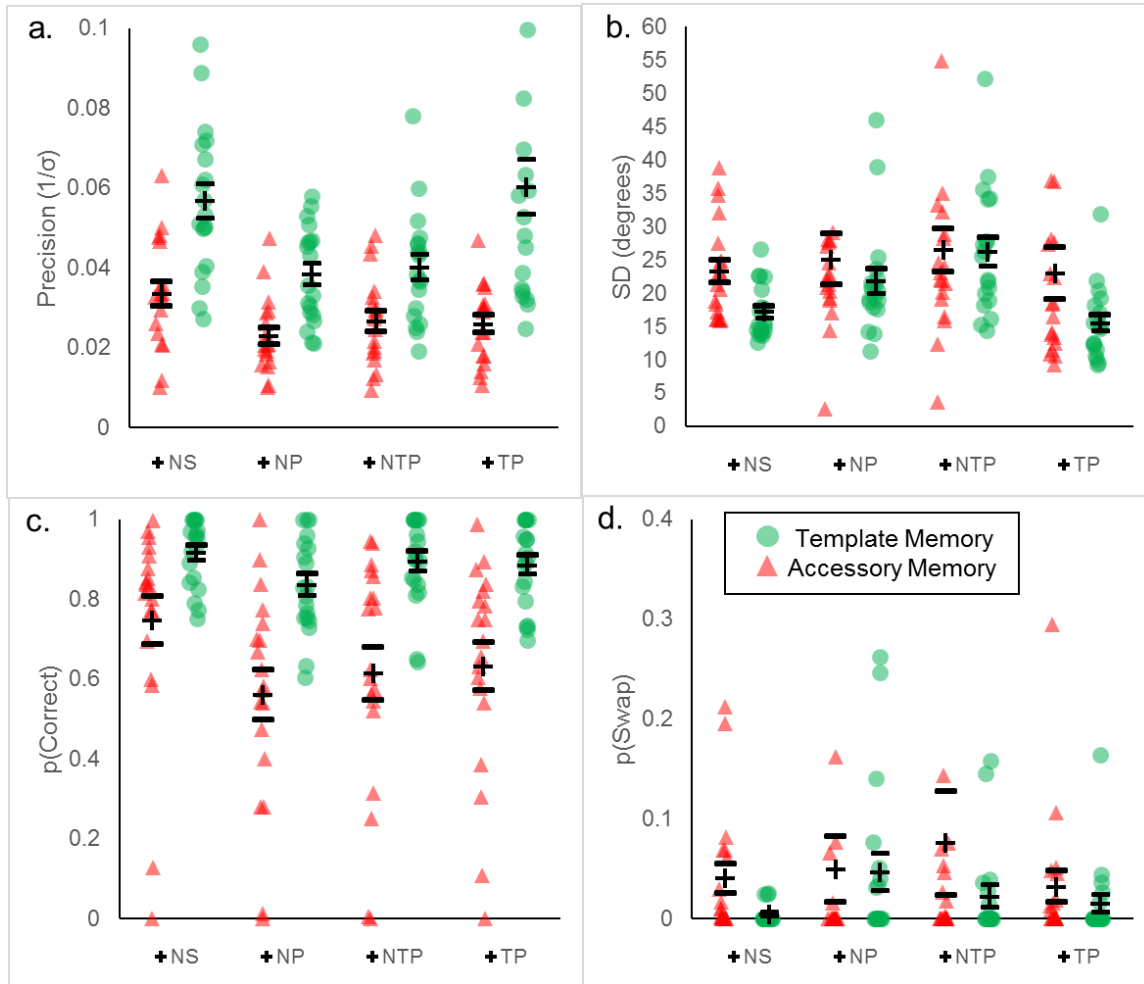
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Five of the twenty-four participants were excluded from data analysis for having
 poor search accuracy (less than 80% correct). Once again, trials with overly fast
 (<100ms) or overly slow (>2SD of overall search RT) were excluded in all analyses. For
 the remaining participants, correct mean search time surprisingly did not differ between
 no target, accessory present, and template present trials, $F(2, 36) = 0.49$, $p = .62$, $\eta^2_p =$
 0.03 , $M_{\text{template present}} = 737\text{ms}$, $SE_{\text{template present}} = 23\text{ms}$; $M_{\text{accessory present}} = 749\text{ms}$,
 $SE_{\text{accessory present}} = 22\text{ms}$; $M_{\text{neither present}} = 753\text{ms}$, $SE_{\text{neither present}} = 25\text{ms}$. Search accuracy,
 however, did differ, $F(1, 36) = 16.90$, $p < .001$, $\eta^2_p = 0.48$, such that accuracy was lower
 on template present trials, $M = 83\%$, $SE = 1.9\%$, than on accessory present trials, $M =$
 93% , $SE = 1.4\%$, and neither present trials, 94% , $SE = 1.4\%$. While unusual, this
 reduction in accuracy for target present trials may have occurred because of the low
 prevalence of targets in our experiment, as in Experiment 1.

