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9 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.

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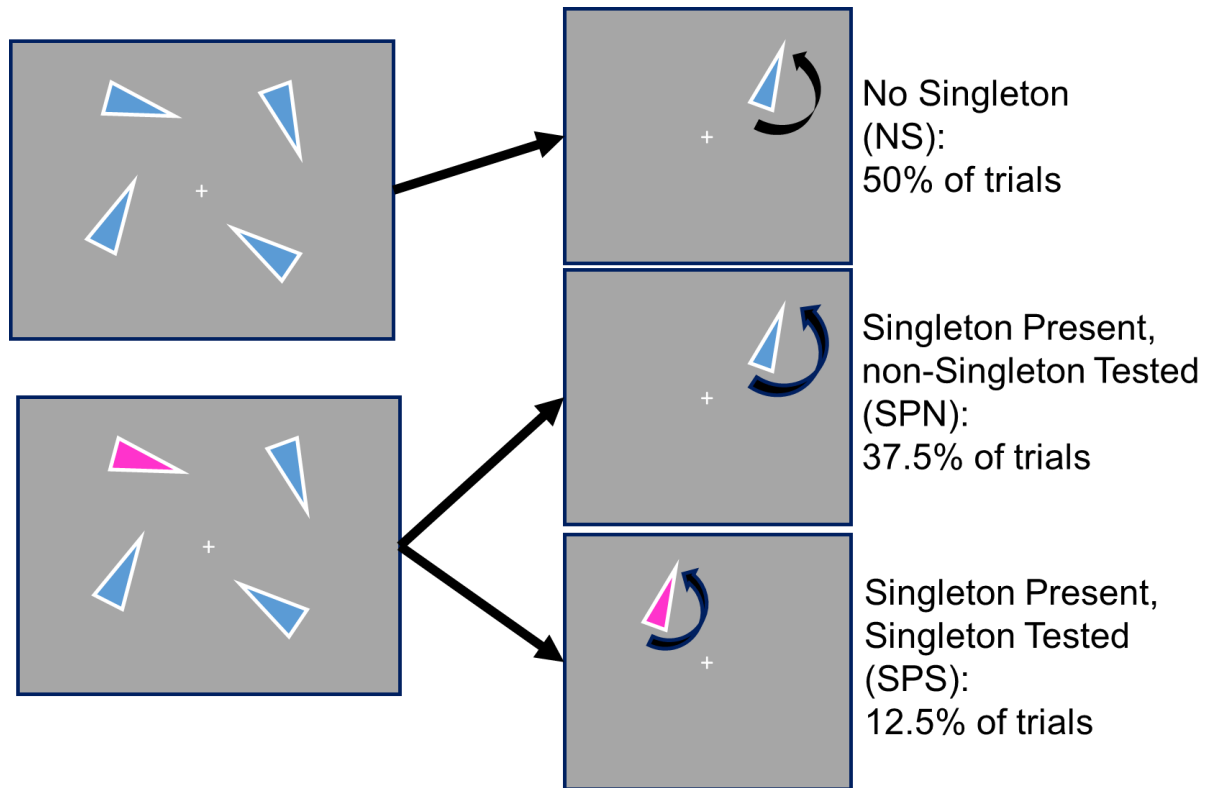
Figure 1. A schematic of the trial types used in the experiment. Memory samples consisted of

four isosceles triangles whose orientations were pseudo-randomized and to be remembered. On

half of all trials, one triangle was colored in a unique color. After a retention interval, one of the

four items was probed, and participants reported its previous orientation by adjusting the probe's

orientation. On Singleton Present trials, the singleton was just as likely to be tested as any of the

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.

143   **Results**

144   For each trial, memory error was calculated by subtracting the reported angle of

145   orientation (in degrees) from the actual angle of orientation for the probed object and taking the

146   absolute value. The average error was 41.16°, and the standard error of the sample mean (SEM)

147   was 2.36°.

