

1 **Context information supports serial dependence of multiple visual** 2 **objects across memory episodes**

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15 **Running Title**

16 Context information supports serial dependence of multiple objects

17 **Keywords**

18 serial dependence, working memory, proactive interference, context, binding

19 **Abbreviations**

20 WM, working memory, RDP, random dot pattern.

21 **Conflicts of interest**

22 None.

23

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24 **Abstract**

25 Visual perception operates in an object-based manner, by integrating associated features via
26 attention. Working memory allows a flexible access to a limited number of currently relevant objects,
27 even when they are occluded or physically no longer present. Recently, it has been shown that we
28 compensate for small changes of an object's feature over memory episodes, which can support its
29 perceptual stability. This phenomenon was termed 'serial dependence' and has mostly been studied
30 in situations that comprised only a single relevant object. However, since we are typically confronted
31 with situations where several objects have to be perceived and held in working memory, the central
32 question of how we selectively create temporal stability of several objects has remained unsolved.
33 As different objects can be distinguished by their accompanying context features, like their color or
34 temporal position, we tested whether serial dependence is supported by the congruence of context
35 features across memory episodes. Specifically, we asked participants to remember the motion
36 directions of two sequentially presented colored dot fields per trial. At the end of a trial one motion
37 direction was cued for continuous report either by its color (Experiment 1) or serial position
38 (Experiment 2). We observed serial dependence, i.e., an attractive bias of currently toward
39 previously memorized objects, between current and past motion directions that was clearly
40 enhanced when items had the same color or serial position across trials. This bias was particularly
41 pronounced for the context feature that was used for cueing and for the target of the previous trial.
42 Together, these findings demonstrate that coding of current object representations depends on
43 previous representations, especially when they share similar content and context features.
44 Apparently the binding of content and context features is not completely erased after a memory
45 episode, but it is carried over to subsequent episodes. As this reflects temporal dependencies in
46 natural settings, the present findings reveal a mechanism that integrates corresponding bundles of
47 content and context features to support stable representations of individualized objects over time.

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49 **Context information supports serial dependence of multiple visual objects across memory** 50 **episodes**

51 Visual cognition relies heavily on the interplay between perception and memory processes.
52 Behavioral research has shown that we create distinguishable visual objects from a current scene
53 by integrating individual features that belong together (Treisman, 1986). Moreover, we are able to
54 maintain mental representations of these objects in working memory (WM) over short periods of time
55 (Luck & Vogel, 1997). This enables us to use object information flexibly for a variety of cognitive
56 tasks even when they are occluded or physically no longer present. However, which objects need to
57 be maintained in WM can change from one moment to another, because the world around us
58 changes constantly. As situations often change gradually instead of abruptly, many of these changes
59 are foreseeable, and current object representations can often be based on preceding ones. Thus,
60 the exploitation of such short-term dependencies over time represents an important requisite of
61 perceived environmental stability.

62 A series of recent studies have examined in detail how an object representation that is currently
63 encoded into WM is influenced by an object representation that was encoded in the previous trial. In
64 the seminal study by Fischer and Whitney (2014), participants encoded the orientation of a Gabor
65 patch. After a short delay, they were asked to report it in a continuous manner, i.e. by orienting a
66 response line to match the memorized orientation. They found that the reported orientation in the
67 current trial was systematically attracted by the orientation remembered in the previous trial.
68 Importantly, this attractive bias was strongest for orientations that were about 30° apart, and
69 decreased rapidly for larger orientation differences, which shows that it was tuned to the feature
70 similarity between objects across trials. Additional experiments showed that the bias was enhanced
71 by spatial and temporal item proximity. Furthermore, they observed that items needed to be attended
72 and encoded in order to elicit this bias on subsequent items. Fischer and Whitney (2014) coined the
73 term 'serial dependence' for this attractive bias, as it shows a systematic and highly specific
74 dependence of serially encoded objects. Serial dependence has since been observed for other
75 stimulus types, such as faces (Liberman, Fischer & Whitney, 2014), spatial positions (Bliss, Sun &
76 D'Esposito, 2017) or ensemble representations (Manassi, Liberman, Chaney & Whitney, 2017) (see
77 Kiyonaga, Scimeca, Bliss & Whitney, 2017 for an overview). As serial dependence reduces the

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78 perceptual difference between consecutive objects that are similar to each other, it has been
79 interpreted as a mechanism that promotes perceptual stability and continuity of a visual object over
80 time (Fischer & Whitney, 2014).

81 Most studies so far have examined a special case that occurs rarely in nature, i.e. they studied serial
82 dependence in a situation that comprised only a single relevant object. In the real world, however,
83 we are commonly confronted with situations where several objects have to be perceived and
84 maintained in WM. The central question of how we create stability of several object representations
85 over time has remained unsolved.

86 A possible answer to this question refers to the idea that objects are maintained in WM as integrated
87 representations of their features (Luck & Vogel, 1997; Treisman, 1986). Such multi-feature
88 representations would facilitate associations between objects over time. Alternatively, multi-feature
89 objects could be represented in WM by a simultaneous, but independent storage of individual
90 features (Bays, Wu & Husain, 2011). Reconciling both approaches, Brady, Konkle and Alvarez
91 (2011) have proposed that information in WM is structured as a hierarchical feature bundle consisting
92 of two levels. The top level of a bundle represents an integrated object, while the bottom level
93 contains low-level features that are stored independently. In line with this model, Oberauer and Lin
94 (2017) have proposed that objects in WM consist of several features that are bound together. They
95 explicitly distinguish between object 'content' denoting the feature that needs to be reported, and
96 object 'context' representing the feature dimensions via which an object can be cued for report.
97 Context feature can hence refer to the spatial position or the serial position in an encoding sequence,
98 but also to other object features like color. Moreover, context features can differ with regard to their
99 relevance for the ongoing cognitive task. Context features that serve as cues to identify the currently
100 task-relevant object can be referred to as 'task-relevant context features'. In contrast, context
101 features that also differ between objects but are neither reported nor serve as a cue can be referred
102 to as 'task-irrelevant context features' (Figure 1a).