369 Mean squared memory error was lower for template than accessory items, $F(1,$
370 $18) = 39.03, p < .001, \eta^2_p = 0.68$, and was also affected by search condition (i.e., the no-
371 search [NS], neither present [NP], non-tested present [NTP], and tested-present [TP]),
372 $F(3, 54) = 12.03, p < .001, \eta^2_p = 0.40$, as can be seen in Figure 4. For both template and
373 accessory items, searching incurred a memory cost. Furthermore, template memory
374 improved when the template appeared in search compared to when the accessory item
375 appeared in search, $t(18) = 2.84, p = .01$, but the reverse was not true; seeing an
376 accessory item in search did not improve accessory item memory, $t(18) = 0.39, p = .70$.
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Figure 4. Memory results for Experiment 2. The x-axes depict memory for the four trial conditions (NS: no search; NP; neither present; NTP; non-tested present; TP: tested present) for accessory items (red triangles) and templates (green circles). Panel A depicts raw memory precision ($1/\sigma$ of memory report errors), Panel B depicts estimated SD of correct memory responses, Panel C depicts estimated probability of a correct response, and Panel D depicts estimated probability of a swap response.

386 To determine the nature of these memory errors, we again analysed memory
387 parameter estimates given by the three-component model (Bays, Catalao, & Husain,
388 2009). Memory SD, was again better for templates than accessory items, $F(1, 18) =$
389 5.89 , $p = .03$, $\eta^2_p = 0.25$, and better after no-search (NS) trials and TP (target present)
390 trials for both template and accessory items, $F(3, 54) = 3.47$, $p = .022$, $\eta^2_p =$
391 0.16 . However, the benefit in memory SD of seeing the tested object in search was
392 greater for the template than for the accessory item (i.e., template vs. accessory, for TP
393 trials), $t(18) = 2.33$, $p = .032$. Critically, however, even when no search occurred,
394 template memory SD was lower than accessory memory SD (i.e., template vs.
395 accessory for NP trials), $t(18) = 3.70$, $p = .002$, showing that template precision is
396 increased in anticipation of search.

397 Estimated $p(\text{Correct})$ was also better for templates than accessory items, $F(1,$
398 $18) = 18.82$, $p < .001$, $\eta^2_p = 0.51$, and was affected by search, $F(3, 54) = 5.95$, $p = .001$,
399 $\eta^2_p = 0.25$. As can be seen in Figure 4, performing a visual search was more deleterious
400 to accessory items than templates. Whether this is due to the increased retention
401 intervals associated with search trials or the visual and cognitive interference that they
402 likely produced is not clear. However, even when no search occurred, templates were
403 more often remembered than accessory items, $t(18) = 2.68$, $p = .015$. Overall, these
404 results show that changes in the representational status of objects in VWM occur in
405 anticipation of, and not only as a consequence of, visual search.

406 We again analysed correct search RT as a function of memory quality, as in
407 Experiment 1. As in Experiment 1, searches were faster when memory quality was

408 higher, $F(1, 18) = 8.82$, $p = .008$, $\eta^2_p = 0.33$, $M_{\text{good}} = 736\text{ms}$, $SE_{\text{good}} = 22\text{ms}$, $M_{\text{bad}} =$
409 757ms , $SE_{\text{bad}} = 21\text{ms}$. No other differences were observed, $F_s < 1.65$, $p_s < .21$,

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Discussion

411 In the present experiments, we measured the quality of memory for objects in
412 VWM that were (templates) and were not (accessory items) used to guide search.
413 Overall, we found that Templates were recalled with greater precision, and were also
414 less likely to be forgotten. Our inclusion of baseline conditions showed that search
415 templates and accessory items compete for limited memory resources; when one object
416 in VWM became a template, it caused the other item to be forgotten more often. Seeing
417 an object held in memory during the context of visual search also improved its precision,
418 although this did not always occur for accessory items. Experiment 2, however, showed
419 that actually searching is not necessary for such a change to occur; Templates were
420 remembered more often and with more precision even when no search occurred. These
421 results paint a picture of how VWM representations are modulated by visual search, and
422 show that search templates are not just prioritized, but better represented (Olivers et al.,
423 2011). However, they also go beyond this proposal in showing a representational cost
424 for accessory items: Search templates' colors were nearly always recalled at test,
425 whereas accessory items' colors were correctly recalled on approximately half of the
426 memory tests; approximately 15% less often than our baseline VWM condition.

