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Visual working memory load does not eliminate visuomotor repetition effects

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Abstract

When we respond to a stimulus, our ability to quickly execute this response depends on how combinations of stimulus and response features match to previous combinations of stimulus and response features. Some kind of memory representations must be underlying these visuomotor repetition effects. In the present paper, we tested the hypothesis that visual working memory stores the stimulus information that gives rise to these effects. Participants discriminated the colors of successive stimuli while holding either three locations or colors in visual working memory. If visual working memory maintains the information about a previous event that leads to visuomotor repetition effects, then occupying working memory with colors or locations should selectively disrupt color-response and location-response repetition effects. The results of two experiments showed that neither color nor spatial memory load eliminated visuomotor repetition effects. Since working memory load did not disrupt repetition effects, it is unlikely that visual working memory resources are used to store the information that underlies visuomotor repetitions effects. Instead, these results are consistent with the view that visuomotor repetition effects stem from automatic long-term memory retrieval, but can also be accommodated by supposing separate buffers for visual working memory and response-selection.

47 When we make a response to a stimulus, the speed of that response is dependent on
48 whether stimulus properties repeat across trials. However, such repetition effects can depend on
49 whether the response repeats as well, such that the repetition of feature-response pairings affects
50 speeded responses. For example, if the location of a stimulus repeats along with the response to
51 the previous stimulus across subsequent trials, observers' response times (RTs) are faster than if
52 one of these two features (location or response) changes across back-to-back trials. Given that
53 these visuomotor repetition effects are defined as an effect of the past on present behavior, some
54 kind of memory storage must be at work. The goal of this study was to test the hypothesis that
55 visual working memory stores the representations that cause visuomotor repetition effects.
56 Before discussing the potential role of visual working memory in visuomotor repetition effects,
57 we will briefly review what they are and how they are explained.

58 Visuomotor repetition effects are one of many kinds of repetition effects that can be
59 observed in speeded decision-making. Repetition of a stimulus location (inhibition of return:
60 Posner & Cohen, 1984; position priming: Malkjovic & Nakayama, 1996), repetition of stimulus
61 category, color, or shape (stimulus repetition effect: Pashler & Baylis, 1991; priming of pop-out:
62 Malkjovic & Nakayama, 1994), and repetition of the motor response (response repetition effect:
63 Bertelson, 1965) can independently affect the speed of responses. However, whether the
64 repetition of a single stimulus feature (such as the location or color of a stimulus) affects
65 response time often depends on whether the response also repeats (Hommel, 1998; Kleinsorge,
66 1999; Hommel, Proctor & Vu, 2004; Rothermund, Wentura, & De Houwer, 2005; Hommel &
67 Memelink, 2014). These visuomotor repetition effects have been explained by the theory of
68 event coding, as we describe next.

69 The theory of event coding borrows the concept of incidental feature-binding from
70 object-file theory (Kahneman, Treisman, & Gibbs, 1992) and includes response codes as features
71 that can be bound with stimulus codes into what are called *event files* (Hommel, 1998; Hommel,
72 Proctor, & Vu, 2004; Hommel & Colzato, 2004; Hommel, 2005; Henson et al., 2014). The core
73 idea is that responding to a stimulus causes features of that stimulus (i.e., its location, color, or
74 shape) to be automatically associated with, or bound to, the response codes that co-occurred
75 during that stimulus-processing episode. These event files can then influence how quickly we
76 can respond to a subsequent stimulus, leading to partial-repetition costs. Partial repetition costs
77 occur when a current event contains information that partially matches an event file. For

78 example, producing a response to a leftward stimulus requiring an index-finger response is
79 typically slower after having recently produced a middle-finger response to a leftward stimulus.
80 This is because, in this case, the *left* location code is bound to the *index* response code in the
81 current event file, and this binding must be updated to produce the correct response (Hommel,
82 2004). When all stimulus and response features repeat, the match between the current event and
83 the features in an event file can facilitate response time, although in some cases response times
84 are no faster than when no features match (a full-switch; Hommel, 1998). Whether or not full-
85 repeats facilitate responding relative to the intuitive baseline of full-switches may depend on the
86 number of feature-response alternatives, as many-to-one stimulus-response mappings tend to
87 show full-repeat advantages (cf. Experiments 1 and 2 from Hilchey, Rajsic, Huffman, & Pratt,
88 2017a)

89 Despite considerable research, there have been few investigations into what memory
90 system stores event-files. On the one hand, the event-files that lead to visuomotor repetitions
91 effects are hypothesized to be relatively transient, which may suggest that a temporary
92 information storage system is responsible (Hommel, 2004; Hommel & Colzato, 2009; see
93 Hommel, 2019 for a recent summary of this proposal). Such transience is supported by the
94 findings that the magnitude of visuomotor repetition effects does not appear to depend on the
95 relative frequency of specific feature combinations (Colzato, Raffone, & Hommel, 2006), and
96 that manipulations that increase repetition effects do not necessarily lead to larger incidental
97 stimulus-response learning (Moeller & Frings, 2017). In other words, incidental associations
98 between features of events seem not to be represented in long-term memory. More broadly,
99 Pashler and Baylis (1991a; 1991b) found that stimulus-response repetition effects were strongest
100 when a specific stimulus repeated rather than just the response-category, but that practice-related
101 response time improvements were more categorical, which implies that repetition effects are
102 driven by different codes than learning effects. Thus, broadly speaking, repetition effects may
103 occur at least partly because the most recently used stimulus-response link is still actively
104 maintained in working memory between successive decisions (Oberauer, 2009; Schneider &
105 Anderson, 2011). If this is the case, a concurrent working memory load ought to disrupt these
106 repetition effects. It is also, however, plausible that repetition effects are largely independent of
107 working memory. Rather, the repetition effects may reflect the more or less automatic
108 consequence of stimulus processing, and dual-route models of performance tend to associate

109 automaticity with long-term memory (Logan, 1990). Consistent with this possibility, visuomotor
110 repetition effects are robust even when people have to make decisions about one or more stimuli
111 in between two sequentially presented stimulus events (Hilchey et al., 2017; Rajsic, Bi, &
112 Wilson, 2014; Wilson, Castel, & Pratt, 2006), similar to stimulus-task bindings (Waszak,
113 Hommel, & Allport, 2003; Pösse, Waszak, & Hommel, 2006). If repetition effects depend
114 instead on memory resources that do not overlap with working memory, then we should see that
115 working memory load leaves repetition effects just as potent as in the absence of load.

116 The logic of our tests is simple; we will fill visual working memory with different types
117 of feature information to assess whether this knocks out the visuomotor repetition effects. That
118 is, the present design takes advantage of the fact that visual working memory is highly capacity
119 limited (Luck & Vogel, 1997; Cowan, 2000). As such, if information about previous stimulus
120 features and locations is represented using these limited-capacity resources, then requiring
121 participants to maintain additional stimulus information in visual working memory should
122 interfere with the maintenance of a previous target's location or color, thus reducing or
123 eliminating the repetition effects. Furthermore, if visuomotor repetition effects involve codes
124 stored in visual working memory, then it should be possible to selectively disrupt location-
125 response repetition effects and color-response repetition effects using location and color memory
126 load, respectively. We expect this selective disruption because storage of color and location in
127 working memory appears to depend on which features are task relevant (Woodman & Vogel,
128 2008; Woodman, Vogel, & Luck, 2012, but see Olson, Jiang, & Chun, 2000). To test whether
129 visuomotor repetition effects are supported by visual working memory resources, we conducted
130 two experiments, each of which required two-alternative forced choice color discriminations
131 responses to sequentially presented stimuli in the presence or absence of visual working memory
132 load (see Figure 1). In addition to varying the presence of visual working memory load, we
133 varied whether participants were required to maintain locations or colors in memory to assess
134 whether the type of working memory load would selectively disrupt the visuomotor repetition
135 effects. To preview our results, both experiments indicated that visuomotor repetition effects
136 were robust against visual working memory loads, suggesting that visual working memory is not
137 responsible for visuomotor repetition effects.

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Experiment 1

Experiment 1 provided a first test of the role of visual working memory in visuomotor repetition effects. Participants completed a discrimination task where they made keypress responses to serially presented target colors appearing randomly at one of two locations, with and without a concurrent memory load. More specifically, trials consisted of two tasks: a change detection task and a target discrimination task. Each trial started with an array of colored rectangles, which either required memorization (until the end of the trial) or not. This was followed by two sequentially presented colored rectangles, each randomly left or right of fixation, with both requiring an arbitrary keypress discrimination response (e.g., index finger for green and blue, middle finger of red and purple) and with the appearance of the second being temporally contingent on the response to the first. On memory load trials, one group of participants was instructed to remember the locations of three colored squares that appeared at the beginning of trials, whereas another group was instructed to remember their colors for a memory probe task that occurred after the two sequentially presented colored rectangles. The to-be-remembered colors and locations were always different than the target colors and locations used in the keypress discrimination task. Visuomotor repetition effects were measured for color-response combinations (same color/same response, different color/same response, and different color/different response) and location-response combinations (same location/same response, different location/same response, and different location/different response).

