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Eye movements can cause item-specific visual recognition advantages

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Abstract

Prior research suggests that spontaneous saccades localized towards blank regions of space during memory storage and recall improve memory for items at the saccade locations. In the present study, we examined whether a recognition advantage can be observed when a single, exogenously directed saccade occurs during memory maintenance. We manipulated whether participants made a saccade to an item's previous location or maintained fixation, as well as whether tested items reappeared in their original location or not. The results of three experiments showed that visual recognition was better after a saccade to the location of a probed object than after no saccade or after a saccade to the location of a non-probed object, so long as saccades went to the to-be-tested location more often than chance. Taken together, our findings demonstrate that eye movements can elicit an item-specific recognition advantage in visual working memory.

Keywords: eye movements, memory, recognition

52 Eye movements bridge our internal perceptual representation of the world and the external visual
53 space. Decades ago, Donald O. Hebb (1968) ascribed a pivotal role to eye movements during
54 visual imagery, positing that they serve to organize and assemble parts into whole images.
55 Consistent with this notion, it is well established that people make spontaneous eye movements
56 during image recall that overlaps spatial scanpaths from encoding (Johansson, Holsanova, &
57 Holmqvist, 2006; Laeng & Teodorescu, 2002; Richardson & Spivey, 2000; Spivey & Geng,
58 2001). It thus follows that overt shifts of attention during maintenance may not be
59 epiphenomenal but rather serve a functional role in memory retrieval. In the present study we
60 examine whether single saccadic eye movements affect visual recognition. Specifically, we
61 investigated whether an obligatory, retrospective saccade initiated towards a to-be-tested location
62 would improve for a target probe.

63 Over the past two decades, numerous studies have reported that spontaneous saccades
64 localized towards blank regions of space occur during memory recall. Preliminary evidence for
65 a functional role of eye movements in memory came from the blank screen paradigm by Spivey
66 and Geng (2001; Richardson & Spivey, 2000). Observers saw four peripherally presented
67 shapes of varying colour and orientation displayed in a 3 x 3 grid, followed by a blank screen
68 delay. After a one second delay, three of the stimuli reappeared while participants were asked
69 about the colour and orientation of the missing item. Indeed, there was spontaneous activation of
70 the oculomotor system during this recall phase towards the location of a prior stimulus, even
71 when this stimulus was no longer present (Brandt & Stark, 1997; Johansson, et al., 2006; Laeng
72 & Teodorescu, 2002; Richardson & Spivey, 2000; Spivey & Geng, 2001). Likewise, in a mental
73 imagery task, Laeng and Teodorescu (2002) found highly correlated patterns between eye
74 scanpaths of observers during perceptual encoding of images (grid patterns or natural object) and

75 mental visualization. Subsequently, they hypothesized that the re-enactment of eye movements
76 during perceptual encoding plays a role in the reconstruction of mental images encoded during
77 the initial scanpath sequence.

78 The robustness of the saccade re-enactment component of Laeng and Theodorescu's
79 theory was later challenged by Johansson, Holsanova, Dewhurst, & Holmqvist (2012) who
80 showed in a free viewing blank screen paradigm that even when subjects held their gaze at
81 central fixation during encoding, they still elicited eye movements during retrieval that reflected
82 spatial overlaps to the original visual scene. These data point to the conclusion that eye
83 movements, rather than simply providing an episodic memory cue, may serve a role in accessing
84 spatially organized information. Further support for this conclusion comes from Johansson &
85 Johansson's (2014) finding that directing eye movements to a location improves memory for the
86 stimulus that had occupied that location. Eye movements, then, seem to serve a functional, and
87 not simply epiphenomenal, role in memory retrieval.

88 Despite the research interest on the role of eye movements in memory, it is not clear
89 whether a single saccade, executed towards the previous location of a stimulus during memory
90 maintenance, will affect memory for that stimulus. The studies reviewed above rely primarily on
91 verbal recall of the stimuli, and so do not provide a great deal of information about the memory
92 representations available to eye movements. To determine the characteristics of the memory
93 traces that are accessed by eye movements, it is ideal to use visual recognition methods. For
94 example, Olsen et al. (2014) have shown that eye movement patterns that are more similar
95 between study and tests are associated with better visual recognition of a location change, but
96 only when tests allowed the comparison of remembered items' spatial relations.