148   To assess the effect of irrelevant color singletons on VWM, we calculated average

149   absolute report error for three conditions: No Singleton present (NS), Singleton Present and Non-

150   singleton tested (SPN), and Singleton Present with a Singleton tested (SPS), shown in Figure 2.

151   A one-way, repeated measures ANOVA with Condition (NS, SPN, SPS) as within-subjects

152   factors showed a main effect of Condition, $F(2, 106) = 4.03$, $p = .02$, $\eta^2 = .07$, such that SPS

153   trials led to better memory performance than NS trials, $F(1, 53) = 3.96$, $p = .05$, $\eta^2 = .07$, and

154   SPN trial led to poorer memory performance than NS trials, $F(1, 53) = 4.34$, $p = .04$, $\eta^2 = .08$, as

155   shown by follow-up, pairwise contrast analyses. Thus, irrelevant singletons received a boost in

156   accuracy, and this increase in accuracy came at the expense of memory for non-singletons in the

157   memory array.
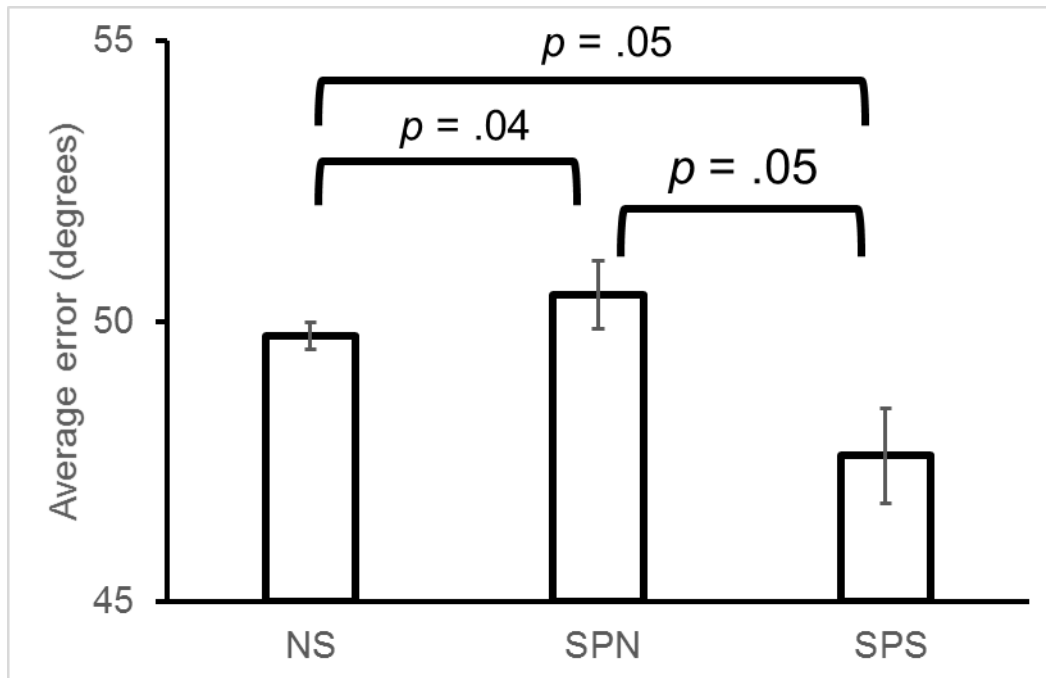
Figure 2. Average absolute memory error, in degrees, for the three conditions. NS: No

Singleton, SPN: Singleton Present; Non-singleton tested, SPS: Singleton Present; Singleton

tested. Error bars represent one within-subjects standard deviation (Cousineau, 2005).