Methods

Participants

Thirty-five undergraduates enrolled in a first-year Psychology course at the University of Toronto volunteered to participate for either course credit or monetary compensation (\$10). Seventeen participants completed the color WM version of our task and eighteen participants completed the spatial WM version of our task. All participants provided informed consent before participating. The average participant age was 20.4 ($SD = 2.2$), and twenty-five participants were female.

167 *Stimuli and Apparatus*

168 Stimuli were displayed on the black background (RGB: 0, 0, 0) of a 17" CRT monitor,
169 which was connected to a Dell computer running custom Python software. Head position was
170 stabilized with a chin and head rest 50 cm from the monitor. Responses were made on a standard
171 QWERTY keyboard. During experimental trials, there was always a fixation stimulus, a white
172 crosshair ($0.15^\circ \times 0.15^\circ$ of visual angle), at the center of the monitor.

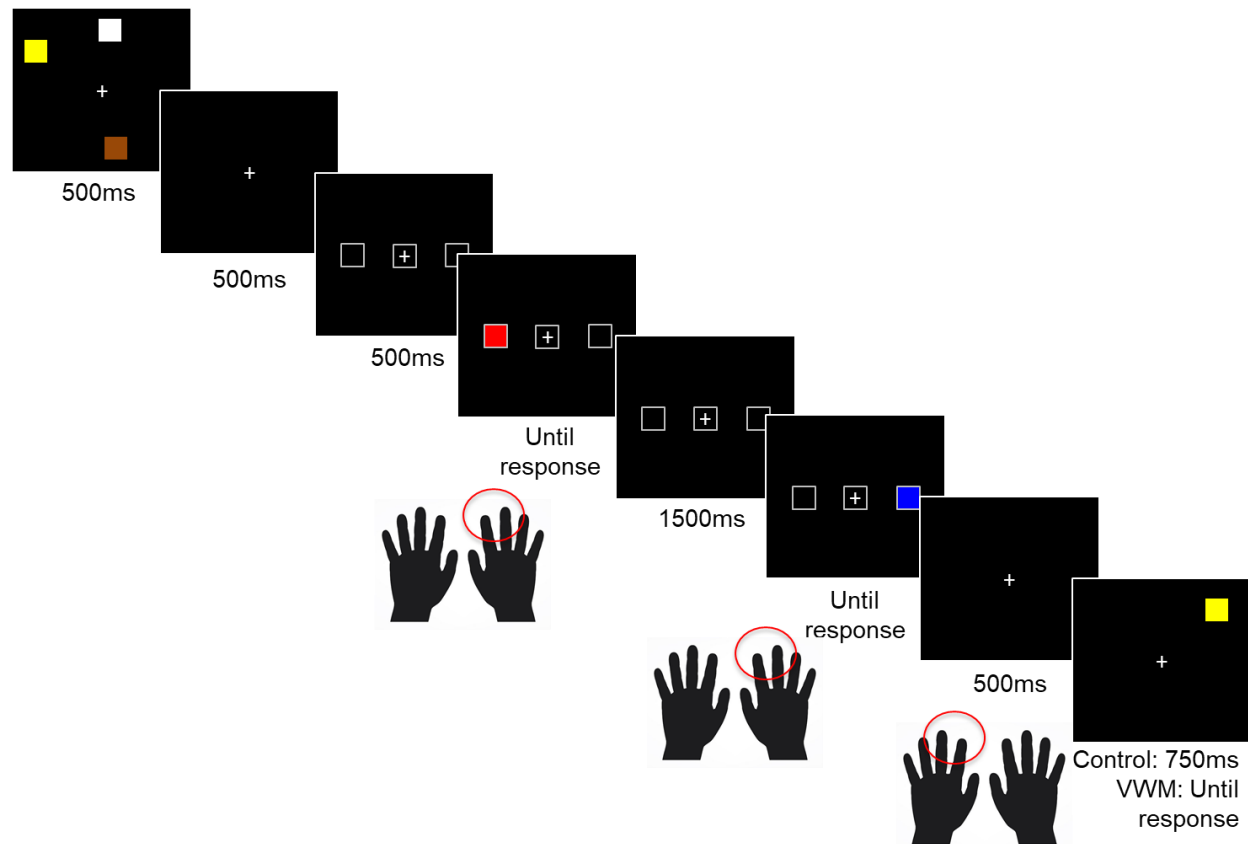
173 *Memory preview displays.* Three preview colors ($1.00^\circ \times 1.00^\circ$ filled squares) were
174 randomly selected, without replacement, from a list that included white, orange, yellow, khaki,
175 brown, and slate gray. These colors appeared at locations on the circumference of an imaginary
176 circle (radius = 4.00°) that was centered on fixation. The color locations were randomly selected,
177 without replacement, from a list of polar coordinates that included 30° , 60° , 90° , 120° , 150° ,
178 210° , 240° , 270° , 300° and 330° . Importantly, the potential locations of color targets were not
179 included in the set of potential memory preview locations. No keypress responses were made
180 during this display.

181 *Color target displays.* One gray outline box ($1.00^\circ \times 1.00^\circ$) appeared at the center of the
182 display, and two additional outline boxes were positioned 4.00° away from center on the left
183 (180° in polar coordinates) and right side (0° in polar coordinates). Target colors were red, green,
184 blue and purple. The left or right outline box was filled with the target color. Two colors were
185 responded to with the 'o' key (right index finger) and the other two were responded to with the
186 'p' key (right middle finger). These color-response mappings were counterbalanced across
187 participants.

188 *Memory probe displays.* A single probe color ($1.00^\circ \times 1.00^\circ$ filled square) appeared at one
189 of the possible locations in the memory preview display. On half of all trials, the memory probe
190 appeared at the same location as a preview color and on the other half it appeared randomly at
191 one of the unused preview locations. On half of all trials, the probe was the same color as a
192 preview color and on the other half it was one of the unused preview colors. Depending on the
193 condition, participants made either no response to the probe (control), or indicated whether the
194 preview and probe color or location matched (q key, left middle finger; w key, left index finger
195 for mismatch) in the visual and spatial working memory conditions, respectively.

196 *Trial feedback displays.* All trials ended with two feedback displays. The first feedback
197 display indicated whether an error had been made to the target colors. If an error was made, an

198 error message appeared along with the color-response mappings. If there were no errors, the
 199 message *Successful target identifications* appeared. The second feedback display, which applied
 200 only to the memory conditions, indicated whether a correct response was made to the memory
 201 probe. If an error was made, an error message appeared along with the probe-response mappings.
 202 If there was no error, the message *Successful memory* appeared. All feedback was displayed in
 203 white font, was centred on the display and was acknowledged with the spacebar.



204
 205 **Figure 1.** An illustration of a sample trial from Experiment 1. Stimuli are not drawn to scale.

206 The memory probe array depicts a different location, same color probe.

207

208 Procedure

209 Possible trial sequences are illustrated in Figure 1. Each trial began with the appearance
 210 of the fixation cross. Half of a second later, the memory preview display appeared for 500 ms. In
 211 the color working memory condition, participants were told to remember the preview colors
 212 without verbalizing them. Participants were also informed that (1) the preview locations were
 213 irrelevant, (2) there was a 50% chance that the memory probe color would match a memory

214 preview color, and (3) the target colors were never preview or probe colors. In the spatial
215 working memory condition, participants were told to remember the preview color locations
216 without verbalizing them. Participants were also informed that (1) the preview colors were
217 irrelevant, (2) there was a 50% chance that the memory probe color would match a memory
218 preview color and a 50% chance that the memory probe location would match a memory
219 preview location, and (3) the target locations were never preview or probe locations. In the
220 control condition, participants were told that both the memory preview and probe displays were
221 completely meaningless and should be ignored.

222 Half of a second after the disappearance of the memory preview display, the gray outline
223 boxes appeared, which signalled the beginning of the color target displays. The first target color
224 appeared 500 ms later, in either the left or right box. After the response, the target disappeared.
225 One and a half seconds later, the second target color appeared, in either the left or right box.
226 After the response, the target and outline boxes disappeared. Each target color and location was
227 randomly selected, of which all participants were duly informed. Participants were told to keep
228 their gaze on the fixation stimulus at all times and that their goal was to respond as quickly and
229 accurately as possible to the colors.

230 Half of a second after the disappearance of the color target displays, the memory probe
231 display appeared. In the control condition, the memory probe display remained onscreen for 750
232 ms, after which the probe disappeared and trial feedback appeared. In the working memory
233 conditions, the memory probe display remained onscreen until a response was made, after which
234 the feedback screen appeared. There was a 500 ms black screen between trials. Participants were
235 told that the goal was to respond as accurately possible to memory probes.