97 A separate, but related, literature on the role of attention in the short-term maintenance of
98 visual information has shown that internal attention can be voluntarily directed to a particular
99 object representation via its location (Griffin & Nobre, 2003; Sligte, Scholte, & Lamme, 2008;
100 see Souza & Oberauer, 2016 for a recent review). A large portion of this literature is concerned
101 with what it is that attention does to memory representations to allow for improvements in
102 memory for attended items (e.g., Makovski, Sussman, & Jiang, 2008; Pertzov, Bays, Joseph, &
103 Husain, 2013; Souza, Rerko, & Oberauer, 2016). Given that eye movements and attention are
104 often closely related (Kowler, Anderson, Doshier, & Blaser, 1995; Hoffman & Subramaniam,
105 1995; Deubel & Schneider, 1996; Godijn & Pratt, 2002; Theeuwes, Belopolsky, & Olivers,
106 2009, but see Belopolsky & Theeuwes, 2009), it is possible that eye movements both affect and
107 reflect memory by virtue of their relationship to the current locus of attention. Indeed,
108 maintaining locations in working memory can affect the dynamics of eye movements
109 (Theeuwes, Olivers, & Chizk, 2005; Beloposky & Theeuwes, 2011), and VWM may underlie
110 trans-saccadic integration (Prime, Tsotsos, Keith, & Crawford, 2007; Hollingworth, Richard, &
111 Luck, 2009), suggesting that eye movements may affect attention and working memory directly.
112 This is in contrast to retro-cues, which appear to rely primarily on voluntary allocation signaled
113 by a cue (Berryhill, Richmond, Shay, & Olson, 2012; Shimi, Nobre, Astle, & Scerif, 2014;
114 Gunseli, van Mooreselaar, Meeter, & Olivers, 2015)..

115 The present study was designed to provide an experimental test of the effect of eye
116 movements on visual recognition memory. Given that scan-path similarity is associated with
117 recognition of spatial relations (Olsen et al., 2014), we hypothesized that eye movements could
118 selectively enhance spatiotopic memory traces. As such, we compared visual recognition

119 memory performance across two conditions: the presence and absence of a saccade, and whether
120 or not the spatiotopic location of a tested item matched between study and test.

121 **Experiment 1**

122 Our first experiment was designed to address two questions. First, we sought to
123 determine whether a single saccade, to the location of a remembered item, would boost memory
124 performance in a visual recognition task. Second, we tested whether these benefits were spatially
125 specific by comparing performance on trials where memory for an item was probed at its
126 previous spatiotopic location in the periphery or at another location (in this case, at the center of
127 the display).

128 **Method**

129 **Participants.**

130 Sixteen undergraduate students (12 female, $M = 18.50$ years, $SD = 1.15$) from the
131 University of Toronto took part in the experiment for additional course credit. Fifteen of the
132 subjects were right handed and all reported normal to corrected-to-normal vision. Participants
133 were unaware of the purpose of the study and provided written consent prior to the session. All
134 experimental protocols were approved by the Research Ethics Board at the University of
135 Toronto.