103 The present study investigated whether multiple objects that are encoded into WM can be related to
104 each other across memory episodes via corresponding context features. If this was the case it would
105 indicate that not only content features, but also context features leave traces in memory that support
106 serial dependence between objects. Furthermore, as the task-relevant context should at least be

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107 attended more strongly than the task-irrelevant context, the former should have a stronger impact
108 on serial dependence than the latter. Finally, serial dependence could also be influenced by whether
109 or not a previous object served as a target that was selected and reported (Czoschke, Fischer,
110 Beitner, Kaiser & Bledowski, 2019). As attentional selection and retrieval processes affect the
111 representations themselves (Griffin & Nobre, 2003; Landman, Spekreijse & Lamme, 2003; Souza &
112 Oberauer, 2016), they are likely to influence the strength of the traces objects leave behind in WM,
113 too. Accordingly, targets should produce a stronger serial dependence.

114 To answer these questions, we conducted two experiments, in which two motion directions per trial
115 were sequentially presented as colored dot fields. After a short delay, one motion direction was retro-
116 cued and had to be reported by adjusting the direction of a probe line. In the first experiment, color
117 was the task-relevant context feature by which the target was cued. In the second experiment, the
118 item was cued by its serial position. This enabled us to investigate the impact of three factors that
119 may promote serial dependence of multiple visual objects across memory episodes: the congruence
120 of context features, their task-relevance, and internal attentional selection of a target object (Figure
121 1b).

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122 **Experiment 1: Color Cueing**

123 **Methods**

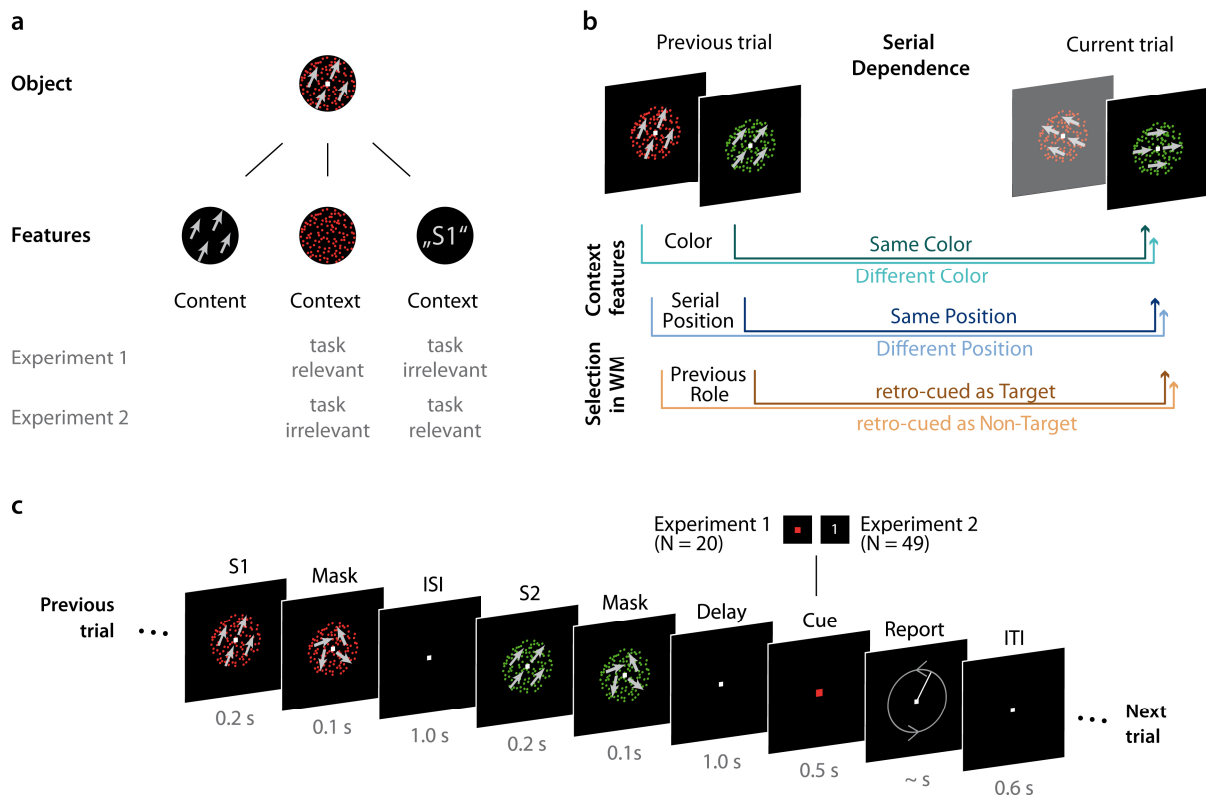
124 *Subjects.* Twenty-two subjects who were recruited from the Goethe-University Frankfurt and the
125 Fresenius University of Applied Sciences Frankfurt participated in experiment 1. All subjects reported
126 normal or corrected-to-normal vision. Two subjects aborted the experiment after the practice trials
127 due to difficulties to perform the task. This resulted in a sample of 20 subjects (10 male), aged
128 between 18 and 32 years (mean: 23.3 years). All subjects gave informed consent and were
129 compensated with € 10/h or course credit. The study was approved by the Ethics Committee of the
130 Medical Faculty of the Goethe-University Frankfurt am Main and therefore complied with their ethical
131 regulations.

132 *Stimuli.* Random dot patterns (RDP) were presented centrally on the screen and consisted of 200
133 dots colored in red (RGB: [255, 0, 0]) or green (RGB: [0, 0, 255]) on a black (RGB: [0, 0, 0])
134 background. The dots were presented within an invisible circular aperture which had a radius of 7.5°
135 of visual angle. The dots had a diameter of 0.15° of visual angle and were placed randomly within
136 the circular aperture of the RDP at stimulus onset. The dots moved with a velocity of 3.5°/s and fully
137 coherent in a direction randomly drawn from a pool of directions between 5° and 355° spaced 10°
138 from one another, therefore avoiding cardinal directions. Dots reaching the edge of the aperture were
139 repositioned randomly on the edge of the opposing side of the aperture, so that dot density was kept
140 constant throughout the presentation. Throughout the whole experiment a white fixation square with
141 a diagonal of 0.15° of visual angle was presented centrally on the screen, except for the cue
142 presentation, when the fixation square changed its color to red or green to cue which item should be
143 reported. The item was reported by adjusting a randomly oriented line to match the recalled direction.
144 The response line was white, with a width of 0.6° and a length equaling the dot field radius. The
145 starting point of the line was the fixation square and the end point could be altered so that the line
146 could point in all possible directions.

