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Pop-out and Pop-in: Visual working memory advantages for unique items

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Abstract

Attentional control is thought to play a critical role in determining the amount of information that can be stored and retrieved from visual working memory (VWM). Here, we tested whether and how task-irrelevant feature-based salience, known to affect the control of visual attention, affects VWM performance. Our results show that features of a task-irrelevant color singleton are more likely to be recalled from VWM than non-singleton items, and that this increased memorability comes at a cost to the other items in the display. Furthermore, the singleton effect in VWM was negatively correlated with an individual's baseline VWM capacity. Taken together, these results suggest that individual differences in VWM storage capacity may be partially attributable to the ability to ignore differences in task-irrelevant physical salience.

38 Over the past two decades of research in cognitive neuroscience, there has been considerable
39 interest in understanding the relationship between attention and working memory (Awh &
40 Jonides, 2001; Postle, 2006; Chun, 2011; Kiyonaga & Egner, 2013). Such research has
41 demonstrated that attentional control can determine what is remembered (Griffin & Nobre, 2003)
42 and that the contents of memory can influence what is attended (Soto, Hodsoll, Rotshtein, &
43 Humphreys, 2008; Sun, Shen, Shaw, Cant, & Ferber, 2015), indicating that these two cognitive
44 faculties are indeed linked. The investigation of how attention contributes to memory
45 representations has been especially pivotal in our understanding of individual differences in
46 visual working memory (VWM) capacity (Engle, 2001; Vogel, McCullough, & Machizawa,
47 2005; McNab & Klingberg, 2008; Fukuda & Vogel, 2009; Fukuda, Woodman, & Vogel, 2015),
48 where differences in the control of attention have been found to covary with differences in
49 performance in visual working memory tasks. However, it is not clear how the control of
50 attention could contribute to the amount of information encoded into VWM in canonical tasks
51 where no filtering, the simultaneous process of enhancing some while suppressing other items, is
52 required (Luck & Vogel, 1997; Wilken & Ma, 2004). Using a VWM task without any filtering
53 requirement, we show that differences in salience between stimuli— a factor well known to
54 determine the distribution of attention – affect which items are more frequently recalled from
55 VWM, and that an individual’s memory capacity predicts the degree to which their memory
56 performance is susceptible to differences in physical salience.

57 We used feature singletons (Theeuwes, 1992), which are defined as stimuli that differ
58 from concurrently viewed stimuli along a salient visual dimension (e.g., color). In the same way
59 that target stimuli pop-out from a display when they possess a unique salient feature, allowing
60 for rapid target detection (e.g., Treisman & Gelade, 1980), a distractor that possesses a unique

61 feature tends to attract attention in an automatic manner, slowing down processing of the target
62 stimulus (Theeuwes, 1992), unless the appropriate task-set is adopted (Bacon & Egeth, 1994;
63 Theeuwes, 2004; Belopolsky, Zwaan, Theeuwes, & Kramer, 2007). While standard tasks used to
64 measure VWM capacity do not present singletons in memory sample arrays, items that are to be
65 encoded vary in many visual features, leading to an imbalance in salience. Salience itself, of
66 course, is typically task-irrelevant; participants are supposed to simply extract the feature values
67 of the presented items for storage in memory. However, attentional research on singletons
68 demonstrates that ignoring differences in task-irrelevant salience is nearly impossible when all
69 stimuli must be sampled. In other words, given that task-irrelevant singletons reliably attract
70 attention, it is reasonable to assume that singletons, when present, would be rapidly uploaded
71 into VWM and may even be recalled more frequently from VWM than non-singletons. That is,
72 any increase in the memorability of one item could lead to a reduction in the memorability of
73 other items, such that a highly salient item (i.e., a singleton) is encoded at the expense of less
74 salient items (i.e., the non-singleton items). Indeed, to the extent that task-irrelevant salience
75 orients visual attention, singletons may increase memory for items in a similar manner to
76 voluntary attention, directed saccades, and uninformative onsets (Bays & Husain, 2008; Bays et
77 al., 2011; Schmidt et al., 2002). However, task-irrelevant singletons can be successfully ignored
78 when attention is controlled using a top-down set (Bacon & Egeth, 1994; Leber & Egeth, 2006),
79 meaning that salience might not always translate into VWM priority.