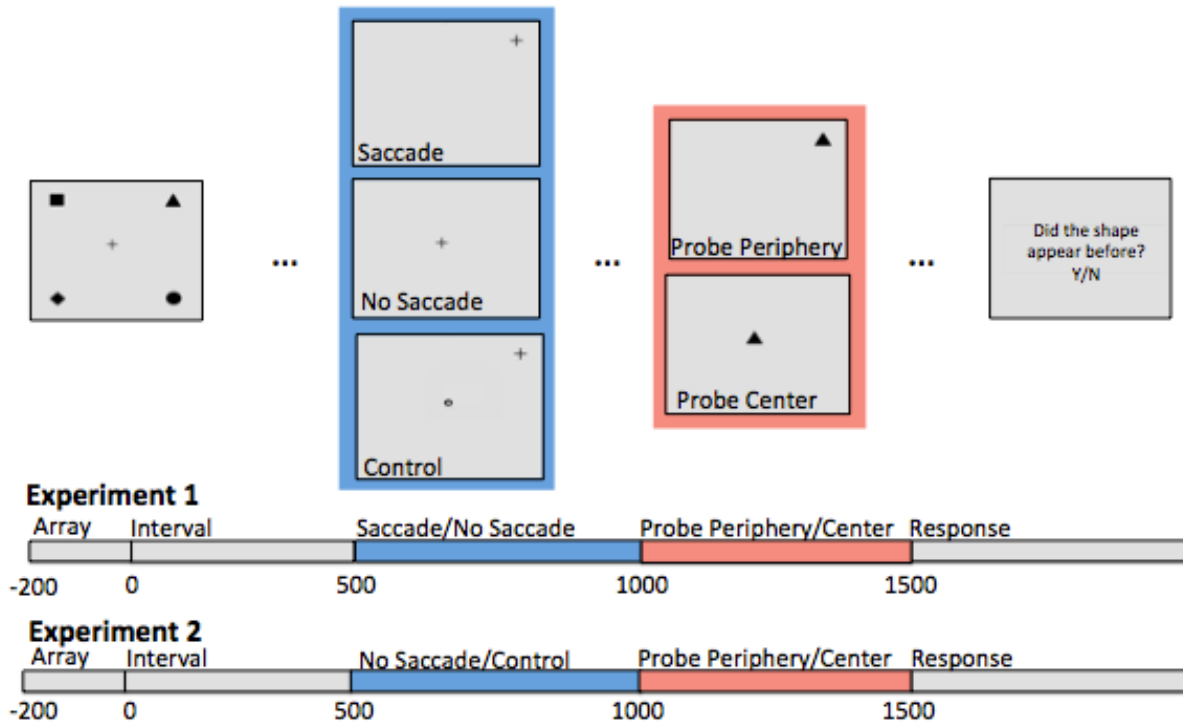
136 **Apparatus.**

137 Eye movements were monitored by the camera-based eyetracker (SR Research Eyelink
138 1000) at a temporal resolution of 1000 Hz and RMS spatial resolution of 0.01° of visual angle.
139 Gaze position was monitored using the right eye and standardized by using a 9-point calibration
140 and validation procedure. The beginning and ending of a saccade was determined using a $30^\circ/\text{s}$
141 velocity and $8000^\circ/\text{s}^2$ acceleration threshold. Stimuli were displayed on 19" CRT monitors set at
142 1024 x 768 resolution and 85 Hz refresh rate. Responses were given on the QWERTY-keyboard.
143 Using a head-rest, participants' distance from the screen was fixed at approximately 60 cm. The
144 experiment was programmed in Experiment Builder.

145 **Stimuli.**

146 The stimulus display consisted of 4 peripherally presented geometrical shapes from a
147 selection of 8 possible shapes: triangle ($1.25^\circ \times 1.25^\circ$), circle ($1.25^\circ \times 1.25^\circ$), diamond ($1.25^\circ \times$
148 1.25°), heart ($1.25^\circ \times 1.25^\circ$), star ($1.25^\circ \times 1.25^\circ$), rectangle ($0.95^\circ \times 4^\circ$), crescent ($1.25^\circ \times 1.42^\circ$)
149 and trapezoid ($1.42^\circ \times 0.95^\circ$). The stimuli occupied 4 peripheral locations, each of which was
150 4.8° from fixation: upper left, upper right, lower left, and lower right (see Figure 1). All stimuli
151 were displayed against a uniform gray background.

152



153

154 **Figure 1.** An illustration of the stimuli and trial sequences used in all experiments. Participants
 155 were instructed to remember an array of 4 geometric shapes. In Experiment 1, participants
 156 moved their eyes following a peripheral fixation cross (saccade condition) or remained at center
 157 fixation (no saccade condition). In Experiment 2, participants maintained center fixation (no
 158 saccade condition) or fixed centrally while being shown a peripheral fixation cross (control
 159 condition). At test, a single target probe, either a previously presented or novel stimulus, was
 160 presented at either the periphery or center of screen. In Experiment 3, all trials fell in to the
 161 saccade condition, but the location of the saccade cue and the probe position matched on 33% of
 162 trials (Experiment 3A) and 25% of trials (3B).

163

164 **Design and Procedure.**

165 In Experiment 1, we manipulated two factors: Saccade cue (present or absent) and Probe
 166 Location (peripheral or central), where each combination was tested in a separate block of trials.

167 Each experimental block began with a calibration and validation phase which was performed
168 until an average error rate of less than 0.5° . Participants first performed 10 practice trials before
169 proceeding to the experimental phase. Recalibration was executed prior to the start of each
170 block. Each trial was initiated when participants fixated at the center of the screen (at the drift
171 correction stimulus: a white ring with an outer diameter of 0.358° and an inner diameter of
172 0.168°). The trial started automatically once the participant's gaze was centered and 500 ms had
173 elapsed. Next, a centrally presented fixation cross ($0.5^\circ \times 0.5^\circ$) remained on screen for 500 ms.
174 Participants were then shown four peripheral shape stimuli for 200 ms during the encoding
175 phase. The shapes were drawn randomly on each trial, for each observer, from a list of 72 sets of
176 shapes, constructed such that each shape appeared in each position equally often. After stimuli
177 offset, the fixation cross was again presented centrally for 500 ms. A saccade cue was then
178 delivered, where the fixation cross would move to the periphery at the location of a to-be-probed
179 item. Subjects were instructed to perform a saccadic eye movement towards the fixation cross.
180 Saccade cues were 100% predictive, but participants were not explicitly informed of this
181 probability. Prior literature on the timing and kinematics of saccadic eye movements suggest
182 that saccade initiation to unexpected stimuli takes approximately 200 ms while saccade duration
183 for amplitudes below 10° take 60ms or less (e.g., Robinson, 1964). In our study, an additional
184 200 ms was added once participants terminated their saccade to the periphery, making the total
185 saccade cue duration approximately 500 ms. For the saccade cue absent conditions, the fixation
186 cross remained in the center for 500 ms.