147 *Procedure.* Experiment 1 consisted of a delayed-estimation task, in which two sequentially presented
148 motion directions had to be retained in memory, one of which after a short delay was cued for report
149 (Figure 1c). Specifically, subjects saw two sequentially presented RDPs per trial (S1 and S2), each
150 with a different motion direction and a different color, either red or green. Each trial began with the

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151 presentation of the first stimulus (S1) for 200 ms followed by a noise mask for 100 ms consisting of
 152 dots moving with 0% coherence (i.e., randomly) and of the same color as the preceding RDP. After
 153 a 1000 ms interval (ISI) the second stimulus (S2) and its noise mask were presented for 200 ms and
 154 100 ms, respectively. Following a delay of 1000 ms, the fixation square changed its color to red or
 155 green for 500 ms, thereby cueing which motion direction had to be reported. Immediately after cue
 156 offset, a randomly oriented line was presented. Subjects had to report the motion direction by rotating
 157 the line via horizontal mouse movements. No time limit was given for the response and subjects
 158 were encouraged to work as precisely as possible. After adjusting the line direction, subjects had to
 159 confirm their response by pressing the left mouse button. If the entered direction differed more than
 160 30° from the cued direction, another line pointing in the correct direction was presented for 500 ms
 161 as an error feedback (see Kang & Choi, 2015, for a similar procedure). At the end of each trial, a
 162 fixation screen of 600 ms was presented. Subjects were instructed to fixate the fixation square
 163 throughout the whole experiment.



164

165 *Figure 1. Object definition and experimental paradigm.* a) Every object can be defined regarding its content feature, here
 166 motion direction of 25°, and regarding its context features, here color (red) and serial position (first in the sequence, S1).
 167 The context feature by which targets were cued was the task-relevant feature, whereas the other feature was task-
 168 irrelevant (e.g. color and serial position in Experiment 1, respectively). b) We assessed the effects of three factors on the
 169 response error for a cued item (target) in the current trial: color (same or different), serial position and role (target or non-
 170 target) of an item in the previous trial. c) In every trial, participants had to memorize motion directions of two sequentially

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171 presented dot fields (S1 and S2) and report one of them after a short delay by adjusting the orientation of a line. The to-
172 be-reported target item was cued via color (Experiment 1) or via serial position (Experiment 2).

173 In every trial, two different directions were presented, differing between 10° and 170° , equally spaced
174 in steps of 10° , from one another. Over trials, the direction differences were balanced so that every
175 possible direction difference occurred equally often. The order of the dot field colors was balanced
176 across trials, so that both items were presented in both colors equally often, but in each trial the two
177 stimuli had different colors from one another. In half of the trials, the red stimulus had to be reported,
178 and in the other half the green one, which was balanced over encoding positions and direction
179 difference combinations. The order of the trials was not balanced, therefore resulting in a different
180 number of trials per subject and condition for the serial dependence analysis. Each item could be
181 described with regard to its content (i.e., its motion direction), its context (i.e., its color and serial
182 position) and its previous role (i.e., whether it was a target or a non-target) (see Figure 1a).
183 Additionally, here the context feature color served as the task-relevant cueing feature, whereas the
184 context feature serial position was task-irrelevant (see Experiment 2 below for the opposite
185 assignment). The bias produced by an item from a previous trial on the report of the target item of
186 the current trial could therefore be investigated with regard to three analysis factors with two levels
187 each: item color (same or different color as the target of the next trial), serial position (same or
188 different serial position as the target of the next trial) and previous role (target or non-target) (Figure
189 1c). Therefore, the impact of three factors on serial dependence was examined in a $2 \times 2 \times 2$ design.
190 On average, 392.24 trials per factor level combination were analyzed in Experiment 1, with an
191 average 10.6 trials per factor level combination and distance, and 393.46 and 10.6 trials in
192 Experiment 2, respectively.

193 Every subject completed 1632 trials in two sessions on different days, lasting for approximately 2
194 hours each (including instruction and practice trials). Each session was divided into eight blocks of
195 102 trials with self-paced breaks in between. After 45 minutes a general break was given, which was
196 around the half of one session for most subjects. Up to three subjects completed the experiment in
197 parallel in a dimly lit room, acoustically and visually shielded from one another. Subjects were seated
198 at a viewing distance of approximately 50 cm from the display. MATLAB software with the
199 Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997) was used for stimulus generation

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200 and presentation. Three different LCD-monitors with a 4:3 display ratio and running with 60 Hz
201 refresh rate were used.

202 *Analysis.* Prior to the estimation of serial dependence, we excluded trials in which the response error
203 was at least 3 SDs higher than the subject's mean response error, or in which the response time
204 exceeded 20 s, indicating potential attentional lapses, accounting on average for 2.74% of trials in
205 Experiment 1 and 2.47% in Experiment 2. We also excluded the first trial of each session as well as
206 trials following a break, because in the analysis of serial dependence we were interested in the effect
207 of the previous trial on the current one. We also demeaned the response errors by subtracting the
208 overall mean response error of a participant from each individual response error to remove general
209 individual response biases independent of serial dependence.

210 The evaluation of serial dependence was based on individual response errors, defined as the
211 deviation between presented and entered direction. The errors were sorted regarding the difference
212 between the target stimulus of the current trial and a stimulus from the previous trial as well as the
213 relation of difference between the current item and the item of the previous trial (clockwise or counter-
214 clockwise). For the target item of a current trial, the influences of two different items of the previous
215 trial (S1 previous trial and S2 previous trial) were evaluated separately. The difference was computed
216 by subtracting the direction of the current item from the direction of the item of the previous trial.
217 Therefore, when the current item was oriented more clockwise or more counter-clockwise, this
218 resulted in a negatively or positively signed distance, respectively. A mean response error for a
219 signed distance (distance*relation) deviating from 0 indicated a systematic response bias. When the
220 sign of this systemic bias matched the sign of the distance between the directions, it indicated an
221 attractive response bias. Conversely, an opposite sign of the systematic bias compared to the signed
222 distance indicated a repulsive response bias.