236 *Design*

237 Each participant performed the control condition first, as pilot testing revealed that
238 participants found it very difficult to learn the arbitrary color-response mapping and remember
239 the items in the memory preview display at the same time. Half of the participants completed the
240 visual working memory condition after the control condition, whereas the other half completed
241 the spatial working memory condition after the control. Each condition comprised 192
242 experiment trials. Prior to the experimental trials, each participant practiced, and was free to ask
243 question to the experimenter (MDH), until they were ready to begin. Data from practice trials
244 were not recorded.

245 *Analysis*

246 In analysing RT data, we first excluded participants whose overall memory performance
247 was not statistically different from chance performance (57.29%, $n = 2$, both from the color
248 memory condition). Following that, we excluded trials with target errors on the color target
249 displays, which accounted for 5.4% of trials. Next, any trial with a RT to the first target or
250 second target that were 2.5 standard deviations above or below each participant's mean response
251 times to the first and second color targets, respectively, were excluded as outliers, which
252 accounted for 2.4 and 2.5% of the total trials, respectively. Finally, we only analysed RTs on
253 trials with correct memory responses (75.5% of all trials), to help ensure that the preview stimuli
254 were indeed in working memory. Memory accuracy for included participants was 69.9% ($SD =$
255 10.5%) in the color load condition and 80.2% ($SD = 7.5%$) in the location load condition.
256 Overall, 80% of trials were retained for analysis. First and second target accuracy on trials with
257 target response errors included (but other exclusion criteria applied) was near ceiling, $M_{\text{first}} =$
258 97.3, $SD_{\text{first}} = 1.5\%$ $M_{\text{second}} = 97.6\%$, $SD_{\text{second}} = 1.9\%$.

259

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Results

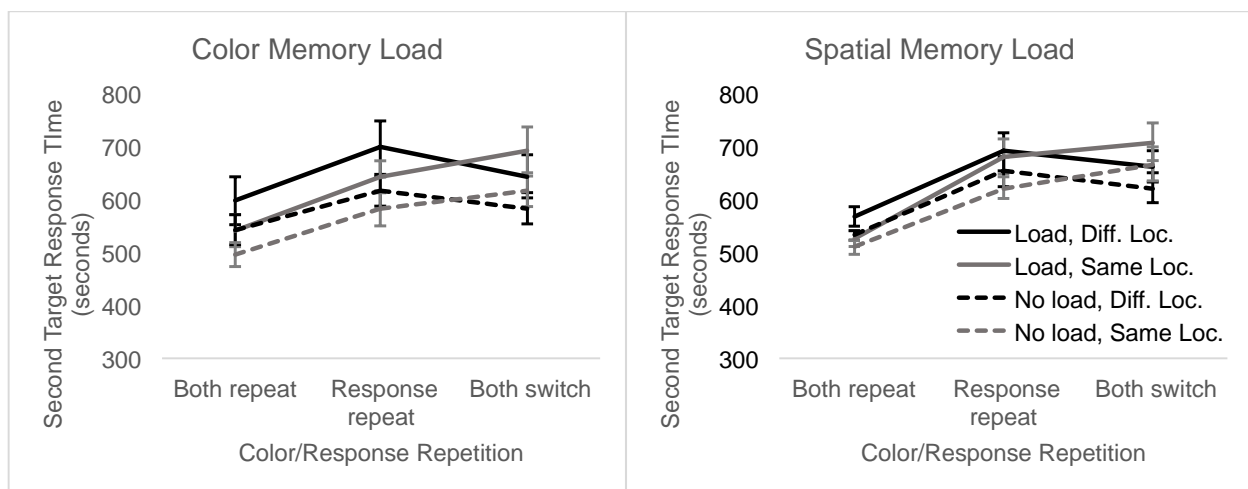
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262 Mean RTs are shown in Figure 2. The working memory loads did not reduce either the
263 color-response repetition effect (i.e., the main effect of stimulus-response repetition) or the
264 location-response repetition effect (i.e., the interaction between location-repetition and stimulus-
265 response repetition). In fact, working memory load increased the stimulus-response repetition
266 effect (for both location and color load), which is the opposite of what one would expect if event
267 files were held in working memory. These findings suggest that visual working memory does not
268 maintain the representations underlying the speeding of RTs due to repetitions.

269 The data were analysed with a mixed-model ANOVA, with load type (color or spatial) as
270 a between-subjects factor and load (present or absent), location repetition (repeat or switch), and
271 color-response repetition (both repeat, response repeat, both switch) as within-subjects factors.
272 Greenhouse-Geisser corrections were applied when sphericity assumptions were violated, though
273 these corrections did not change any inferences. We first checked that the expected visuomotor
274 repetition effects were elicited in this task. Color-response repetitions affected RTs, $F(1.61,$
275 50.00) = 55.32, $p < .001$, $\eta^2_p = .64$, with faster RTs when the color and response repeated than

276 when only the response repeated or when neither repeated. Location repetition reduced RTs
 277 overall, $F(1, 31) = 4.68, p = .04, \eta^2_p = .13$, but its effect differed in combination with response
 278 repetition, $F(1.62, 50.10) = 33.69, p < .001, \eta^2_p = .52$. As expected, location repetitions speeded
 279 RT when the response repeated, but slowed it when the response switched. Thus, we indeed
 280 observed the visuomotor repetitions effects that we sought to selectively reduce via working
 281 memory load.

282 We next checked whether memory load of either type (location or color) affected
 283 visuomotor repetition effects. Memory load slowed overall RTs, $F(1, 31) = 23.35, p < .001, \eta^2_p =$
 284 $.43$, but only interacted weakly with color-response repetition, $F(2, 62) = 3.20, p = .05, \eta^2_p = .09$.
 285 As can be seen in Figure 2, color-response repetition was slightly more advantageous to
 286 performance with than without memory load. Without memory load, color-response repetitions
 287 were 98ms ($SE = 24ms$) faster than partial repetitions, but with memory load, color-response
 288 repetitions were 121ms ($SE = 45ms$) faster than partial repetitions. Load did not interact with
 289 location repetition, $F(1, 31) = 0.03, p = .88, \eta^2_p = .001$, nor did it interact with the location-
 290 response repetition effect (that is, the location X color-response repetition effect), $F(2, 62) =$
 291 $0.55, p = .58, \eta^2_p = .02$. Thus, adding a memory load did not reduce visuomotor repetition
 292 effects, and in the case of color-response repetition effects, may have instead increased them.



293
 294 **Figure 2.** Second target response times in Experiment 1 as a function of color-response
 295 repetition type (horizontal axes), location repetition (gray lines: location repeat, black lines:
 296 location switch), memory load (present: solid lines, absent: dashed lines), and load type (color
 297 load, left panel, spatial load, right panel). Error bars depict one standard error of the mean.

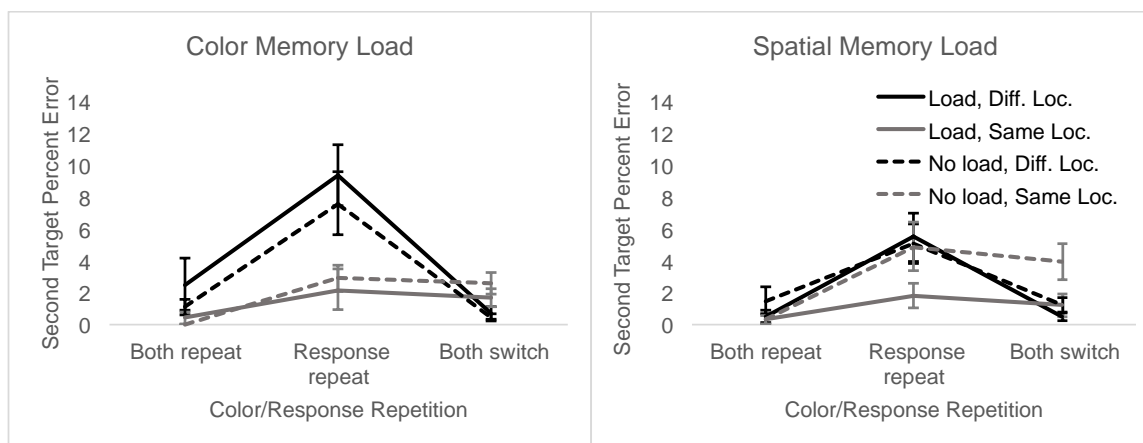
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299 Most critically for the present study, the type of load made little to no difference to any of
300 the repetition effects (location X load type: $F(1, 31) = 3.04, p = .09, \eta^2_p = .09$; color-response
301 repetition X load type: $F(1.61, 50.00) = 1.76, p = .19, \eta^2_p = .05$; color-response repetition X
302 location repetition X load type: $F(1.62, 50.10) = 0.46, p = .59, \eta^2_p = .02$; location repetition X
303 load X load type: $F(1, 31) = 0.14, p = .72, \eta^2_p = .004$; color-response repetition X load X load
304 type: $F(2, 62) = 0.01, p = .99, \eta^2_p < .001$; location repetition X color-response repetition X load
305 X load type: $F(2, 62) = 1.01, p = .37, \eta^2_p = .03$). This shows that neither the specific kind of
306 information being remembered, nor the instruction to attend to one dimension, affected the
307 robustness of repetition effects. Load type also did not affect overall response time, $F(1, 31) =$
308 $0.18, p = .68, \eta^2_p = .006$, and there was no load X load type interaction either, $F(1, 31) = 1.32, p$
309 $= .26, \eta^2_p = .041$.