187 At test, a single target shape was displayed at either the center or the periphery. The
188 target probe was either a new shape, not presented during the encoding phase, or was the one of
189 the shapes presented during the encoding phase. On saccade cue present trials, this shape was

190 always the shape whose location had been the target of the saccade. Participants were instructed
 191 to press “Y” if the probe shape has been presented in the previous array and “N” if the shape was
 192 different. Eye movements made during the probe phase of the trial were not controlled or
 193 recorded. Probe same and probe new trials were equally likely to occur. All participants
 194 completed four blocks of the experiment with approximately 72 trials per block with short breaks
 195 in between. All trials where participants blinked or deviated from central fixation before the
 196 onset of the probe were recycled (i.e., the trial was presented later at a random point in the
 197 experiment). We employed a 4 x 4 Latin Square design in conducting order of the experimental
 198 blocks to minimize learning effects due to order of presentation.

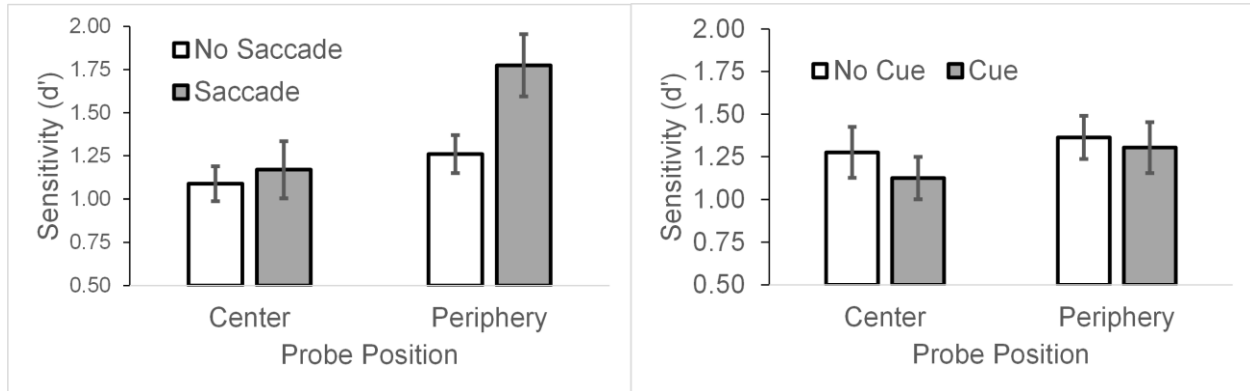
199 **Results and Discussion**

200 We ran a repeated measures analysis of variance (ANOVA) with the factors Saccade
 201 Condition (No Saccade and Saccade) and Probe Position (Center and Periphery) on sensitivity
 202 scores to determine whether saccades made during the retention interval affected subsequent
 203 recognition. Sensitivity was calculated as d' (Macmillan & Creelman, 2004), using the equation
 204 $d' = z(HR) - z(FA)$. Sensitivity was affected by both Saccade Condition, $F(1, 15) = 5.43, p = .03,$
 205 $\eta^2_p = .27,$ and Probe Position, $F(1, 15) = 18.57, p < .001, \eta^2_p = .55.$ As can be seen in Figure 2
 206 (left panel), Saccade Condition and Probe Position also interacted, $F(1, 15) = 4.63, p = .048, \eta^2_p$
 207 $= .24,$ such that Saccades did not affect sensitivity when probes appeared in the center, $t(15) =$
 208 $0.47, p = .65,$ but did increase sensitivity when probes appeared in their original peripheral
 209 position, $t(15) = 3.42, p = .004.$ In addition, this saccade effect using peripheral probes, $t(15) =$
 210 $2.17, p = .046, M_{\text{saccade}} = .45, SE_{\text{saccade}} = .03, M_{\text{no saccade}} = .55, SE_{\text{no saccade}} = .05,$ and central probes,
 211 $t(15) = .042, p = .68, M_{\text{saccade}} = .38, SE_{\text{saccade}} = .03, M_{\text{no saccade}} = .40, SE_{\text{no saccade}} = .05,$ held when

212 calculating memory sensitivity using a high-threshold equation,

213 $s = HR - FA$ (Rouder, Morey, Morey, & Cowan, 2011).

214



215

216 **Figure 2.** Memory recognition as a function of saccade condition and probe position. The left

217 panel depicts results from Experiment 1, and the right panel depicts results from Experiment 2.

218 Error bars depict one standard deviation of the mean.

219

220 An analysis of response time (RT) further corroborated the location-specific benefit of
 221 saccades; no main effects on average RT existed, $F_s(1, 15) < 2.15$, $p_s < .16$, $\eta^2_p s < .13$, but an
 222 interaction between the two factors was present, $F(1, 15) = 4.77$, $p = .045$, $\eta^2_p = .24$, such that
 223 RT did not differ between saccade conditions for central probes, $t(15) = 0.50$, $p = .62$, but did
 224 differ for peripheral probes, $t(15) = 3.31$, $p = .005$, with RT being lower when a saccade had
 225 been made, $M = 633\text{ms}$, $SE = 68\text{ms}$, than when a saccade had not been made, $M = 682\text{ms}$, $SE =$
 226 76ms .