223 Trials were then sorted according to their respective levels of the three analysis factors (see
224 Procedure) before computing the mean response bias per signed distance for each factor level
225 combination. Then we could examine the effects of the two context factors as well as task relevance
226 on serial dependence (see Fig. 1C). To assess the effect of those factors, we computed the mean
227 response bias per factor level by averaging response biases of the appropriate conditions. For
228 example, to examine the effect of color, we computed the mean of mean response biases of all

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229 conditions where items had the same color (regardless of serial position and task relevance) and
230 different colors, which resulted in one mean response bias per level of the factor “color”, signed
231 distance and subject.

232 The individual mean response biases were used to evaluate the serial dependence per contrast
233 level. We fitted the first derivative of a Gaussian curve (DoG; e.g. Fischer & Whitney, 2014), a model
234 which is usually used to describe serial dependence. The DoG, given by

$$235 \quad y = xawce^{-(wx)^2}$$

236 was fitted to the pooled mean response biases of all subjects (similar to the procedure by Fritsche
237 et al., 2017) per factor level, i.e. one data point per subject and distance for the respective factor
238 level. In the DoG, x is the relative direction difference of two stimuli, a is the amplitude of the curve
239 peak, w scales the curve width, and c is the constant $\sqrt{2}/e^{-0.5}$. The w parameter was constrained to
240 a value range of .01 to .1. We optimized the log likelihoods of our curve fitting using Bayesian
241 adaptive direct search (BADs; Acerbi & Ma, 2017). BADs alternates between a series of fast, local
242 Bayesian optimization steps and a systematic, slower exploration of a mesh grid. To estimate the
243 variability of the parameters a and w , we bootstrapped the DoG curve fit 1,000 times, sampling the
244 data with replacement on each iteration, and computed the standard deviation of the resulting
245 bootstrapped distributions of a and w (see Fischer & Whitney, 2014, for a similar procedure). For an
246 easier interpretation of the w parameter, we converted it into the full width at half maximum (FWHM).

247 *Statistical analysis.* Permutation tests were used to assess effects on the group level. Specifically,
248 to test whether there was a significant serial dependence, we randomly inverted the signs of each
249 participant’s mean response error. Subsequently, we fitted a new DoG model to the pooled group
250 data and collected the resulting amplitude parameters a in a permutation distribution. We repeated
251 this permutation procedure 1,000 times. As p-values we report the percentage of permutations that
252 led to equal or higher values for a than the one estimated for the empirical data. Based on previous
253 findings (Czoschke et al., 2018; Fischer & Whitney, 2014; Fritsche et al., 2017), we expected a
254 positive serial dependence and therefore the significance level was set to $\alpha = 0.05$ (one-sided
255 permutation test). Significance of the model fit was assessed by a permutation test of the a

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256 parameter only. The w parameter was constrained to a range that excludes zero and zero would be
257 the expected value of w if the fitted data randomly fluctuated around zero without a systematic bias.
258 To test whether serial dependence differed significantly between factor levels, we applied the same
259 procedure as above except that we randomly shuffled the labels of factor levels per participant.
260 Thereby we generated a distribution of a and w differences, against which the a and w difference of
261 the empirical data could be tested. Based on our hypotheses, we expected an enhancement of serial
262 dependence, either in strength (i.e., higher amplitude) or width (i.e., broader tuning width) for same
263 color or serial position in comparison to different color or serial position as well as for targets in
264 comparison to non-targets. Therefore, the significance level was set to $\alpha = 0.05$ (one-sided
265 permutation test). The p -value was given by the proportion of permuted differences whose values
266 were equal or greater than the empirical difference.

267 The same permutation procedure was used to examine possible interactions between the three
268 investigated factors. To this aim, we investigated the difference of differences for two factors. For
269 example, to investigate an interaction between task relevance and color, we computed the difference
270 same vs. different color separately for targets and non-targets, which resulted in two differences. As
271 an indicator for an interaction, we computed the difference between those two differences. In the
272 permutation procedure, in each iteration (1,000) the labels of factor levels for both factors were
273 shuffled per participant. As we did not have clear expectations regarding interactions between the
274 factors, we conducted a two-sided permutation test, i.e. the p -value was given by the proportion of
275 permuted differences, whose absolute values were equal or greater than the absolute empirical
276 difference. The significance level was set to $\alpha = 0.05$.

277 *Effect size calculation.* Our fitting procedure yielded group estimates for amplitude and width,
278 whereas for the calculation of mean-based effect sizes, individual estimates are necessary. As there
279 is no standard procedure for estimating the effect sizes for our analysis, we aimed at obtaining an
280 approximation of the effect sizes that reflects the effects revealed by our permutation tests as good
281 as possible. An estimation of the effect sizes analog to Cohen's d was calculated separately for the
282 amplitude and width of the serial dependence, based on the obtained fittings for every condition. We
283 used computations of the individual data informed by the group fitting to obtain individual estimates.
284 Specifically, for amplitude, we calculated the individual mean response bias per factor level at the

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285 corresponding motion direction difference (current trial versus previous trial) that was closest to the
286 obtained peak of the fitted curve. For example, if the fitting procedure yielded a w parameter that
287 indicated a curve peak at 22° , we obtained the individual response errors for 20° and -20° , inverted
288 the response error for the negative distance and then averaged the two values. For the width of the
289 curve, we calculated individual FWHM estimates. Therefore we first smoothed the individual mean
290 response biases across all motion direction difference per condition using locally weighted non-
291 parametric regression fitting (LOESS, implemented as the fLOESS MATLAB function by Marsh,
292 2016; analog to e.g. Bliss, Sun, & D'Esposito, 2017). We then calculated the FWHM of the smoothed
293 function corresponding to its individual maximum peak between 0 and 60° . If the individual maximum
294 was negative, FWHM was set to 0° . Based on those estimated individual amplitudes and FWHMs
295 we calculated an estimated Cohen's d as effect size in the following way for the comparison against
296 zero:

$$297 \quad d_{est} = \frac{\mu_{amp}}{\sigma_{amp}}$$

298 where μ_{amp} is the mean of the individual amplitude estimates and σ_{amp} their standard deviation. For
299 the amplitude contrasts between factor levels, we calculated an estimated Cohen's d as:

$$300 \quad d_{est} = \frac{\mu_{amp_1} - \mu_{amp_2}}{\sigma_{amp_{pooled(1,2)}}$$

301
302 with $\mu_{amp_{1/2}}$ as the mean amplitude for the first and second factor level, respectively and $\sigma_{amp_{pooled(1,2)}}$
303 the pooled standard deviation. To calculate the effect sizes for the width contrasts between factor
304 levels, the same formula was used as for amplitude contrasts, but with $\mu_{FWHM_{1/2}}$ and $\sigma_{FWHM_{pooled(1,2)}}$,
305 respectively.