310 We conducted two additional analyses; one to independently assess the robustness of the
311 visuomotor repetition effects with and without working memory load and another to assess the
312 likelihood of there being no interaction between working memory load and visuomotor repetition
313 effects. First, we analysed our data separately for the no load and memory load conditions to
314 ensure that visuomotor repetition effects robustly occurred in both conditions. They did: with no
315 memory load, color-response repetition had a strong effect on RT, $F(1.50, 46.36) = 49.68, p <$
316 $.001, \eta^2_p = .62$, and it interacted with location repetition, $F(2, 62) = 27.47, p < .001, \eta^2_p = .47$. The
317 same was true with memory load. Color-response repetition strongly affected RT, $F(2, 62) =$
318 $48.32, p < .001, \eta^2_p = .61$, and it interacted with location repetition, $F(1.66, 51.51) = 14.89, p <$
319 $.001, \eta^2_p = .32$. A careful reader may notice that the η^2_p for the location-response repetition effect
320 in the memory condition is about half of that of the no memory condition. However, this is due
321 to noisier data, as the mean squared value for this interaction effect is actually larger in the
322 memory condition (0.05, compared to 0.03 in the no load condition). Our second approach was
323 to calculate Bayes factors using JASP (JASP Team, 2018) for the critical interaction effects.
324 Specifically, we used the Bayes Factor for inclusion, which estimates the change in prior
325 probability to posterior probability (given the data) of the set of models including a particular
326 effect. The $BF_{inclusion}$ estimate for the load X location repetition X color-response repetition was
327 0.013, meaning that this effect was 76.92 times more likely to not exist. Similarly, the $BF_{inclusion}$
328 estimate for the 4-way interaction (including load type) was 6.032×10^{-6} , meaning it is $1.66 \times$
329 10^5 times more likely that this interaction does not exist. Thus, we believe the data compel a

330 rejection of the hypothesis that representations in visual working memory underlie these
 331 repetition effects.

332 It is possible that visual working memory load did reduce color-response and location-
 333 response repetition effects by way of reducing target-response errors instead of RT, or by
 334 affecting how many locations and/or colors could be remembered. Before proceeding we note
 335 that this analysis should be read with caution, as the low error rates led to some observations
 336 being at ceiling (i.e., 100% performance) which artificially restricts variability and can produce
 337 spurious differences. Two conditions contained zero errors, and thus zero variability. The mean
 338 error rates for each condition can be seen in Figure 3.



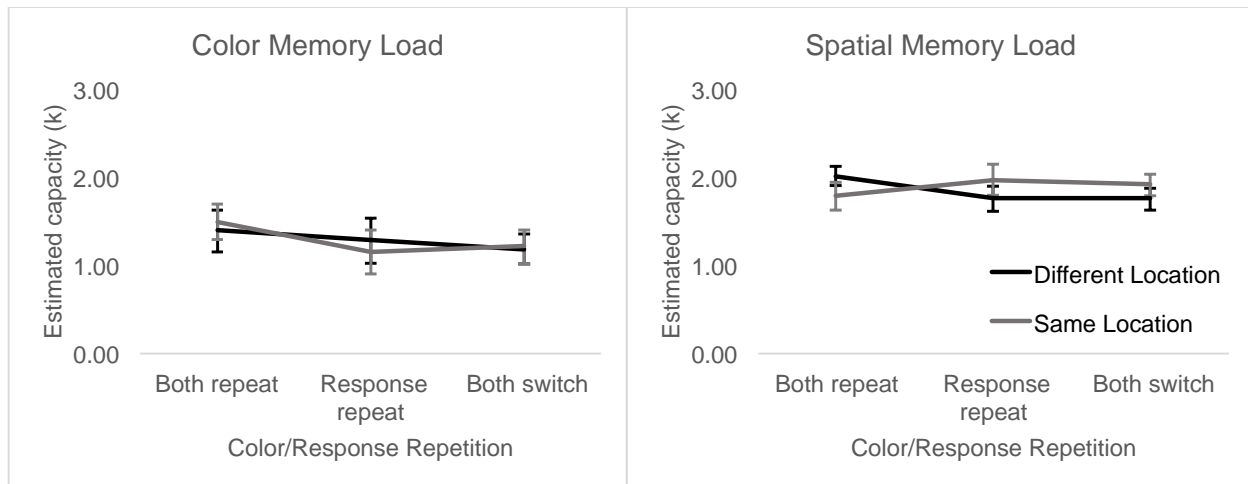
339
 340 **Figure 3.** Target response error rates as a function of memory load and repetition type. Error
 341 bars depict one standard error of the mean.

342
 343 We found evidence that both color-response repetition, $F(1.54, 47.65) = 38.18, p < .001,$
 344 $\eta^2_p = .55,$ and location-response repetition, $F(2, 62) = 21.49, p < .001, \eta^2_p = .41,$ affected errors as
 345 they affected response time. However, with respect to color-response repetition, partial
 346 repetitions led to uniquely high error rates, unlike with response times. Location switches led to
 347 higher errors overall, $F(1, 31) = 11.49, p = .002, \eta^2_p = .27,$ although this is best interpreted in light
 348 of the location-response repetition effect, as partial repetitions of location-response bindings
 349 (specifically, repeating a response to a target in a new location) seem to be driving this main
 350 effect. The location repetition effect interacted with load type, $F(1, 31) = 5.92, p = .02, \eta^2_p = .16,$
 351 such that a location switch affected errors more for color-load participants. Load also interacted
 352 with location repetition, such that location repetition mattered more with memory load than
 353 without load, $F(1, 31) = 7.05, p = .012, \eta^2_p = .19.$ The location-response repetition effect

354 interacted with load type, $F(2, 62) = 2.94, p = .06, \eta^2_p = .09$, such that it was most pronounced
355 for participants in the color load condition. Finally, load and load type interacted, $F(1, 31) =$
356 $5.92, p = .02, \eta^2_p = .16$, such that spatial memory load lowered, but color memory load slightly
357 increased errors. As is evident in Figure 3, this is largely attributable to the uniquely low error
358 rates when target location repeated in the spatial memory load condition. Additionally, a
359 Bayesian ANOVA revealed that the $BF_{inclusion}$ for the memory load X color-response repetition X
360 location-response repetition effect was 0.06, meaning a null effect was 16.67 times more
361 probable, and the $BF_{inclusion}$ for the 4-way interaction (including load type) was 1.25×10^{-4} ,
362 meaning a null effect was 8,000 times more probable. In sum, the accuracy also data do not
363 support a reduction in the potency of color-response or location-response repetitions in
364 producing errors under load.

365 Additionally, we analyzed the effect of repetition type on change detection performance.
366 Change detection performance was quantified as Cowan's k using the equation $N^*(HR-FAR)$,
367 where N is the number of to-be-remembered items and HR and FAR are the hit rate and false
368 alarm rate, respectively (Rouder, Rouder, Morey, & Cowan, 2011). These data are shown in
369 Figure 4. While there was an effect of load type, $F(1, 31) = 8.32, p = .007, \eta^2_p = .21$, reflecting
370 the lower capacity estimates for color memory, there were no effects of color-response
371 repetition, $F(2, 62) = 1.71, p = .19, \eta^2_p = .05$, location repetition, $F(1, 31) = 0.22, p = .64, \eta^2_p =$
372 $.007$, or location-response repetition, $F(2, 62) = 0.42, p = .66, \eta^2_p = .01$. Load type did not
373 interact with location repetition, $F(1, 31) = 0.24, p = .63, \eta^2_p = .008$, or color-response repetition,
374 $F(2, 62) = 0.65, p = .53, \eta^2_p = .02$, nor with location-response repetition, $F(2, 62) = 1.90, p = .16,$
375 $\eta^2_p = .06$. A Bayesian ANOVA revealed that the null model was 4.24 times more likely than the
376 next best model (a main effect of color-response repetition).