227 The results of Experiment 1 showed that a saccade made to the location of a remembered
 228 item increased the likelihood that it would be recognized, but only when the item appeared in its
 229 previous spatiotopic position. Before concluding that saccades automatically shape memory,
 230 however, it is important to rule out an alternative possibility. Saccade and no-saccade trials in

231 Experiment 1 were blocked, and all trials in the saccade blocks were executed towards the
232 location of the to-be-tested item. As such, the execution of a saccade may have been
233 unimportant; participants may instead have simply used the location information from the
234 saccade as a cue for memory. Indeed, a growing body of research has shown that attention can be
235 retrospectively oriented in VWM to enhance the representation of a particular item (Griffin &
236 Nobre, 2003; Murray et al., 2013). Experiment 2 was designed to assess the isolated contribution
237 that saccades made in our task.

238 **Experiment 2**

239 As noted above, the recognition advantage following saccades in Experiment 1 may have
240 been due to the strategic orienting of attention in memory to items that occupied the saccade
241 destinations in our task. In Experiment 2, we duplicated the design of Experiment 1, but enforced
242 fixation across all blocks. This provided participants with all of the same information with which
243 to form rehearsal strategies, namely, a stimulus that signaled the location of the to-be-tested item.
244 If the memory improvement reported in Experiment 1 was due to strategic, voluntary allocation
245 of attention in memory, then the results of Experiment 2 ought to mirror those of Experiment 1.
246 However, if the location-specific improvement of memory was a consequence of eye
247 movements, we should find no difference between the two block types.

248 **Method**249 **Participants.**

250 A new group of sixteen undergraduate students (10 female, $M = 18.50$ years, $SD = 1.15$).
251 from the University of Toronto took part in the experiment for additional course credit. All
252 subjects were right handed and reported normal to corrected-to-normal vision.

253 **Procedure.**

254 The procedure for Experiment 1 was replicated with the exception that participants no
255 longer performed saccades following the movement of the fixation cross. Instead, a saccade
256 control condition was implemented where the fixation cross moved to the periphery, but a
257 fixation dot was presented centrally (a white ring with an outer diameter of 0.358 and an inner
258 diameter of 0.168) to localize participants' gaze to center screen.

259 **Results and Discussion**

260 As in Experiment 1, memory sensitivity was quantified using d' and analyzed using a
261 repeated measures ANOVA. None of the main effects, nor the interaction, proved statistically
262 reliable, $F_s(1, 15) < 1.08$, $p_s > .32$, $\eta^2_{ps} < .07$ (see right panel of Figure 2). This was also true
263 when analyzing sensitivity using high-threshold methods, $F_s(1, 15) < .57$, $p_s > .46$, $\eta^2_p < .04$.
264 Finally, no differences in RT were observed either, $F_s(1, 15) < 1.07$, $p_s < .32$, $\eta^2_p < .07$.

265 The results of Experiment 2 were clear; no difference in memory was produced by
266 signaling the location of the tested item during the retention interval. While this may appear to
267 contradict results from the retro-cuing literature, we note that participants were not informed of
268 the relationship between saccade cues and memory tests, and would have had to develop the
269 strategy themselves. Therefore, it simply appears as though participants did not adopt a possible
270 strategy, and that the results of Experiment 1 can be attributed to the execution of saccades.

271 Experiment 3

272 Although the results thus far indicate that an eye movement towards the previous location
273 of an item leads to a greater probability of recognizing that item, at least when it appears in its
274 previous location, it remains unclear whether this should be attributed to the shared locations of
275 the remembered item and the saccade or the mere presence of an eye movement. More
276 specifically, in Experiment 1, eye movement conditions were blocked, and so the overall better
277 memory in these blocks may have been due to a non-specific effect of having to make eye
278 movements. To address this possibility, we conducted a third experiment, wherein eye
279 movements occurred on every trial, but the eye movements were randomly crossed with which
280 item was probed for recognition. Eye movements, as a potential memory cue, had low predictive
281 value in signaling which item would be tested (33% in Experiment 3A, 25% in Experiment 3B).
282 If eye movements indeed improve memory for objects that had appeared in the fixated location,
283 we should observe a higher probability of correct recognition when saccades are executed
284 towards the location of the to-be-tested item.

285 Methods**286 Participants.**

287 Thirty-two participants participated in Experiment 3A, none of whom had participated in
288 either of our previous experiments, and a separate group of twenty-one participants participated
289 in Experiment 3B. All participants provided informed consent before participating, and were
290 compensated with either \$10CAD or course credit for participation.