306 *Software.* All Analysis were performed with MATLAB 2018a and the following toolboxes/functions:
307 Circular Statistics Toolbox (Berens, 2009), fLOESS (Marsh, 2016), BADS (Acerbi & Ma, 2017),
308 EzyFit (Moisy, 2016).

309 *Code availability.* Code is available from the authors upon request.

310 *Data availability.* Data are available via <https://osf.io/azpwy> and will be made publicly accessible
311 upon publication.

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312 **Results**

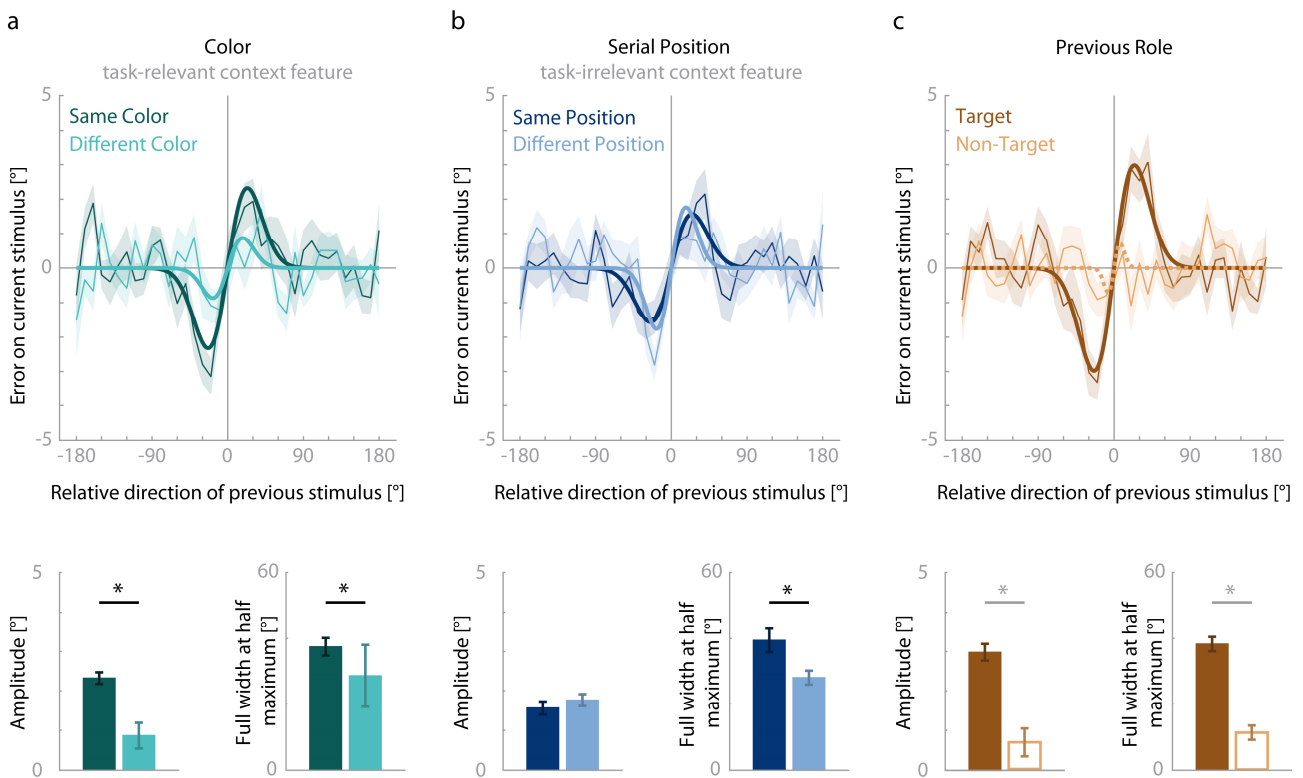
313 *Serial dependence across trials.* In line with previous findings (Bliss et al., 2017; Czoschke et al.,
314 2019; Fischer & Whitney, 2014; Fritsche, Mostert & de Lange, 2017), we observed significant serial
315 dependence across trials even though in this experiment two items were encoded and one was cued
316 for report. Specifically, the reported motion direction of the cued item in the current trial was
317 systematically attracted toward items presented in the previous trial, irrespective of whether the
318 current and previous items shared the same color, serial position or whether the previous item was
319 task-relevant. This attraction followed a DoG-shaped curve with an amplitude parameter of 1.59°
320 (bootstrapped SD: 0.303° , lower 95% of permutations between -1.38° and 0.89° , $p < .001$,
321 permutation test ($n = 20$ participants), $d_{est} = 0.966$, $R^2 = .078$). In line with previous studies a
322 maximum attraction was observed for relative small motion direction differences of about 21.44° and
323 a w parameter of 0.033 , equaling a width of 34.38° (full width at half maximum, FWHM).

324 *Effects of context features.* Serial dependence was clearly modulated by the task-relevant context
325 feature, i.e., color (Fig. 2A). We observed a larger serial dependence when the current item had the
326 same color as a stimulus of the previous trial (amplitude = 2.32° , SD = 0.295° , lower 95% of
327 permutations between -1.95° and 1.16° , $p < .001$, $d_{est} = 1.359$, $R^2 = .091$) as compared to when they
328 had different colors (amplitude = 0.87° , SD = 0.646° , lower 95% of permutations between -1.30° and
329 0.84° , $p = .038$, $d_{est} = 0.252$, $R^2 = .012$) (amplitude difference = 1.46° , $p < .001$, $d_{est} = 0.856$).
330 Similarly, the observed serial dependence was more broadly tuned when the current item had the
331 same color as a previous stimulus (FWHM = 37.45°) as compared to when they had different colors
332 (FWHM = 28.59°) (w difference: -0.010 , equals FWHM difference: 8.86° , $p = .047$, $d_{est} = 0.727$).