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378

379 **Figure 4.** *Memory performance following repetition types in Experiment 1. Error bars depict*
 380 *one standard error of the mean.*

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Discussion

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Experiment 1 showed little to no direct relationship between visual working memory and the repetition effects (location repetition x response repetition; color-response repetition) that occur when serially-presented stimuli are discriminated. If such information was stored in visual working memory, concurrent memory load ought to have selectively eliminated visuomotor repetition effects depending the information (location or color) held in visual working memory. Instead, both color-response and location-response repetition effects were robust against, and largely unaltered by, visual working memory load.

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However, the design of Experiment 1 had some drawbacks. First, memory-load (but, critically, not load type) was confounded with block order, in that participants always completed the memory load trials in the second half of the experiment. We did this for practical reasons, but it is a concern no less. Second, the memory load was imposed before the two discrimination stimuli were presented. It is possible that attending to the first discrimination stimulus caused its color and location to be obligatorily encoded into working memory (Bundesen, 1990), displacing stored colors or locations from the memory array presented at the beginning of the trial and remaining in visual working memory until the second target stimulus appeared. If this were the case, then visual working memory representations might still underlie visuomotor repetition effects. Experiment 2 addresses these concerns.

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Experiment 2

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Experiment 2 modified the design of Experiment 1 in two ways. First, we varied memory load randomly across trials by always presenting a memory array, and cuing participants at the outset of each trial to either remember or ignore the array. Second, the memory array was presented in between the two discrimination stimuli. Hilchey et al. (2017a; 2017b) have shown that location-response repetition effects are largely unaltered by intervening stimulus events, and so we expect that we will be able to observe them even though the display interrupts the sequence of discrimination stimuli compared to Experiment 1.

Methods

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Participants

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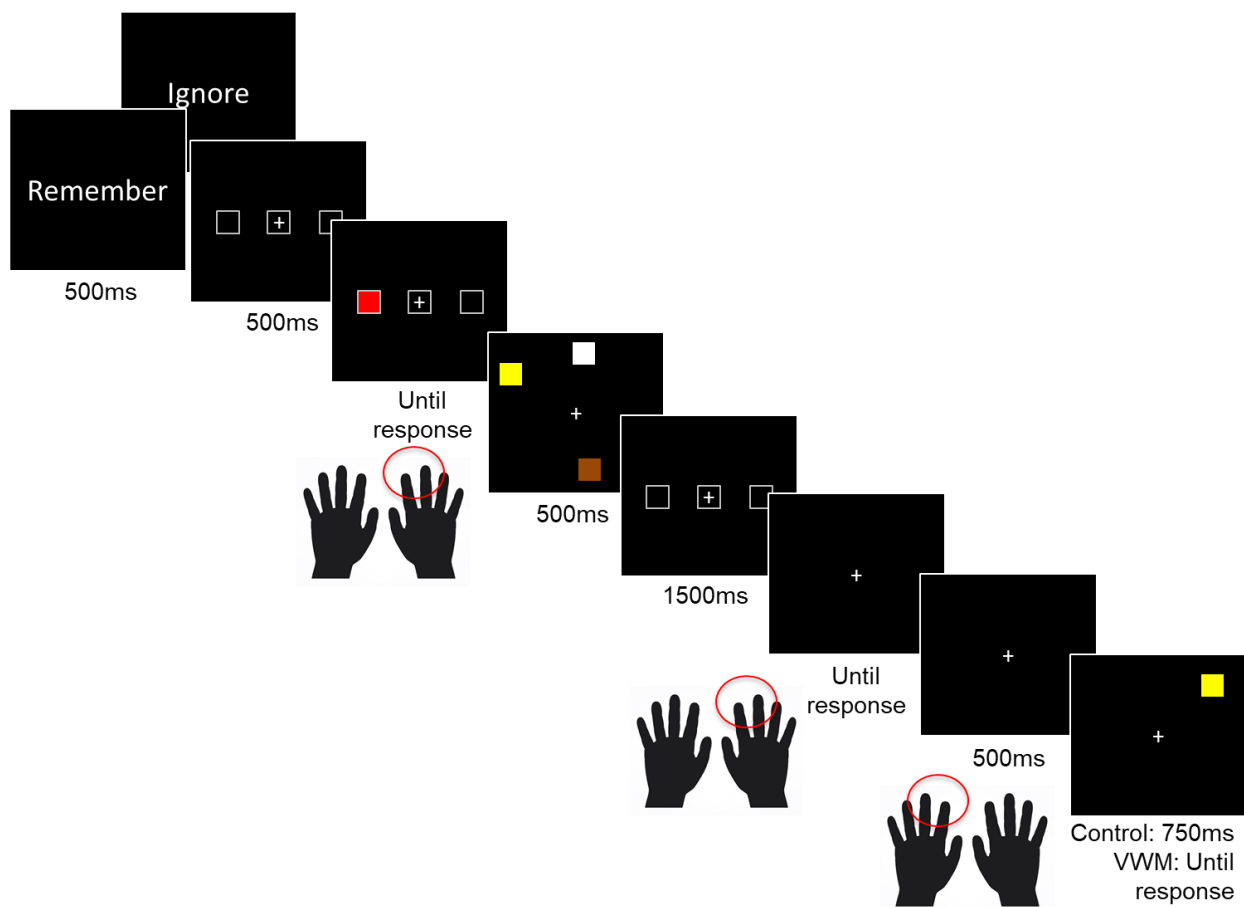
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Fifty-two participants from the Vanderbilt community completed Experiment 2 for course credit. Twenty-eight participated in the color memory condition, and twenty-four participants completed the location memory condition. In both conditions, participants were run until twenty-four participants remained after exclusion criteria were applied (see Results). All participants provided informed consent before participating. The average participant age was 19.4 ($SD = 1.2$), and twenty-eight participants were female.

415 *Stimuli, Apparatus, and Procedure*

416 Stimuli were presented to participants on ASUS VG248 LED monitors using Mac mini
 417 computers. Responses were collected using standard USB keyboards. Stimuli were generated
 418 using Matlab and the Psychophysics toolbox (Kleiner et al., 2007). Stimulus sizes were
 419 calculated to match those of Experiment 1 using the new apparatus and viewing distance of
 420 approximately 80cm. The only new display type used was the cue display used at the beginning
 421 of the trial that instructed participants about whether or not they should complete the memory
 422 task on a given trial. All other displays were drawn to match those in Experiment 1. A schematic
 423 depiction of a trial is shown in Figure 5.



424

425 **Figure 5.** An illustration of a sample trial from Experiment 2. Stimuli are not drawn to scale.

426 The first event of each trial was either Remember or Ignore. The memory probe array depicts a
 427 different location, same color probe.

428

429 *Cue displays.* Each trial began with a word cue that instructed participants about whether
430 or not they should remember the three colors or locations presented in the memory displays on
431 that trial. These word cues were *Remember* and *Ignore*, respectively, printed in the center of the
432 screen in 24-point Arial font. Cue displays lasted for 500ms.

433 The overall sequence of events in the trial was as follows: 500ms of a black screen;
434 500ms of a cue display; 500ms of a black screen with a single fixation cross; 500ms of empty
435 placeholders; the first peripheral color target, presented until a response was entered; the memory
436 display, presented for 500ms; the empty placeholder display, presented for 500ms; the second
437 peripheral color target, presented until responses; and the memory test display, presented until
438 response on memory trials and for 750ms for ignore trials. After a trial was completed,
439 participants were informed of their accuracy for each response, and pressed the space bar to
440 initiate the next trial. Participants completed 20 trials of practice on the color target task alone to
441 acquaint themselves with their randomly generated S-R mapping. The practice phase was
442 repeated if participants made three or more response errors. Following practice, participants
443 completed 384 trials where each condition was randomly intermixed, with 3 repetitions of each
444 combination of memory load, target 1 location, target 2 location, target 1 color, and target 2
445 color. Breaks were given every 50 trials.

446 *Analysis*

447 Four participants were excluded for having memory performance that could not be
448 distinguished from chance ($< 57.29\%$), all of whom had completed the color memory condition.
449 For the remaining participants, average response times for the second color targets were
450 calculated for each condition, excluding trials where the first or second color response was
451 slower or faster than 2.5 *SD* of all target responses (3.0% for the first color response, 2.5% for
452 the second), and where an error in any response was made (5.0% in target responses, 24.3%
453 errors in memory responses). Overall, 79.2% of all trials were retained for analysis. Memory
454 accuracy in the color load condition was 71.3% ($SD = 6.8\%$) and 80.1% ($SD = 9.3\%$) in the
455 location load condition. Again, accuracy for both first-target and second-target responses on
456 trials with target response errors included (but other exclusion criteria applied) was near ceiling
457 after exclusions were applied, $M_{first} = 97.6\%$, $SD_{first} = 2.1\%$, $M_{second} = 97.3\%$, $SD_{second} = 2.2\%$.