80 To test these two possibilities, we used task-irrelevant singletons to determine whether
81 differences in salience contribute to capacity limitations in VWM, compared to displays with
82 homogenous objects. We predicted that in the former displays, singletons would show a memory
83 gain when tested. We further compared the memory for non-singleton objects in these displays to

84 a baseline condition (no singleton, but the same set size) to assess whether the predicted memory
85 gain for the singleton would come at a cost to the non-singleton items. To ensure that we could
86 disentangle differences between graded and discrete changes in VWM representation,
87 participants completed a delayed estimation task (Wilken & Ma, 2004; Zhang & Luck, 2008;
88 Bays, Catalao, & Husain, 2009) where memory error for orientation was measured and fit with a
89 three-component model to obtain estimates of the contribution of different sources of memory
90 error (precision, correct responses, swap responses, and guess responses).

91 **Methods**

92 **Participants**

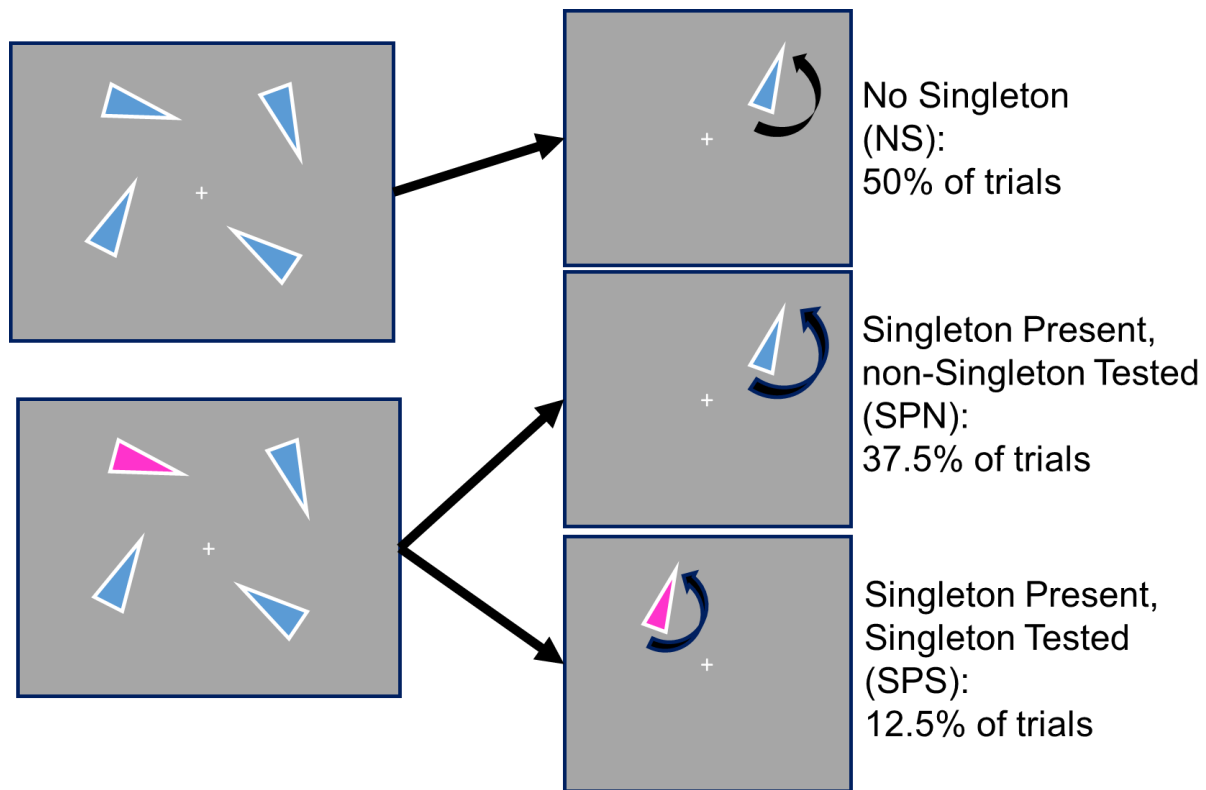
93 Fifty-five undergraduate volunteers participated in this experiment for monetary
94 compensation. All participants were naïve to the experimental hypotheses and provided informed
95 consent before participation in accordance with procedures approved by the University of
96 Toronto Research Ethics Board.