333 In contrast, serial position modulated serial dependence only partially (Fig. 2B). The strength of serial
334 dependence was comparable when the current stimulus was presented at the same serial position
335 (amplitude = 1.56° , SD = 0.331° , lower 95% of permutations between -1.60° and 0.89° , $p < .001$, d_{est}
336 = 0.520 , $R^2 = .052$) as compared to when they were presented at different serial positions (amplitude
337 = 1.76° , SD = 0.303° , lower 95% of permutations between -1.43° and 0.94° , $p < .001$, $d_{est} = 1.178$,
338 $R^2 = .046$) (amplitude difference = -0.20° , $p = .239$, $d_{est} = -0.328$). However, we observed a more
339 broadly tuned serial dependence when the current stimulus was presented at the same serial

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340 position (FWHM = 39.45°) as compared to when they were presented at different serial positions
 341 (FWHM = 28.03°) (w difference: -0.012, equals FWHM difference: 11.42°, $p = .011$, $d_{est} = 0.266$).
 342 *Effects of previous role.* Serial dependence was also influenced by the role of an item in the previous
 343 trial (Fig. 2C). We observed a serial dependence from previous targets (amplitude = 2.99°, SD =
 344 0.428°, lower 95% of permutations between -2.80° and 1.40°, $p < .001$, $d_{est} = 1.351$, $R^2 = .140$;
 345 FWHM = 38.30°), but no significant attractive bias from previous non-targets (amplitude = 0.71°, SD
 346 = 0.699°, lower 95% of permutations between -1.23° and 0.72°, $p = .0519$, $d_{est} = 0.358$, $R^2 = .003$;
 347 FWHM = 11.33°). Therefore, the parameters of the curve fitting analysis are not interpretable for the
 348 effect from the non-targets. However, since the permutation test was close to being significant, we
 349 calculated the test between the two factors, which showed a stronger and more broadly tuned serial
 350 dependence from targets than from non-targets (amplitude difference = 2.28°, $p < .001$, $d_{est} = 1.042$;
 351 w difference: -0.070, equals FWHM difference: 26.97°, $p < .001$, $d_{est} = 1.359$), but emphasize that
 352 this result is only restricted interpretable.



353
 354 *Figure 2. Results of Experiment 1.* The response errors (ordinate) are shown as a function of the motion direction difference
 355 (abscissa) between an item of the previous trial and the target of the current trial. Positive values on the abscissa indicate
 356 that the target direction was shifted counterclockwise relative to an item of the previous trial. Positive values on the ordinate
 357 indicate that the response direction deviated clockwise from the true target direction. Serial dependence was revealed by
 358 the group averages of response errors (thin lines), with the corresponding shaded regions depicting the standard error of
 359 the group mean. A derivative of Gaussian (DoG, model fit shown as bold lines) was fitted to the response errors to estimate
 360 the systematic response bias. Solid lines indicate a significant bias, whereas dashed lines depict a non-significant and

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361 therefore non-interpretable bias. Bar plots depict the amplitudes and full widths at half maxima (FWHM) with error bars
362 reflecting one SD of a bootstrapped distribution of the parameters. Asterisks indicate significant differences between
363 compared factor levels. a) Both amplitude and width of serial dependence were greater between items with the same color
364 than between items with different colors. b) The width of serial dependence was greater between items with the same
365 serial position than between items with different serial positions. c) A significant serial dependence was observed from a
366 target of the previous trial, but not from a previous non-target. See the online article for the color version of this figure.

367 *Interaction effects of task-relevant and task-irrelevant context features and previous role.* In addition
368 to the computed contrasts, we examined possible interactions between those three contrasts. First,
369 we examined the interaction of color and serial position. While there was no interaction for amplitude
370 (difference of differences in a: 0.07° , $p = .919$, $d_{est} = 0.072$), we observed a significant interaction for
371 width (difference of differences in w: 0.024, equals FWHM difference: -10.77° , $p = .041$, $d_{est} = -$
372 0.077). The width difference between the same versus different serial positions was more
373 pronounced when the items had different colors (w difference: -0.0304 , equals FWHM difference:
374 18.64°) than when they had the same color (w difference: -0.0066 , equals FWHM difference: 7.87°).
375 This effect was driven by the difference between items with the same (FWHM = 33.04°) compared
376 with different colors (FWHM = 18.64°) when both had a different serial position. For stimuli of the
377 same serial position, the tuning widths were quite similar for items of the same (FWHM = 40.91°)
378 and different color (FWHM = 37.28°). As only the target showed a significant serial dependence and
379 the influence of the non-target was not clear, we computed the interactions for the other two factors
380 with the previous role of an item, but emphasize that they are only restricted interpretable. We
381 observed a significant interaction between serial position and previous role for width (difference of
382 differences in w: -0.037 , equals FWHM difference: 10.80° , $p = .022$, $d_{est} = 0.121$). While for targets
383 only, the effect of serial position on width had the same direction as the overall observed effect (w
384 difference: -0.004 , equals FWHM difference: 5.16°), for non-targets the effects was reversed (w
385 difference: -0.033 , equals FWHM difference: -5.63°), as serial dependence was broader for items
386 with different serial positions. However it should be noted that the width obtained for non-targets with
387 the same serial position was fitted as $w = 0.1$, which equals the upper bound of the fitting procedure
388 for the w parameter. This indicates that no plausible fit was obtained for this subset of trials, as was
389 already evident in the non-significance of the fit to the non-target trials (see above). We therefore
390 restrain from interpreting this interaction. The interaction of widths was not significant for previous

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391 role and color ($p = .153$) as well as the interactions of amplitude that involved previous role (*minimum*
392 $p = .311$).

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393 **Results summary**

394 Experiment 1 showed that context features clearly influence serial dependence of object content,
395 but to a different extent. Specifically, both the amplitude and the tuning width of serial dependence
396 were enhanced between items of the same color in comparison to items of different colors. In
397 contrast, while there was no effect of serial position on amplitude, the tuning width of the bias was
398 broader between items with same compared with different serial positions. While the amplitude
399 reflects the strength of the bias, the tuning width describes how similar two consecutive items had
400 to be in order to produce a bias between them. Therefore, while serial position did not affect the
401 strength of the bias, it modulated how similar two items had to be in order to observe a bias between
402 them. Importantly, in this experiment color was the task-relevant context feature, which served for
403 cueing, whereas serial position was task-irrelevant. However, the observed differences in serial
404 dependence between these context features cannot be unambiguously attributed to task relevance,
405 because both features may also differ in salience. Color is a salient feature inherent in the visual
406 appearance of an item. On the other hand, serial position defines the temporal structure of a trial
407 and is inherent in the encoding of the stimuli even if it is task-irrelevant. To test whether the
408 modulation by context congruence was determined by whether the context feature was task-
409 relevant, we swapped the task relevance of both features in Experiment 2.