458

Results

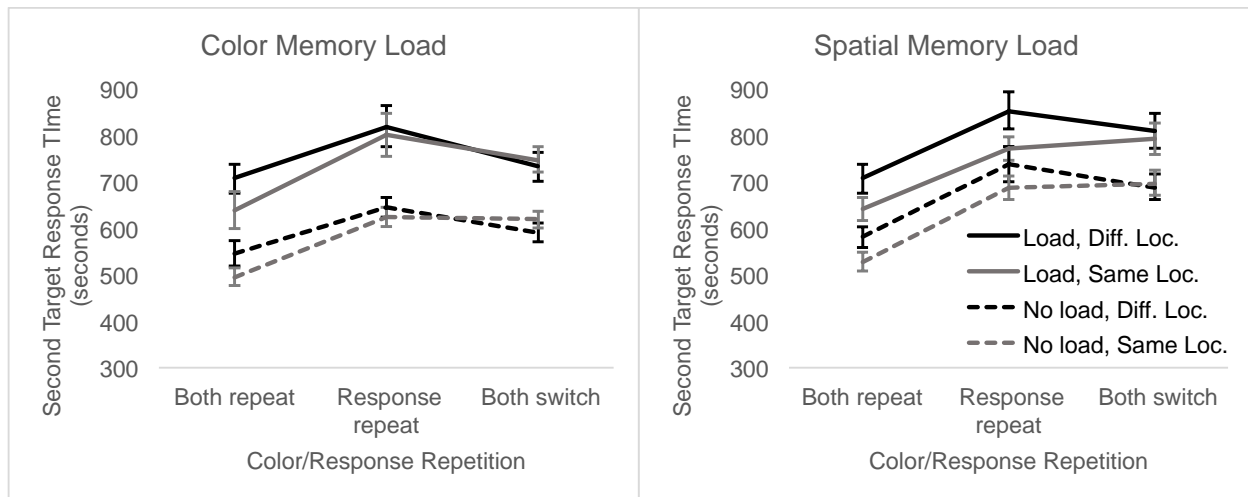


Figure 6. Second target response times in Experiment 2 as a function of color-response repetition type (horizontal axes), location repetition (gray lines: location repeat, black lines: location switch), memory load (present: solid lines, absent: dashed lines), and load type (color load, left panel, spatial load, right panel). Error bars depict one standard error of the mean.

Mean RTs are shown in Figure 6. These findings replicate the hypothesis-pertinent results of Experiment 1, in that RTs were slower in the dual-task condition in which the working memory load was maintained, but the memory load did not reduce visuomotor repetition effects, selectively or otherwise. The relative insensitivity of the visuomotor repetition effects to working memory load again indicate that these repetition effects are not due to working memory storage. A mixed-model ANOVA showed three repetition effects: color-response repetition speeded responses, $F(1.71, 78.85) = 80.65, p < .001, \eta^2_p = .64$, as did location repetitions, $F(1, 46) = 27.48, p < .001, \eta^2_p = .37$, but the latter depended on response repetition, $F(2, 92) = 15.50, p < .001, \eta^2_p = .25$, as in Experiment 1 and elsewhere (Hilchey et al., 2017a; Hilchey et al., 2017b). Thus, we again were successful in measuring visuomotor repetitions effect in this task.

With respect to working memory's involvement in visuomotor repetition effects, memory load slowed responses overall, $F(1, 46) = 94.91, p < .001, \eta^2_p = .67$, and may have increased the magnitude of the overall location repetition benefit, $F(1, 46) = 3.02, p = .09, \eta^2_p = .06$, potentially reflecting a reduction in IOR (Castel, Pratt, & Craik, 2003), which we know to be overshadowed by visuomotor repetition effects (Hilchey, Rajsic, Huffman, Klein & Pratt, 2018),

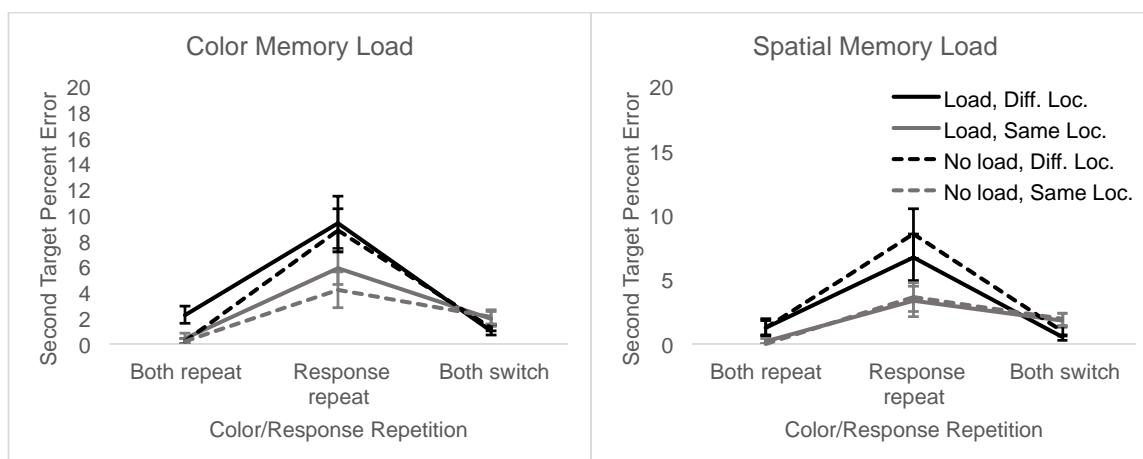
482 but this did not interact with load type, $F(1, 46) = 0.56, p = .46, \eta^2_p = .01$. Color load seemed to
483 slow responses more than location load, but this effect was not significant, $F(1, 46) = 2.79, p =$
484 $.10, \eta^2_p = .06$. Load did not affect the color-response repetition effect overall, $F(2, 92) = 1.21, p$
485 $= .30, \eta^2_p = .03$, but memory load may have selectively, albeit weakly, modulated the size of the
486 color-response repetition effect, as indicated by a memory load X load type X color-response
487 interaction, $F(2, 92) = 2.58, p = .08, \eta^2_p = .03$, such that difference in RT between the partial
488 matching condition (different color, same response) and the full switch condition (different color,
489 different response) was larger under color memory load than location memory load.

490 Interestingly, load type affected color-response repetition effects even when the memory array
491 was irrelevant, $F(1.45, 66.48) = 3.67, p = .04, \eta^2_p = .07$, albeit in a different way: the benefit of
492 color-response repeats over the other two color-response conditions was larger under location
493 than color memory instructions. The fact that load type affected color-response repetition effects
494 even when the load was irrelevant makes it difficult to attribute this interaction to memory load
495 per se. Critically, memory load did not modulate the location-response repetition effect, $F(2, 92)$
496 $= 0.06, p = .94, \eta^2_p = .001$, nor did it modulate it differently when load type was considered, $F(2,$
497 $92) = 0.52, p = .60, \eta^2_p = .011$. Considered separately from whether or not the memory sample
498 needed to be remembered, load type showed a trend of an interaction with the location repetition
499 effect, $F(1, 46) = 3.73, p = .06, \eta^2_p = .08$, such that the RT cost for location changes was larger
500 for participants instructed to remember locations. Load type also interacted with the color-
501 response repetition effect, $F(1.71, 78.85) = 3.30, p = .05, \eta^2_p = .07$, as noted earlier, Load type
502 did not interact with the location-response repetition effect, $F(2, 92) = 1.70, p = .19, \eta^2_p = .04$.
503 Finally, load type did not affect overall RT, $F(1, 46) = 1.44, p = .24, \eta^2_p = .03$.

504 As in Experiment 1, we conducted additional tests to assess whether our data showed
505 evidence for a lack of a relationship between memory load and repetition effects. Analysed
506 alone, no load trials showed both a color-response repetition effect, $F(1.45, 66.48) = 90.48, p <$
507 $.001, \eta^2_p = .66$, and a location-response repetition effect, $F(2, 92) = 14.14, p < .001, \eta^2_p = .24$.
508 Trials with memory load also showed both a color-response repetition effect, $F(2, 92) = 47.58, p$
509 $< .001, \eta^2_p = .51$, and a location-response repetition effect, $F(2, 92) = 6.98, p = .002, \eta^2_p = .13$.
510 The mean square estimate was slightly smaller for the memory load condition ($MS_{no\ load} = 0.032,$
511 $MS_{load} = 0.027$), but the MSE was also larger ($MSE_{no\ load} = 0.002, MSE_{load} = 0.004$), so the
512 halving of the effect size comes from two sources. Bayesian effects estimates showed a $BF_{inclusion}$

513 of 0.007 for the load X color-response repetition X location-response repetition effect, meaning
 514 it is 143 times more likely that no interaction exists. We found even stronger evidence against
 515 the 4-way interaction, with $BF_{inclusion} = 2.234 \times 10^{-5}$, meaning it is 4476 times more likely that
 516 no interaction exists, given the data.