291 **Stimuli and Procedure.**

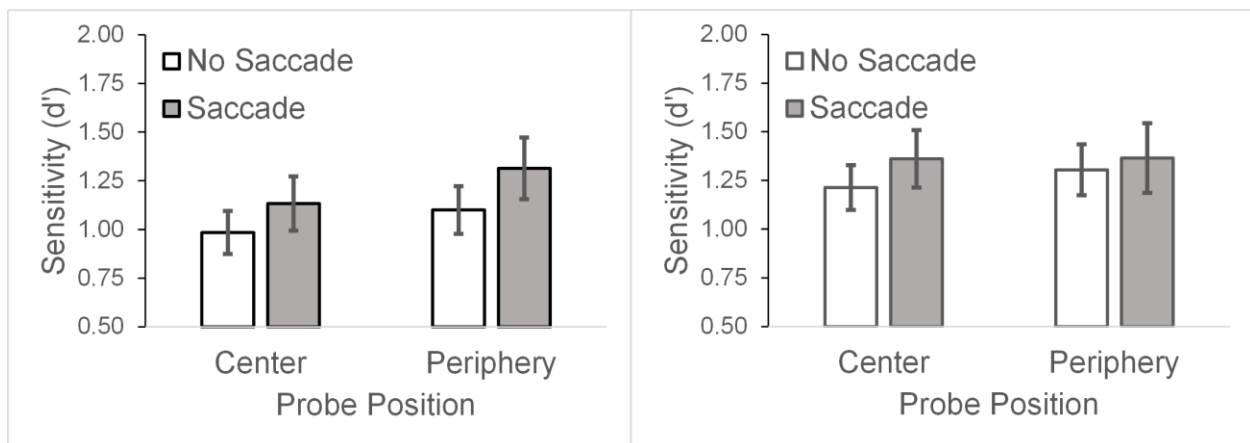
292 Stimuli and Procedure were the same as in Experiment 1, with the following changes.

293 Probe Position was again blocked, and participants completed two blocks of 72 trials in
294 alternating order from each condition (half of participants completed the Peripheral Probe
295 condition first, and half of participants completed the Central Probe condition first, alternating
296 between probe conditions after each block (e.g., Peripheral, Central, Peripheral, Central). All
297 trials required an eye movement between the encoding and test phases of the trial, with a
298 peripheral fixation mark appearing in the to-be-fixated location. Due to a condition balancing
299 error in Experiment 3A, trials ended with a probe at the fixated location on 33% of trials (note
300 that, for central probe blocks, all “new” probe items had no validity, since they matched neither
301 the shape nor the location of any display items). In Experiment 3B, validity was reduced to 25%
302 to assess performance when saccades were strictly randomly associated with probe location.
303 Finally, we anticipated that invalid saccade trials would be especially difficult in peripheral
304 probe blocks, since an additional saccade would be needed to fixate the probe when the eye was
305 not already there. To mitigate this possibility, we extended the probe’s duration to 1000ms.

306 **Results and Discussion**

307 The results of Experiment 3A and 3B are plotted in Figure 3. In Experiment 3A, six
308 participants were excluded for having an overall accuracy that was statistically indistinguishable
309 from chance (i.e., less than 55.9%) in Experiment 3A, and three participants were excluded in
310 Experiment 3B for the same reason. Following these exclusions, we analyzed recognition
311 performance using a mixed-model ANOVA, with Saccade Condition and Probe Position as
312 within-subjects factor, and Block Order (central first and peripheral first) as a between-subjects
313 factor separately for each experiment. For Experiment 3A, d' scores showed a main effect of

314 Saccade Condition, $F(1, 24) = 6.50, p = .018, \eta^2_p = .21$, with no main effect of Probe Position,
 315 $F(1, 24) = 2.21, p = .15, \eta^2_p = .08$, and no interaction, $F(1, 24) = 0.16, p = .70, \eta^2_p = .006$,
 316 Overall sensitivity was higher for trials when the tested item's location was fixated, $M = 1.26, SE$
 317 $= 0.13$, compared to when a non-tested item's location was fixated, $M = 1.04, SE = 0.11$. A
 318 similar pattern of results was seen using High-Threshold measures of memory (Hits – False
 319 Alarms), $M_{\text{fixated}} = 0.38, SE_{\text{fixated}} = .04, M_{\text{not-fixated}} = 0.34, SE_{\text{not-fixated}} = .03, F(1, 24) = 4.23, p =$
 320 $.05, \eta^2_p = .15$. No response time difference was found between Saccade Conditions, $F(1, 24) =$
 321 $0.96, p = .34$, but we did observe an effect of Probe Position, $F(1, 24) = 14.59, p = .01, \eta^2_p = .38$,
 322 with no interaction, $F(1, 24) = 0.006, p = .94, \eta^2_p = < .001$. Recognition responses were slower
 323 when memory was tested with central probes, $M = 564\text{ms}, SE = 52\text{ms}$, than when tested with
 324 peripheral probes, $M = 478\text{ms}, SE = 58\text{ms}$. Although these results do not show the same
 325 location-dependent saccade benefit, there was an overall benefit for items whose previous
 326 positions are fixated, regardless of testing position.
 327