410 Experiment 1 also revealed that a significant attractive bias was only observed towards target items
411 of the previous trial. This result is consistent with our recent study that also found serial dependence
412 in a WM paradigm only towards the item that was cued for report (Czoschke et al., 2019). This
413 indicates that when multiple objects were encoded into WM within one trial, only the object that was
414 internally selected for response caused serial dependence. However, since there was a trend
415 towards a positive serial dependence produced by the non-target, this conclusion has to be treated
416 with caution.

417 To overcome the limitations of Experiment 1 we performed Experiment 2 in which we used serial
418 position as task-relevant context feature. We also eliminated any association between serial position
419 and stimulus color by allowing two items within a trial to have the same color. In addition, to obtain
420 more conclusive evidence about the potential serial dependence on non-targets, we substantially
421 increased the number of participants.

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422 **Experiment 2: Serial Order Cueing**

423 **Methods**

424 *Subjects.* Fifty-one subjects who were recruited from the Goethe-University Frankfurt and the
425 Fresenius University of Applied Sciences Frankfurt participated in Experiment 2, none of whom had
426 participated in Experiment 1. All subjects reported normal or corrected-to-normal vision. Two
427 subjects were excluded from the final analysis due to poor task performance (SD of report error > 3
428 SDs of the sample mean). We thus included 49 subjects (19 male), aged between 18 and 33 years
429 (mean: 23.8 years). All subjects gave informed consent and were compensated with € 10/h or course
430 credit. The study was approved by the Ethics Committee of the Medical Faculty of the Goethe-
431 University Frankfurt am Main and therefore complied with their ethical regulations.

432 *Procedure and stimuli.* The procedure and stimuli used equaled the ones described for Experiment
433 1. There were only two differences. First, cueing was now based on the encoding position of the
434 stimuli instead of their color. A number cue replaced the fixation square to indicate which one of the
435 presented directions had to be reported (Figure 1b). To ensure that stimulus color yielded no
436 information about the encoding position of the stimulus, as a second change the stimuli presented
437 in one trial could now have either the same or different colors. This resulted in four possible color
438 combinations within a trial (red-red, red-green, green-green, green-red). Each of those color
439 combinations occurred equally often. In half of the trials, the first presented stimulus had to be
440 reported, and in the other half the second one, which was balanced over the different color and
441 direction difference combinations. Three different monitors with a 4:3 display ratio were used, two
442 running with 60 Hz and one with 75 Hz refresh rate, but with all stimulus parameters kept constant.
443 Subjects were again seated at a viewing distance of approximately 50 cm.

444 *Analysis.* All conducted analysis steps were the same as in Experiment 1.

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445 **Results**

446 *Serial dependence across trials.* When two items were encoded into WM and one of them was cued
447 for report via serial position we observed a significant serial dependence across trials with an
448 amplitude of 2.00° (SD = 0.200° , lower 95% of permutations between -0.93° and 0.57° , $p < .001$,
449 $d_{est} = 1.123$, permutation test (n = 49 participants), $R^2 = .118$) and a FWHM of 34.63° , with the peak
450 of the curve located at 21.44° .

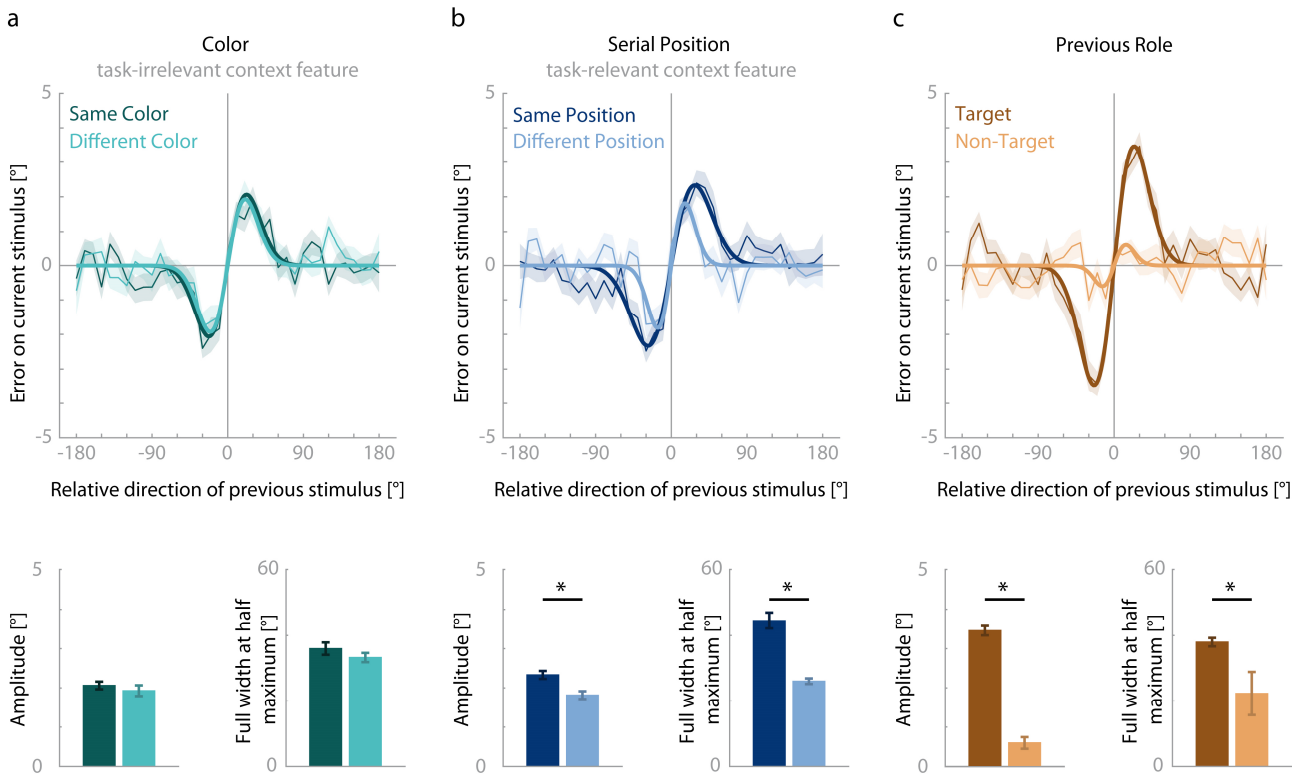
451 *Effects of context features.* Serial dependence was clearly modulated by the task-relevant context
452 feature, i.e., serial position (Fig. 3B). The strength of serial dependence was enhanced when the
453 current stimulus was presented at the same serial position as a previous one (amplitude = 2.33° , SD
454 = 0.204° , lower 95% of permutations between -1.15° and 0.71° , $p < .001$, $d_{est} = 1.243$, $R^2 = .106$) as
455 compared to when they were presented at different serial positions (amplitude = 1.82° , SD = 0.200° ,
456 lower 95% of permutations between -0.87° and 0.56° , $p < .001$, $d_{est} = 0.881$, $R^2 = .045$) (amplitude
457 difference = $.52^\circ$, $p = .009$, $d_{est} = 0.387$). Additionally, we observed a more broadly tuned serial
458 dependence between items at the same serial position (FWHM = 44.60°) compared with different
459 serial positions (FWHM = 26.04°) (w difference: -0.018 , equals FWHM difference: 18.56° , $p < .001$,
460 $d_{est} = 0.840$).