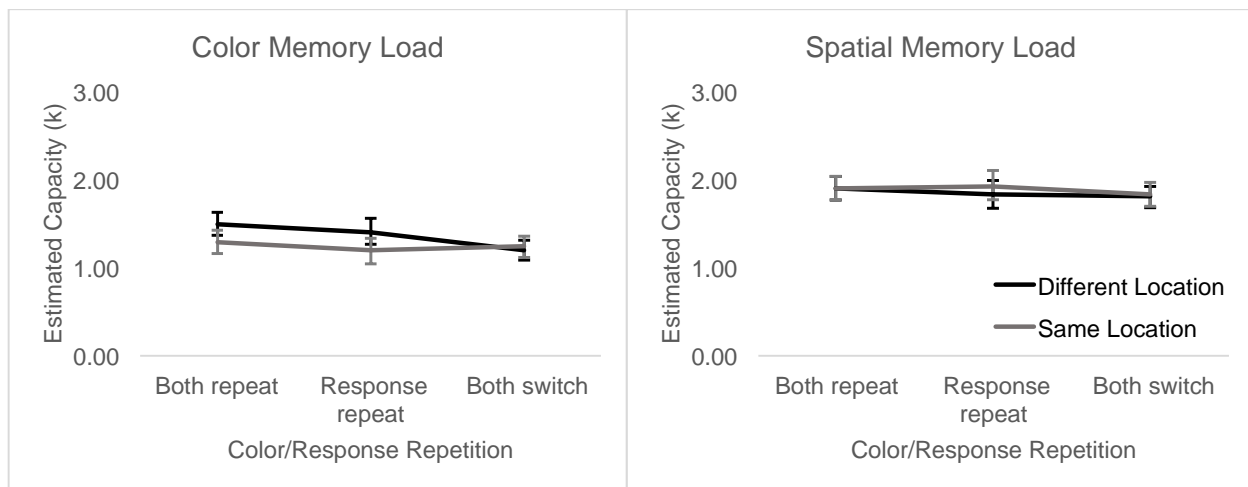
517 Target accuracy painted a similar picture, though again these results should be interpreted
 518 with caution due to ceiling performance (see Figure 7). analyzing target response accuracy
 519 revealed a location repetition effect, $F(1, 46) = 20.37, p < .001, \eta^2_p = .31$, such that error rates
 520 were higher for location switches. This suggests that the location repetition effect in RT may be a
 521 speed-accuracy trade-off instead of IOR. However, as before, this main effect may largely reflect
 522 the higher error rates for repeated responses following a target location change. We also found a
 523 color-response repetition effect, $F(1.08, 49.78) = 45.17, p < .001, \eta^2_p = .50$, and a location-
 524 response repetition effect, $F(1.35, 62.11) = 15.34, p < .001, \eta^2_p = .25$, that revealed a cost for
 525 changing a stimulus feature (color or location) when responses repeated. No other effects were
 526 significant, $F_s < 2.34, p > .13, \eta^2_{ps} < .05$. Using a Bayesian ANOVA, we again calculated the
 527 $BF_{inclusion}$ estimate for the memory X color-response repetition X location repetition interaction,
 528 which was 7.45×10^{-4} (meaning a null effect was 1342 times more likely), and for the 4-way
 529 interaction, which was 2.00×10^{-9} (meaning a null effect was 5.00×10^8 times more likely).
 530 Thus accuracy data provided no suggestion of a relationship between visual working memory
 531 load and repetition effects.



532
 533 **Figure 7.** Target response error rate as a function of repetition type and memory load. Error bars
 534 depict one standard error of the mean.

535

536 Finally, we also analyzed visual working memory performance as a function of target
 537 repetitions as in Experiment 1. As in Experiment 1, k estimates (Figure 8) were lower for
 538 participants memorizing colors than locations, $F(1, 46) = 15.25, p < .001, \eta^2_p = .25$. However,
 539 we found no effects of any repetition type, load type, or interactions, $F_s < 2.69, p_s > .10$. A
 540 Bayesian ANOVA showed that the null model was 4.97 times more likely than the next best
 541 model (a main effect of color-response repetition).



542
 543 **Figure 8.** Memory performance following repetition types in Experiment 2. Error bars depict
 544 one standard error of the mean.

545 Discussion

546 The results of Experiment 2 are consistent with the conclusion from Experiment 1 that
 547 visual working memory load did relatively little to affect visuomotor repetition effects, and in no
 548 way disrupted their influence on response time. When memory load varied unpredictably
 549 throughout the experiment, and memory encoding occurred between the critical target
 550 discrimination events, visuomotor repetition effects were again not disrupted. If anything,
 551 Experiment 2 demonstrated a tendency for the color-response repetition effect to slightly
 552 increase under color visual working memory load, such that the cost of a partial match (same
 553 response but different color) slowed response time more. However, the kind of load mattered
 554 even when participants were cued not to store the memory sample in visual working memory,
 555 and so it's difficult to attribute this to visual working memory load, as opposed to the need to
 556 switch attention between stimulus dimensions (for color-memory participants, color was the
 557 relevant dimension on both tasks in each trial, whereas for location-memory participants,
 558 location needed to be encoded in the memory task, but color was relevant in the target

559 discrimination task), or even task difficulty (colors were generally remembered more poorly than
560 locations).

561 The results of Experiment 2 thus strengthen the conclusion that visual working memory
562 does not store the codes that produce visuomotor repetition effects. Having to encode the
563 memory array in between color targets makes it very unlikely that the first target's color and
564 location were represented in working memory at the time that the second target was processed.
565 While one may argue that three colors and locations could have left spare capacity for
566 representing the features of the first target, the average memory accuracy was decidedly below
567 ceiling for both color and location loads, as can be seen in Figure 8. This was also true for
568 Experiment 1 (see Figure 4). If participants were indeed able to store more than the three
569 locations and colors we presented, their performance ought to have been at ceiling. Furthermore,
570 given that all target – target feature relationships were random, it is not obvious that any strategic
571 advantage could be gained from trying to sustain a memory for the first target's features instead
572 of encoding all three features from the memory array. Thus, we believe that it is most likely that
573 the requirement to encode the locations or colors sufficiently occupied working memory.
574 Nevertheless, maintaining this additional information did not prevent the colors, locations, and
575 responses of previous targets from affecting responses to a subsequent target.

576 **General Discussion**

577 When identification responses are made to sequentially presented stimuli, the speed of
578 these responses is affected in systematic ways by feature and response overlap. If these
579 visuomotor repetition effects depended on short-term, color and location working memory
580 resources, respectively, then working memory loads should have selectively eliminated their
581 respective location-response and color-response repetition effects. Clearly, this did not happen.
582 Our data suggest that the memory representations of previous events that drive visuomotor
583 repetition effects are likely a different kind of memory representation than the kind used to
584 intentionally store visual information (see also Keizer, Hommel, & Lamme, 2015). These data
585 are thus generally consistent with dual-systems views of visually-driven response selection,
586 where response selection based on recently seen stimulus attributes proceeds via an automatic
587 pathway that is not subject to the bottlenecks associated with controlled, rule-based responding
588 (Logan, 1979; Hommel, Proctor, & Vu, 2004; Schneider & Anderson, 2011). This automatic
589 pathway may instead rely on an implicit episodic memory system (Schmidt, De Houwer, &

590 Rothermund, 2016) that can influence response selection when task settings demand that cue-
591 features are processed when responses are being selected (Memelink & Hommel, 2013; Hommel
592 et al., 2014; Huffman, Hilchey & Pratt, 2018).

593 Our data therefore suggest that the memories leading to visuomotor repetition effects do
594 not rely on the capacity-limited system that is used to intentionally remember visual information
595 (Luck & Vogel, 1997). Unlike long-term memory, visual working memory appears to be
596 capacity limited rather than interference-limited (Lin & Luck, 2012; Oberauer, Awh, & Sutterer,
597 2018; but see Hartshorne, 2008; Makovski & Jiang, 2008). Indeed, our experiments were
598 designed to impose a memory load, but not interference; participants always encoded sets of
599 colors or locations that did not overlap with the colors and locations used for the target task. If
600 the repetition of event features affects responses through a retrieval process (see Memelink &
601 Hommel, 2013), then recycling of target features during the memory task could modulate
602 repetition effects through retrieval interference. Thus, our data support the conclusion that
603 visuomotor repetition effects reflect automatic retrieval of information stored in long-term
604 memory (Logan, 1990; Schneider & Anderson, 2011). The apparent transience of event-files
605 could be a consequence of poor long-term memory for specific features and too much retroactive
606 interference for bindings to accumulate over trials, especially when these bindings are not
607 explicitly retrieved (Logie, Brockmole, & Vandenbroucke, 2009).