97 **Materials, Methods, and Procedure**

98 The experiment was conducted on a PC computer equipped with a standard USB mouse
99 and keyboard, and a 40cm x 30cm CRT monitor, with a screen resolution of 1280 x 960 pixels
100 and a refresh rate of 85hz. Stimuli were presented using Matlab (Mathworks, Natick, MA) along
101 with the Psychophysics toolbox (Kleiner et al., 2007), and were viewed from a distance of 40cm.

102 A schematic of the trial types is depicted in Figure 1. Each session consisted of five
103 practice trials and 512 experimental trials, divided into eight blocks. A trial consisted of four
104 events: an initial fixation display (for 1000 ms), a memory sample display (100 ms, to preclude
105 eye movements), a retention interval (900 ms), and a probe display (until response). The fixation
106 display consisted of a central fixation cross drawn in white in the form of a “+” in Courier New

107 Font at a text size of 18 points (approximately 0.5°), centered on a uniform, gray background.
 108 Fixation was not monitored, however, participants were instructed to maintain fixation.



110 **Figure 1.** A schematic of the trial types used in the experiment. Memory samples consisted of
 111 four isosceles triangles whose orientations were pseudo-randomized and to be remembered. On
 112 half of all trials, one triangle was colored in a unique color. After a retention interval, one of the
 113 four items was probed, and participants reported its previous orientation by adjusting the probe's
 114 orientation. On Singleton Present trials, the singleton was just as likely to be tested as any of the
 115 non-singleton items.

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117 The memory sample display consisted of four, pseudo-randomly positioned isosceles
 118 triangles equidistant from the fixation mark. Participants were to memorize the orientations of
 119 each triangle, which were randomized with the constraint that each orientation was a minimum

120 of 30° from all other orientations. The triangles were 2.7° in height, with a base of 1.4° , and
121 appeared 9° from fixation. To ensure that no occlusion occurred, triangles were separated by at
122 least 4.5° , center-to-center. The memory sample display could also differ in the presence or
123 absence of a feature singleton. On No Singleton trials, all four triangles shared the same color,
124 which was randomly sampled from a circular list of L^*a^*b values, all of which shared a radial
125 distance of 50 units from $[70, 0, 0]$ in L^*a^*b space, where the a and b values could vary, but the
126 luminance (L) was held constant. On Singleton Present trials, one triangle was colored such that
127 it was 90° away in L^*a^*b color space from the other triangles (either clockwise or
128 counterclockwise) in the circular color list. The triangles were also drawn with a 0.4° white
129 border to enhance the contrast from the background.

130 The retention interval display was identical to the fixation display, except that it lasted for
131 900 ms, and was followed by a probe display. In this probe display, a single colored circular
132 placeholder, with a radius of 1.3° , was presented in the location of one of the triangles from the
133 sample display. The circular placeholder's location and color matched one of the four memory
134 sample triangles. Importantly, in the Singleton Present condition, this probe matched the
135 singleton triangle with a frequency of one in four trials, so that there was no strategic incentive to
136 encode the singleton item. Once the mouse cursor was moved away from the center of the
137 screen, the probe was redrawn as a triangle whose orientation pointed towards the current
138 location of the mouse cursor. Participants reported the orientation of the probed item by moving
139 the mouse around the probe stimulus to perceptually match it to the remembered orientation of
140 the probed item. To input a response, participants clicked the mouse. For practice trials only,
141 1000 ms of feedback was provided after each response, in the form of the triangle being redrawn
142 in its original position.

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Results

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For each trial, memory error was calculated by subtracting the reported angle of orientation (in degrees) from the actual angle of orientation for the probed object and taking the absolute value. The average error was 41.16° , and the standard error of the sample mean (SEM) was 2.36° .