        To determine whether the effects in absolute error were driven by a change in memory

precision or by a change in the probability of remembering the target item (p(Correct)), we fitted

signed response error scores in each condition using the three-component model of VWM (Bays,

Catalao, & Husain, 2009). Briefly, this model uses maximum-likelihood estimation to

decompose the overall distribution of response error into three different sources: correct

responses (i.e., responses represented by a circular normal distribution, i.e., Von Mises, centered

on the target item's value), swap responses (i.e., responses represented by a circular normal

distribution centered on each of the non-target items' values), and guess responses (i.e., a

uniform distribution, where every response is equally likely). The model provides three

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(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(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, $Fs(2, 106) < 1.02$, $ps > .36$, $\eta^2 s < .02$. 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(Correct) of 0.56 in

196   the NS condition to a p(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(Correct) on SPS trials – p(Correct)

199   on SPN trials) as a function of participants' baseline VWM performance (p(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(Correct) change

202   when a singleton appeared in the memory sample was shared with participants' p(Correct) when

203   stimuli were homogenous, β = -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(Swap) and p(Guess)) between the SPS and SPN conditions with participants' baseline

207   memory performance (p(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, β = .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, β = -.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.

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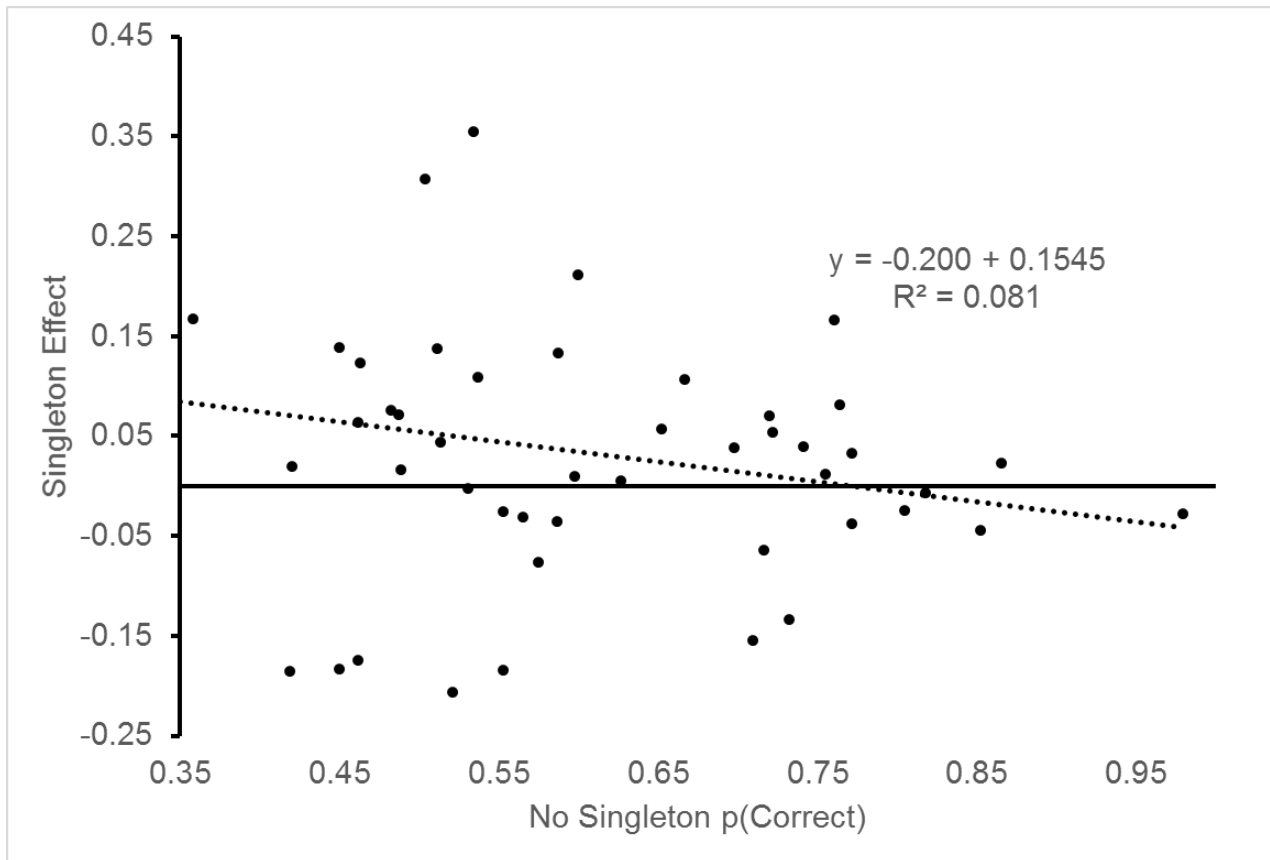
Figure 3. Singleton Effect as a function of Non Singleton (NS) memory performance. For both

measures, the estimated p(Correct) for each observer from the fitted three-component model was

used.