328
 329 **Figure 3.** Memory recognition as a function of saccade condition and probe position in
 330 Experiment 3. The left panel depicts the results of Experiment 3A and the right panel depicts the
 331 results of Experiment 3B. Error bars depict one standard deviation of the mean.

332

333 We also assessed whether block order (i.e., peripheral probe block first or central block
334 first) contributed to the saccade-based recognition advantage. Block order did not interact with
335 the recognition advantage, $F(1, 24) = 0.014$, $p = .91$, $\eta^2_p = .001$, but did interact with the probe
336 location effect, $F(1, 24) = 6.88$, $p = .015$, $\eta^2_p = .22$, such that participants who completed the
337 peripheral probe block first had better performance in the central ($d' = 1.49$, $SE = .17$) than
338 peripheral ($d' = 1.08$, $SE = .17$) probe condition.

339 Experiment 3B, however, showed that lowered validity (i.e., 25%) did not lead to a
340 recognition advantage for fixated item locations, $F(1, 16) = 1.05$, $p = .32$, $\eta^2_p = .06$, even when
341 considering probe location, $F(1, 16) = 0.31$, $p = .59$, $\eta^2_p = .017$. As such, the saccade-driven
342 memory recognition advantage we observed does not seem to be completely automatic – it seems
343 to require at least some form of predictive value to emerge.

344 General Discussion

345 The aim of the present study was to investigate the nature of overt attentional shifts on
346 memory performance through a visual recognition task. While the functional role of
347 spontaneous eye movements during memory maintenance has been examined by prior research
348 (Johansson et al., 2006; Laeng & Teodorescu, 2002; Olsen et al., 2014), the present study
349 explored the effect of the endpoint of a single saccade during memory maintenance on visual
350 recognition memory. Consistent with prior literature on the recall advantage following
351 spontaneous eye movements (Johansson & Johansson, 2014), we demonstrated in Experiment 1
352 that an obligatory saccade can boost memory for items held in VWM. From Experiment 2, we
353 observed that by eliminating the saccade, but retaining potentially informative cues, the saccade
354 benefit was negated, suggesting that the observed memory changes are not simply a function of
355 strategic rehearsal. Experiment 3A revealed that the location of the eye movement per se was
356 important; eye movements towards the locations of non-tested items did not benefit memory. In
357 addition, Experiment 3A showed an improvement in memory for objects whose location was
358 later fixated regardless of the position that the probe item appeared in. Most importantly,
359 Experiment 3B showed that the recognition advantage of a saccade on memory disappeared
360 when the predictive value of a saccade was dropped to chance. Overall, these results suggest that
361 eye movements can reallocate VWM resources to items that occupied the location of the saccade
362 endpoint when they have above chance predictive value in signaling the information that must be
363 remembered.

364 Previous work in retrospective cueing has demonstrated that signaling the location of an
365 upcoming item, post-stimulus offset, can enhance change detection performance (Griffin &
366 Nobre, 2003). The resulting shifts of attention in memory are thought to enhance memory

367 through a variety of mechanisms, including protection from interference, reduction in overall
368 memory load through item removal, strengthening of attended memories through refreshing, and
369 prioritized retrieval (see Souza & Oberauer, 2016). In the majority of these studies, participants
370 are both instructed to use and to incentivized to use the retro cue to allocate attention to an item
371 by testing the cued item more often than other items. Because of this, memory performance can
372 be strategically improved by relying on the cue. Relatively few studies have used chance validity
373 to see whether retro-cue effects are obligatory. Some studies have explored whether retro-cues
374 that do not predict the tested item above chance (i.e., have chance validity) can shift internal
375 attention, and have found that such non-predictive cues can produce recognition advantages
376 (Berryhill, Richmond, Shay, & Olson, 2012; Li & Saiki, 2014). However, these studies also
377 involved presenting participants with trials where retro-cues do predict the tested item, and so
378 these non-predictive retro-cue recognition advantages may be due to the experiment-wide
379 predictive validity of retro-cues. The present results provide a valuable contribution to this issue,
380 as we show a “retro-cuing” type of recognition advantage using saccades as the directional cue.
381 Such a cue does not rely on instructions but seems instead to require only a small amount of
382 predictive value. These results are difficult to explain simply as a voluntary shift of covert
383 attention, given that they did not occur when a visual stimulus (i.e., a cue) provided the same
384 information as saccades. This is especially so in light of findings by Schmidt, Woodman, Vogel,
385 & Luck (2002) who showed that non-predictive onsets following a memory array led to
386 attentional biases. However, our “onset” cues occurred 500ms after the memory array offset,
387 whereas the cues in Schmidt et al. appeared 50ms after the array, and so the timing of these
388 onsets may be important in biasing internal attention involuntarily. As noted earlier, saccades
389 and shifts of attention are often tightly coupled. Any obligatory shifts of attention due to