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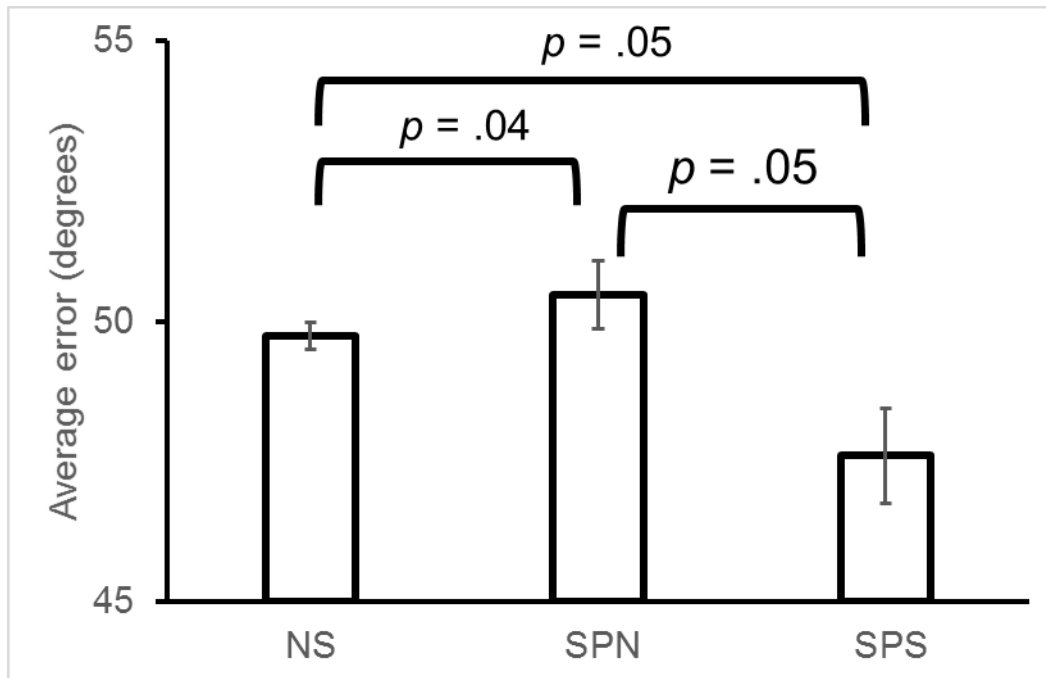
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To assess the effect of irrelevant color singletons on VWM, we calculated average absolute report error for three conditions: No Singleton present (NS), Singleton Present and Non-singleton tested (SPN), and Singleton Present with a Singleton tested (SPS), shown in Figure 2. A one-way, repeated measures ANOVA with Condition (NS, SPN, SPS) as within-subjects factors showed a main effect of Condition, $F(2, 106) = 4.03, p = .02, \eta^2 = .07$, such that SPS trials led to better memory performance than NS trials, $F(1, 53) = 3.96, p = .05, \eta^2 = .07$, and SPN trial led to poorer memory performance than NS trials, $F(1, 53) = 4.34, p = .04, \eta^2 = .08$, as shown by follow-up, pairwise contrast analyses. Thus, irrelevant singletons received a boost in accuracy, and this increase in accuracy came at the expense of memory for non-singletons in the memory array.



158

159 **Figure 2.** Average absolute memory error, in degrees, for the three conditions. NS: No
 160 Singleton, SPN: Singleton Present; Non-singleton tested, SPS: Singleton Present; Singleton
 161 tested. Error bars represent one within-subjects standard deviation (Cousineau, 2005).