608 It is still possible, however, that event-files do reflect transient bindings of the sort
609 suggested by Hommel and Colzato (2009). It may be that event-files are stored in an implicit
610 visual short-term memory, whose representational basis overlaps minimally with that of
611 voluntary visual short-term memory (i.e., visual working memory; see Malkjovic & Nakayama,
612 2000; Carlisle & Kristjánsson, 2018 for such a distinction in the context of priming of pop-out).
613 It may also be the case that visuomotor repetition effects solely reflect the operation of a
614 procedural working memory system, and that remembering visual information relies on a
615 declarative working memory system with an entirely separate capacity (Gade, Druey, Souza, &
616 Oberauer, 2014; Oberauer, 2009; Souza, Oberauer, Gade, & Druey, 2012), and with separate
617 stimulus codes (i.e., “red” or “left”) for the procedural and declarative working memory systems.

618 Although the present results argue against a common representational code for visual
619 working memory and visuomotor repetition effects, they cannot distinguish between long-term
620 memory storage and implicit or procedural short-term memory storage as their representational

621 basis. This is an important issue to be settled, as it bears on the question of whether or not the
622 same memory systems underlying moment-to-moment associations also lead to skilled behaviour
623 that comes from long-term associations (Logan, 1990), an assertion which should only be true if
624 repetition effects stem from long-term memory. Additional experiments investigating whether
625 event-files can have cumulative and remote (e.g., Wilson, Castel, & Pratt, 2006; Rajsic, Bi, &
626 Wilson, 2014) effects would be most informative for this outstanding issue. Whichever the case
627 may be, our results still support the assertion that changes in response efficacy due to visuomotor
628 repetition have little to do with deliberately maintained memory for recently seen visual
629 information.

630 Expanding upon this latter point, a practical implication of our results is that visuomotor
631 repetition effects do not appear to depend on the number of concurrently active features. In our
632 experiments, participants had to maintain additional colors or locations while processing target
633 colors and, implicitly, locations. While slowing responses overall, additional active features did
634 not reduce the effect of recent stimulus-response associations. In general, then, we can predict
635 that actively remembering some information will not directly affect the different states of
636 preparedness that recent stimulus-driven actions cause for future stimulus-driven actions, even
637 when the stimuli and memories are from the same category. Many real-world situations require
638 the execution of a rapid response depending on changes in input. For example, pilots need to
639 respond to complex symbolic displays whose elements share simple visual features (such as
640 radial positions of needles across different instruments, form or locations of icons in a heads-up
641 display) that may partially overlap with recently processed elements. In such situations,
642 visuomotor repetitions can still affect response speed and accuracy (Yamaguchi & Proctor,
643 2006). Our results imply that partial overlap of display features will continue to affect
644 performance in systematic ways whether pilots are actively remembering other visual
645 information, such as the positions of other aircrafts, or are attending solely to the task of
646 responding to display changes, though further research on this topic would surely be valuable.
647 The influence of past actions on current actions seems to depend more on which details are
648 needed for a given visuomotor decision than the active contents of memory (Hommel,
649 Memelink, Zmigrod, & Colzato, 2014).

650 Our results also cast some additional doubt on the involvement of visual attention in these
651 visuomotor repetition effects (see also Hilchey, Antinucci, Lamy, & Pratt, in press; Hilchey,

652 Rajsic, Huffman, & Pratt, 2017b; Hilchey, Rajsic, Huffman, Klein, & Pratt, 2018). Given that
653 spatial working memory load tends to interact with the operation of spatial attention (Castel,
654 Pratt, & Craik, 2003; Woodman & Luck, 2004; Ahn, Patel, Buetti, & Lleras, 2017), spatial WM
655 load ought to have altered visuomotor biases here too if these biases resulted from how spatial
656 attention was deployed during the task. Indeed, Experiment 2 did reveal an interaction between
657 memory load and the benefits of repeating a target location, consistent with a reduction in IOR
658 (Castel, Pratt, & Craik, 2003; Zhang & Zhang, 2011). Our findings also align well with studies
659 of the failure of visual working memory load to affect priming of pop-out, given that simply
660 loading visual working memory with colors does not reduce color-based priming of pop out
661 (Lee, Mozer, & Vecera, 2009; Kristjánsson, Saevarsson, & Driver, 2013; Ahn et al., 2017;
662 Carlisle & Kristjánsson, 2018). Our results similarly show that maintaining visual features in
663 working memory does not reduce the impact of recently processed features on response time.

664 Finally, we should note that in Experiment 1 we found that memory load, regardless of its
665 type, increased the size of the color-response repetition benefit. A similar effect was reported by
666 Keele and Boies (1973) in the context of a task requiring participants to quickly report sequences
667 of target locations while remembering five consonants. However, in Experiment 2, this effect
668 disappeared. Although there were several differences between Experiments 1 and 2, it is
669 tempting to speculate that the critical difference is the position of the memory array in the
670 sequence of a trial's events, given Keele and Boies' similar event ordering and results. In
671 Experiment 1, participants maintained a memory load through both target-response episodes,
672 whereas in Experiment 2, participants encoded object features in between target episodes. While
673 the total load at the time of the second target – where repetition effects occur – was the same in
674 both cases, it may be that encoding new colors in between two responses causes interference that
675 simply maintaining information does not.

676 In sum, although some memory storage system must be responsible for maintaining the
677 event representations that give rise to visuomotor repetition effects, our results suggest that this
678 memory storage system is independent of that used to intentionally remember recently
679 encountered visual information, which is inherently capacity-limited.

680

681

682

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688

Author note

689 The authors declare no conflicts of interest.

690

Open Practices Statement

691 The data for the experiments reported here are available at <https://osf.io/d7tr6/>, and none of the
692 experiments were preregistered.

693

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Appendix.

840 Supplementary Table 1.

ANOVA on target response time in Experiment 1

Effect	SS	df	MS	F	p	η^2 p
Memory load	0.250	1	0.250	23.35	< .001	0.430
Memory load X Load type	0.014	1	0.014	1.32	0.26	0.041
error	0.332	31	0.011			
Location repetition (Lr)	0.011	1	0.011	4.68	0.04	0.131
Lr X Load type	0.007	1	0.007	3.04	0.09	0.089
error	0.073	31	0.002			
Color-response repetition (CRr)	1.053	1.61	0.653	55.32	< .001	0.641
CRr repetition X Load type	0.033	1.61	0.021	1.76	0.19	0.054
error	0.590	50.00	0.012			
Memory load X Lr	7.511e -5	1	7.511e -5	0.03	0.88	0.001
Memory load X Lr X Load type	4.141e -4	1	4.141e -4	0.14	0.72	0.004
error	0.095	31	0.003			
Memory load X CRr	0.009	2	0.004	3.20	0.05	0.093
Memory load X CRr X Load type	2.822e -5	2	1.411e -5	0.01	0.99	< .001
error	0.083	62	0.001			
Location-response repetition (LRr: LR X CR)	0.141	1.62	0.087	33.69	< .001	0.521
LRr X Load Type	0.002	1.62	0.001	0.46	0.59	0.015
error	0.130	50.10	0.003			
Memory load X LRr	0.002	2	0.001	0.55	0.58	0.017
Memory load X LRr X Load type	0.004	2	0.002	1.01	0.37	0.031
error	0.112	62	0.002			

841

842 Note. Greenhouse-Geisser corrected values are reported where sphericity assumptions are

843 violated.

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845 Supplementary Table 2.

ANOVA on target response time in Experiment 2

Effect	SS	df	MS	F	p	$\eta^2 p$
Memory load	2.509	1	2.509	94.91	< .001	0.674
Memory load X Load type	0.074	1	0.074	2.79	0.10	0.057
error	1.216	46	0.026			
Location repetition (Lr)	0.141	1	0.141	27.48	< .001	0.374
Lr X Load type	0.019	1	0.019	3.73	0.06	0.075
error	0.235	46	0.005			
Color-response repetition (CRr)	1.956	1.71	1.141	80.65	< .001	0.637
CRr repetition X Load type	0.080	1.71	0.047	3.30	0.05	0.067
error	1.116	78.85	0.014			
Memory load X Lr	0.010	1	0.010	3.02	0.09	0.062
Memory load X Lr X Load type	0.002	1	0.002	0.56	0.46	0.012
error	0.152	46	0.003			
Memory load X CRr	0.008	2	0.004	1.21	0.30	0.026
Memory load X CRr X Load type	0.018	2	0.009	2.58	0.08	0.053
error	0.322	92	0.004			
Location-response repetition (LRr: LR X CR)	0.118	2	0.059	15.50	< .001	0.252
LRr X Load Type	0.013	2	0.006	1.70	0.19	0.036
error	0.349	92	0.004			
Memory load X LRr	2.889e -4	2	1.444e -4	0.06	0.94	0.001
Memory load X LRr X Load type	0.002	2	0.001	0.52	0.60	0.011
error	0.212	92	0.002			

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847 Note. Greenhouse-Geisser corrected values are reported where sphericity assumptions are

848 violated.

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