390 saccades made during the maintenance of a memory s may thus provide a natural basis for
391 learning strategies of shifting attention within VWM. It is important to emphasize, however, that
392 these internal attention policies seem subject to adaptive control.

393 The fact that such saccade-based recognition advantages occurred in the absence of
394 explicit strategy suggest that the memory traces being affected likely preserve the spatial
395 arrangement of items. In our task, the spatial arrangement was irrelevant; decisions only needed
396 to be made on the identity of stimuli. Although VWM is most often considered an object-based
397 store (Luck & Vogel, 1997; Lee & Chun 2001; but see Fougne, Asplund, & Marois, 2010;
398 Fougne & Alvarez, 2011) numerous findings demonstrate that information about stimulus
399 positions are retained in VWM (Jiang, Olson, & Chun, 2000; Pertzov & Husain, 2014; Rajsic &
400 Wilson, 2014). However, given the timing of the saccades in our experiments, and the fact that
401 they occurred before any visual stimuli that may have led to interference (Makovski et al., 2008),
402 it is possible that the memory benefit we observed stemmed from the enhancement of fragile
403 VSTM representations (Sligte, Scholte, & Lamme., 2008; Pinto, Sligte, & Shapiro, 2013), which
404 are supposed to be location-specific. Given that the benefits we observed in Experiment 3 were
405 location-invariant, we suggest that the eye movements in our experiments may have increased
406 the probability that a fragile VSTM representation is encoded as a location-invariant, VWM
407 representation.

408 The present results provide important information about the nature of the memory
409 enhancement produced by saccades. By testing the effects of a single saccade during memory
410 maintenance on visual recognition, we show a benefit in memory for objects based on their
411 spatial compatibility with this saccade. Although our initial experiment showed a benefit only for
412 object memory when the object appeared in its original location, this may reflect an obscuring

413 cost of the central-test position. Specifically, because our probes offset after 500ms, participants
414 may not have been able to, on some proportion of trials, fixate the probe object in central-test
415 conditions after having made a saccade to the periphery. If this indeed occurred, it would have
416 offset any saccade-based enhancements. Importantly, the results of Experiment 3 suggest that the
417 memory benefit of saccades is object-based, despite relying on a location-based coordinate
418 system. In addition, they suggest that connections between saccades and memory are subject to
419 adaptive control – they can be adjusted as a function of the utility they provide in achieving
420 current goals.

421 The relative ease with which saccades can be used to bias memory reported here (see
422 also Johansson & Johansson, 2014) helps to explain why eye movements are especially
423 associated with retrieving or rehearsing memories of stimuli when spatial relations are relevant
424 (e.g., Olsen et al., 2014). In studies that use large memory sets, or those with spatial structure
425 (e.g., scenes), the activation of localized information by saccades could assist in the retrieval of
426 information by capitalizing on memories of items coded by spatial relation. Specifically, an eye
427 movement that can enhance memory for spatially organized items could be used to strategically
428 recover information that is not yet active (e.g., trying to remember the object that was to the right
429 of a clearly remembered tree in a particular scene). This speculation compliments the suggestion
430 that the spatial indices targeted by eye movements serve as mental “pointers” to visual
431 information exceeding working memory capacity (Altmann, 2004; Chun & Nakayama, 2000;
432 Laeng et al., 2007; Mantyla, T., & Holm, L, 2006). If true, this suggests that the preservation of
433 spatial relations is an important way by which visual memories can be made flexibly accessible,
434 especially in the many contexts where the capacity of visual short-term memory is exceeded.
435 Indeed, spatial relations are the basis of mnemonic strategies that lead to high capacity forms of

436 non-visual memories as well (e.g., the method of loci; Lea, 1975).

437 To conclude, by directing participants' eye positions during the retention interval of a
438 visual recognition task, we have shown that eye movements can lead to an object-specific benefit
439 in the recognition of individual stimuli. These results suggest that eye movements are able to act
440 on spatially organized representations in visual memory, but the memory enhancement can occur
441 for position-invariant memory representations. However, these shifts are not completely
442 obligatory; they persist with above-chance predictive value, but not with chance-validity. Our
443 findings converge on the conclusion that eye movements enhance memories by providing access
444 specifically to spatially structured memories.

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