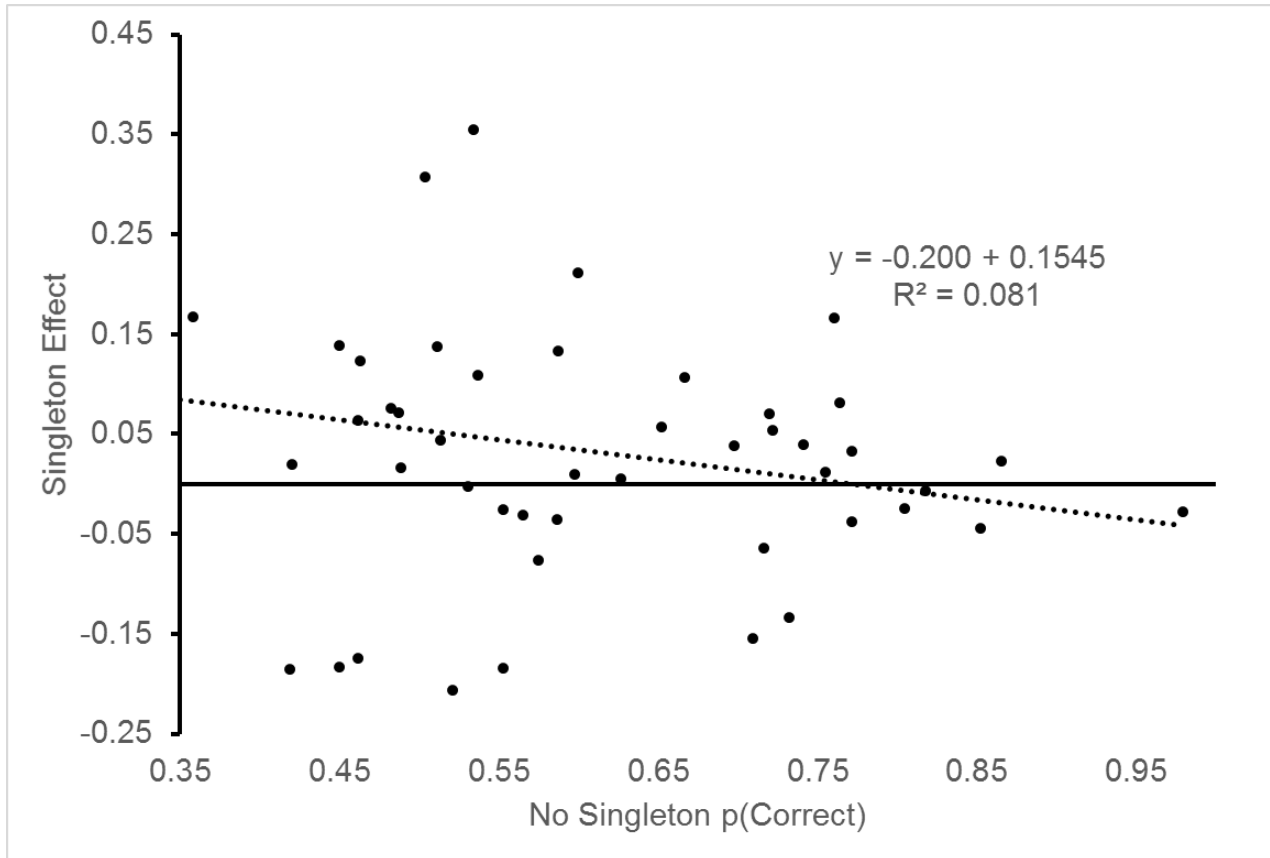
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163 To determine whether the effects in absolute error were driven by a change in memory
 164 precision or by a change in the probability of remembering the target item ($p(\text{Correct})$), we fitted
 165 signed response error scores in each condition using the three-component model of VWM (Bays,
 166 Catalao, & Husain, 2009). Briefly, this model uses maximum-likelihood estimation to
 167 decompose the overall distribution of response error into three different sources: correct
 168 responses (i.e., responses represented by a circular normal distribution, i.e., Von Mises, centered
 169 on the target item's value), swap responses (i.e., responses represented by a circular normal
 170 distribution centered on each of the non-target items' values), and guess responses (i.e., a
 171 uniform distribution, where every response is equally likely). The model provides three
 172 probability values, reflecting the likelihood of each type of responses in the submitted dataset, as

173 well as a measure of memory precision (the standard deviation of the target and non-target
174 distributions). Note that because this estimation procedure uses all responses to estimate
175 parameter presumed to underlie memory performance, it does not classify individual responses
176 into correct responses, swaps, or guesses, rather, the fitting algorithm searches parameter space
177 to optimize parameter estimates in order to yield the best fit to the data.