427 The present data allow us to distinguish between states in VWM based on
428 memory quality; accessory items, are fragile, and have lower precision, whereas items
429 being used for concurrent tasks (e.g., search templates) are robust and have relatively
430 higher precision representations. Although it is too early to tell whether these findings

431 primarily reflect task demands (e.g., the requirement to maintain color-shape bindings,
432 the amount of color-precision required to distinguish targets from non-targets in search)
433 or more fundamental differences in representation between states in VWM, we
434 nonetheless provide initial evidence that the need to use a representation for search
435 can affect its memory representation.

436 The present data also fill a gap in previous investigations of the relationship
437 between memory precision and search guidance. Whereas Hollingworth and Hwang
438 (2013) showed that memories that do *not* guide attention are not necessarily less
439 precise than memories being actively maintained, we show that memories being
440 actively used for search are more precise and stable than accessory items. Additionally,
441 Dowd, Kiyonaga, Beck, and Egnér (2015) showed that the primary difference between
442 instances in which memory-driven capture occurs and does not occur seems to lie in
443 the probability that a memory is maintained, rather than the precision with which it is
444 held. However, this results speaks to dynamics of whether a single item, which can vary
445 in its task-relevance, affects search. In our task, two items in memory likely competed
446 for representation, and thus the differences in precision may have resulted in a shift in
447 representational resources towards the Template and away from the Accessory item
448 due to its momentary task-relevance. An intriguing finding from Experiment 1 was that
449 memory precision for the accessory item was, counter-intuitively, impaired when that
450 very item appeared in search. This finding may reflect the operation of distractor-
451 suppression mechanisms that occur during search (Lamy, Tsal, & Egeth, 2003; Emrich,
452 Al-Aidroos, Pratt, & Ferber, 2010), however we are hesitant to draw strong conclusions
453 from this finding given that it did not re-emerge in Experiment 2.

454 Our results support and extend the proposal of Olivers et al. (2011), who suggest
455 that visual memories used to guide attention exist in a different state than other visual
456 memories (see also Carlisle & Woodman, 2011). Here we have provided empirical
457 evidence that the representational quality of Templates is superior to Accessory items.
458 Our findings are likely related to the shifts in memory quality found using retro-cues
459 (Murray et al., 2013; Gunseli et al. 2014) to the extent that guided visual search requires
460 a form of internally focused attention within visual working memory. Indeed, the present
461 design is similar to the “retro cuing” paradigm used to study voluntary shifts of attention
462 within VWM (e.g., Griffin & Nobre, 2003; Murray, Nobre, Stokes, Cravo, & Stokes,
463 2013), but without the change in testing probability (see Zokaei, Manohar, Husain, &
464 Feredoes, 2014; Zokaei, Ning, Manohar, Feredoes, & Husain, 2014; and van
465 Moorselaar, Theeuwes, & Olivers, 2014 for non-search alternatives). Despite this
466 difference, the present effect and the retro-cue effect reflect common mechanisms. In
467 this case, the suggestion that templates occupy a special state in visual working
468 memory can be seen as an application of Oberauer’s concept of the Focus of Attention
469 (Oberauer, 2002); a single-item capacity state in working memory that maintains the
470 representation currently being used for a mental task. In any case, critical future
471 research needs to address underlying mechanisms behind these state differences,
472 which could be due to differences in the temporal dynamics of task-relevant memories
473 (e.g., Kiyonaga & Egnér, 2014), differences in representational resources (e.g., active
474 neural representation for Templates; Lewis-Peacock, Drysdale, Oberauer, & Postle,
475 2012), or even both.

476 In summary, by measuring memory for VWM representations that guide search
477 and those that do not, we have provided direct evidence for a privileged state in VWM
478 for search templates over non-search items. This is not to say that voluntary attention
479 necessarily requires VWM (see Carlisle et al., 2011), but when it does, search
480 templates enjoy a representational benefit in VWM. Becoming a selection template thus
481 appears to shift VWM resources for the upcoming search task, demonstrating the role of
482 internal attention in visual selection (Kiyonaga & Egnér, 2013).

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