220

221   **Discussion**

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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383

384   **Appendix A: Individual Differences Figures**
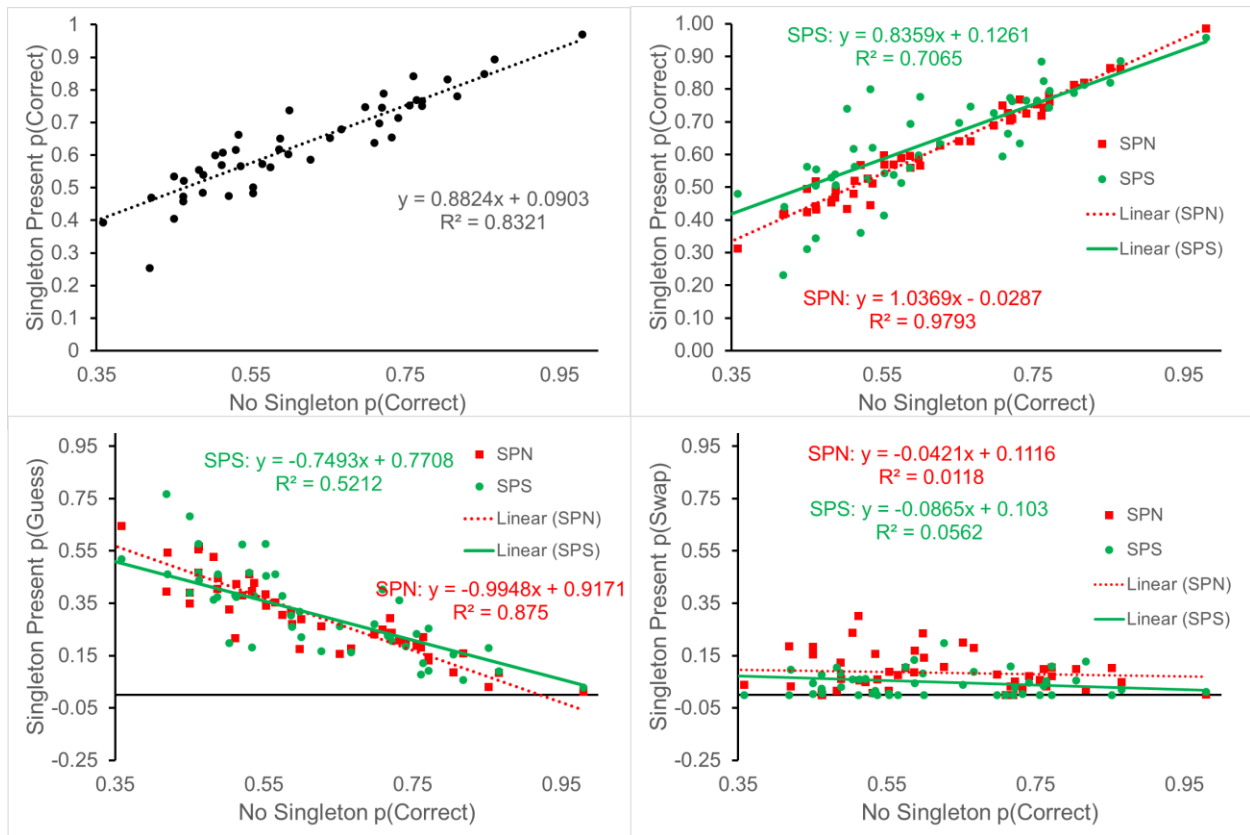
385

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.