178 Given that we observed an effect of singletons on overall memory error, we ran separate
179 one-way, repeated measures ANOVAs to specifically determine which memory parameters were
180 impacted by the presence of a singleton. The results showed that $p(\text{Correct})$, the likelihood of
181 retrieving the orientation of the probed item, however precisely, was modulated by the presence
182 of a singleton, $F(2, 106) = 5.82, p = .004, \eta^2 = .10$, with $p(\text{Swap})$ showing a complementary
183 modulation, $F(2, 106) = 5.92, p = .004, \eta^2 = .10$, but no other aspects of memory performance
184 (precision, or guess responses) were affected, $F_s(2, 106) < 1.02, p_s > .36, \eta^2_s < .02$. The
185 probability of correctly reporting the tested item's orientation was .56 in the NS condition ($SE =$
186 0.03), .55 in the SPN condition ($SE = .03$), and .59 ($SE = 0.03$) in the SPS condition. Follow-up
187 contrasts showed that, as with absolute error, singletons were remembered more often than items
188 in the NS condition, $F(1, 53) = 5.95, p = .018, \eta^2 = .10$, and non-Singletons were remembered
189 less often than NS items, $F(1, 53) = 4.49, p = .039, \eta^2 = .08$. Comparing overall performance on
190 Singleton-Present trials to NS trials, regardless of the tested item, showed a reliable difference,
191 $t(53) = 2.35, p = .023$, such that Singleton Present trials exhibited more correct responses, $M_{SP} =$
192 $0.58, SE_{SP} = 0.02, M_{NS} = 0.56, SE_{NS} = 0.03$, which was driven by a decrease in swap responses,
193 $t(53) = 2.07, p = .02$. Taken together, we conclude that salient items are less likely to be confused
194 with other remembered items, but are not remembered with greater precision.

195 Lastly, we noted that the size of this performance change – from a $p(\text{Correct})$ of 0.56 in
196 the NS condition to a $p(\text{Correct})$ of 0.59 in the SPS condition – was modest. Given that
197 attentional control is known to vary between low- and high-capacity individuals (e.g., Fukuda &
198 Vogel, 2009), we assessed the size of the singleton effect ($p(\text{Correct})$ on SPS trials – $p(\text{Correct})$
199 on SPN trials) as a function of participants' baseline VWM performance ($p(\text{Correct})$ on NS
200 trials), shown in Figure 3. A simple linear regression, using heteroskedasticity-consistent
201 standard errors (see Hayes & Cai, 2007), showed that 8% of the variance in $p(\text{Correct})$ change
202 when a singleton appeared in the memory sample was shared with participants' $p(\text{Correct})$ when
203 stimuli were homogenous, $\beta = -2.00$, $SE = 0.084$, $R^2 = .081$, $p = .02$. Put differently, individuals
204 with lower baseline VWM capacity were more susceptible to singleton capture. To determine the
205 source of the memory change, we further regressed the change in the two types of memory
206 failures ($p(\text{Swap})$ and $p(\text{Guess})$) between the SPS and SPN conditions with participants' baseline
207 memory performance ($p(\text{Correct})$ in the NS condition; see Appendix A for graphical depictions).
208 The resulting regressions showed a marginal relationship between low VWM performance in NS
209 trials and likelihood of guessing the orientation of a non-Singleton compared to a singleton on
210 Singleton Present trials, $\beta = .25$, $SE = .14$, $R^2 = .081$, $p = .08$, and no relationship between
211 baseline VWM performance and the probability of a swap error for Singleton and non-Singleton
212 items, $\beta = -.04$, $SE = .073$, $R^2 = .007$, $p = .58$. Thus, it appears that individual differences in the
213 effect of a task-irrelevant singleton are better characterized as a bias to encode the singleton at
214 the expense of non-singletons, as opposed to a change in the color-based grouping of items in
215 VWM that could have led to increased swaps between non-singletons.



216

217 **Figure 3.** Singleton Effect as a function of Non Singleton (NS) memory performance. For both
218 measures, the estimated $p(\text{Correct})$ for each observer from the fitted three-component model was
219 used.

220

Discussion

221
222 We examined the contribution of visual salience to the temporary storage of visual
223 information. When a unique item appeared in a to-be-remembered display, this item was more
224 likely to be recalled, at the expense of non-unique items. Decomposing performance into
225 different sources of memory error (i.e., Precision, Swap errors, and Guess errors) revealed that
226 singletons were more often discretely remembered than non-singletons, but not remembered with
227 greater precision. Critically, this effect existed in the absence of any incentive to remember the
228 salient item; its unique color was completely task-irrelevant. Additionally, we have shown that
229 individuals with lower baseline VWM capacity, as measured by performance on trials with no
230 singleton (NS), are more susceptible to task-irrelevant salience. Our results are consistent with
231 existing models that include attentional priority as a factor determining encoding into VWM
232 (Bundsen, 1990; Bowman & Wyble, 2007). The effects of task-irrelevant visual salience can thus
233 have cascading implications beyond perception, influencing what can be recalled from VWM.

234 A number of studies have shown that attention can determine what information will be
235 stored in VWM. For instance, providing cues as to which object is likely to be tested will
236 increase its odds of surviving the capacity limits of VWM at the expense of memory for other
237 objects both before (Bays & Husain, 2008; Bays et al., 2011; Zhang & Luck, 2008) and after
238 (e.g., Griffin & Nobre, 2003; Zhang & Luck, 2008; Sligte, Scholte, & Lamme, 2008) encoding.
239 While this demonstrates an ability to strategically allocate VWM resources, investigations of
240 individual differences have shown that the allocation of VWM resources is not always optimal.
241 This conclusion is largely drawn from performance in tasks where some, but not all, items in a
242 display must be encoded into VWM. In these tasks, participants who perform poorly in standard

243 VWM tasks tend to also perform poorly in filtering conditions (Vogel, McCullough, &
244 Machizawa, 2005; Fukuda & Vogel, 2009).

245 Very few studies have, however, investigated whether differences in attentional control
246 can account for variability in the ability to store information in VWM when no filtering is
247 necessary. A recent exception is the work of Fukuda, Woodman, and Vogel (2015), who have
248 argued that the decreased ability to control attention at encoding contributes to the poor
249 performance at high set sizes. Specifically, when more items are presented than can be
250 successfully encoded, the competition between multiple items interferes with the successful
251 encoding of items, thus implicating attentional control as a factor in VWM capacity even when
252 all items are equally relevant. Our results extend this argument in two important ways. First, by
253 controlling the task-irrelevant salience of to-be-remembered items, we have shown that
254 differences in salience between items can cause VWM resources to be unevenly allocated within
255 a set of task-relevant items. Furthermore, salient items are more likely to be encoded for those
256 with lower capacity. Second, our results show that capacity does not need to be exceeded by
257 much before attentional control becomes a limiting factor in performance; our experiment used a
258 set size of 4, typically used as a baseline *from which* the effect of exceeding capacity is measured
259 (Fukuda, Woodman, & Vogel, 2015; Pailian & Halberda, 2014).

260 The effect of singletons on visual search has been attributed largely to the preattentive
261 stage of vision, such that it reliably affects search behavior only when target identification is
262 driven by a global analysis of the search display (Theeuwes, 2006; Belopolsky et al., 2009).
263 Coupling this conclusion with the results of the present experiment, we suggest that differences
264 in salience reduce the ability to equally prioritize all items in memory. Given that the change
265 detection and delayed estimation tasks normally used to assess VWM test memory for

266 individuated items, it would be sensible to encode and store items as separate pieces of
267 information, each with equal priority (unless some items are tested more than others). This is not
268 to say that participants should not selectively encode items, but any selection should be task-
269 relevant. Individuals with low VWM capacity appear to be more strongly affected by task-
270 irrelevant stimulus differences; in our task, color was task-irrelevant, and thus did not carry any
271 predictive values pertaining to the information that would be important. This is consistent with
272 Fukuda and Vogel's (2011) findings that individuals with low capacity have difficulties ignoring
273 irrelevant items that share a feature with a to-be-detected target. Together, these results point to
274 the conclusion that those who perform poorly on VWM tasks have difficulty restricting attention
275 to task-relevant information, whether that requires segregating items by color (e.g., Vogel,
276 McCullough, & Machizawa, 2005) or ignoring irrelevant color differences, as in the current
277 study.

278 The present results further highlight the importance of balancing the salience of to-be-
279 remembered items when measuring individual differences in VWM capacity. Although it is
280 assumed that all items in a memory array will be equally attended when no strategic incentive is
281 provided towards any given stimulus, our results indicate that this assumption should be revised.
282 Differences in physical salience between items are associated with an uneven distribution of
283 attention to items in a display, and these differences will more strongly affect those who tend to
284 perform more poorly in VWM tasks. Although laboratory tasks for measuring VWM capacity
285 tend to use simple, geometric stimuli, even low-level differences can affect subsequent memory;
286 uniqueness in location improves VWM encoding (Emrich & Ferber, 2012), and color
287 homogeneity improves change detection (Lin & Luck, 2009). Both results are consistent with the
288 notion that differences in salience are able to create an uneven distribution of VWM resources.

289 Given the numerous attributes that are argued to reflexively attract attention (e.g., emotional
290 valence: Yiend, 2010; reward history; Anderson, Laurent, & Yantis, 2011; bottom-up priming:
291 Theeuwes, Reimann, & Mortier, 2006) assessing the relationship between salience – broadly
292 construed – and memorability is likely to be an important step in understanding how visual
293 working memory supports cognition and action in real-world contexts.

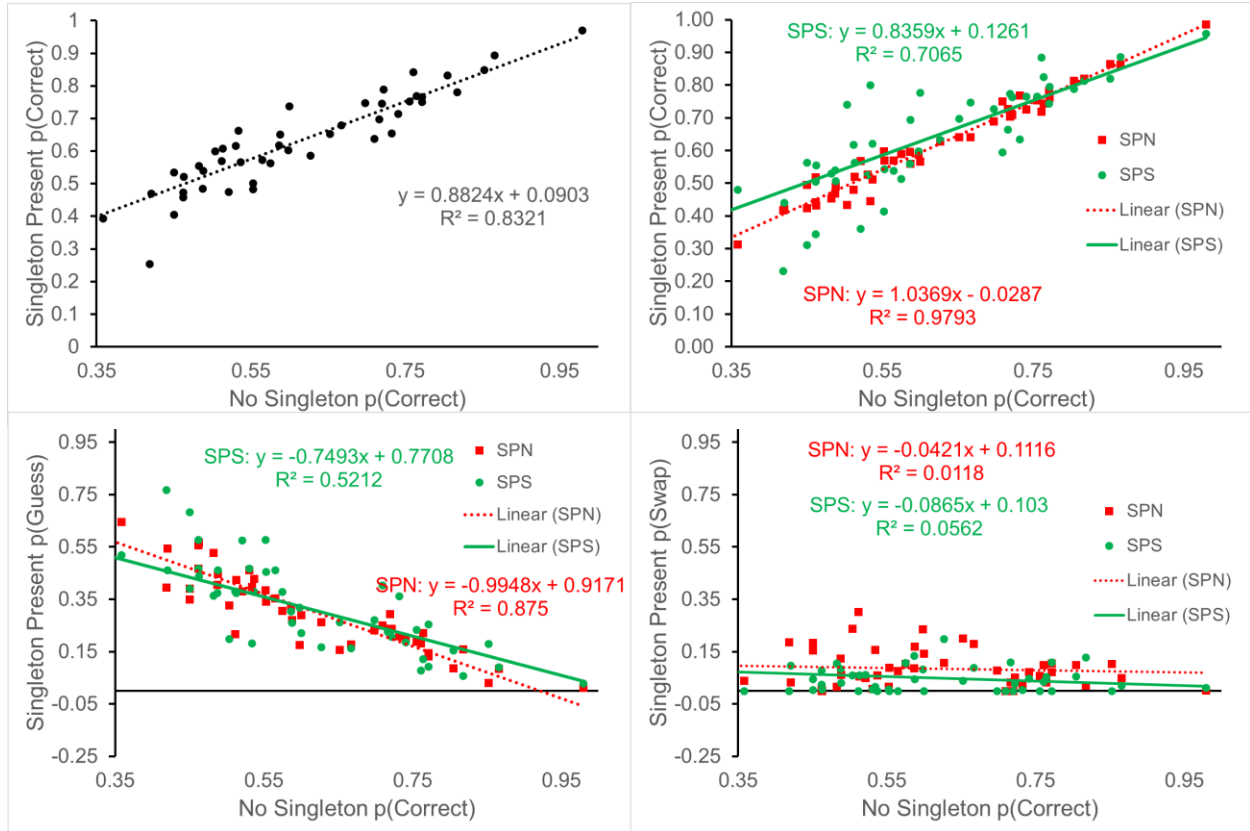
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384 **Appendix A: Individual Differences Figures**

385

386 **Figure 1.** Individual performance as a function of baseline memory performance: p(Correct).

387 Panel A: p(Correct) for trials with a singleton present, regardless of the tested item. Panel B:

388 p(Correct) for trials with a singleton present, with singleton test and non-singleton test

389 performance separated. Panel C: p(Guess) for trials with a singleton present, with test-types

390 separated. Panel D: p(Swap) for trials with a singleton present, with test-types separated.