461 In contrast, the task-irrelevant context feature color did not modulate serial dependence (Fig. 3A).
462 Specifically, we observed a comparable strength of serial dependence when the current item had
463 the same color as a previous stimulus (amplitude = 2.06° , SD = 0.195° , lower 95% of permutations
464 between -1.19° and 0.65° , $p < .001$, $d_{est} = 0.674$, $R^2 = .076$) as when they had different colors
465 (amplitude = 1.93° , SD = 0.275° , lower 95% of permutations between -1.33° and 0.63° , $p < .001$, d_{est}
466 = 0.812 , $R^2 = .057$) (amplitude difference = 0.13° , $p = .347$, $d_{est} = -0.065$). The same was true for
467 tuning widths (same color: FWHM = 36.00° , different colors: FWHM = 33.27° , w difference = -0.0003 ,
468 equals FWHM difference: 2.73° , $p = .228$, $d_{est} < 0.001$).

469 *Effects of previous role.* Experiment 2 confirmed that the role of an item in the previous trial, i.e.
470 whether it was a target or not, strongly modulated serial dependence (Fig. 3C). Again, we observed
471 a serial dependence from previous targets (amplitude = 3.46° , SD = 0.240° , lower 95% of
472 permutations between -1.59° and 0.92° , $p < .001$, $d_{est} = 1.654$, $R^2 = .176$). However, increasing the
473 number of subjects revealed an attractive bias from previous non-targets, too (amplitude = 0.60° ,

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474 SD = 0.297°, lower 95% of permutations between -0.62° and 0.44°, $p = .009$, $d_{est} = 0.421$, $R^2 = .005$).
 475 Importantly, the bias from a previous target was stronger than from a previous non-target (amplitude
 476 difference: 2.86°, $p < .001$, $d_{est} = 1.192$). Furthermore, the tuning width of the serial dependence on
 477 previous targets (FWHM = 37.98°) was broader than on previous non-targets (FWHM = 22.28°) (w
 478 difference = -0.021, equals FWHM difference: 15.70°, $p < .001$, $d_{est} = 1.070$).



479

480 *Figure 3.* Results of Experiment 2. Serial dependence (ordinate) was shown as a function of the motion direction difference
 481 (abscissa) between an item of the previous trial and the target of the current trial. For details see Figure 1 and Methods.
 482 a) Serial dependence did not differ significantly between items with the same color and different colors. b) Both amplitude
 483 and width of serial dependence were greater between items with the same serial position than between items with different
 484 serial positions. c) Both amplitude and width of serial dependence were greater for previous targets than non-targets.

485 *Interaction effects of task-relevant and task-irrelevant context features and previous role.* We also
 486 examined possible interactions between the three contrasts. None of the computed interactions was
 487 significant. For the amplitudes, we observed one weak trend ($p = .111$, $d_{est} = -0.140$) suggesting that
 488 the observed amplitude enhancement between items with the same serial position was more
 489 prominent when the previous item was a non-target (amplitude difference: 1.12°) than when it was
 490 a target (amplitude difference: 0.48°). For the non-target items, position incongruence in fact might
 491 even lead to a reversal of the observed bias (position congruent non-targets: 0.61° amplitude,
 492 position incongruent non-targets: -0.51° amplitude). All other interactions were far from reaching
 493 significance both for amplitude (*minimum* $p = .610$) and width (*minimum* $p = .464$).

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494 **Results summary**

495 Experiment 2 aimed at resolving two open questions: first, whether task-relevant and task-irrelevant
496 context features differentially modulate serial dependence of object content, and second, whether
497 serial dependence also occurs for non-targets from previous trials. We found that color that served
498 as task-relevant context feature in Experiment 1 but was task-irrelevant in Experiment 2 did not
499 modulate serial dependence. Similarly, task-relevant serial position in Experiment 2 affected the
500 amplitude of serial dependence, which was not the case in Experiment 1 where serial position was
501 task-irrelevant. However, in contrast to color, serial position affected the tuning width of serial
502 dependence regardless of whether it was task-relevant or not. Regarding the effect of the previous
503 role on serial dependence, Experiment 2 with an increased number of subjects revealed an attractive
504 bias also from previous non-targets. However, both amplitude and tuning width of serial dependence
505 was notably smaller for previous non-targets than targets.

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506 **General Discussion**

507 Current models assume that objects in WM consist of bound content and context features that are
508 established anew in each memory episode. Recent studies have shown, however, that the content
509 feature of a single object encoded into WM was selectively attracted toward a similar content feature
510 of a past object representation. This phenomenon, termed serial dependence, has attracted much
511 research interest (Kiyonaga et al., 2017). But, as we typically hold several objects in WM, it has
512 remained unclear whether multiple objects interact across memory episodes. To answer this
513 question, we conducted two experiments in which participants memorized two sequentially
514 presented motion directions (S1 and S2) that differed in color. After a brief delay, either a color cue
515 (red or green; Experiment 1) or a serial position cue (first or second stimulus; Experiment 2) indicated
516 which motion direction stimulus to report. We could thus assess the impact of three factors on serial
517 dependence: congruence of context features across trials (color or serial position), task relevance
518 of context features, and the role of the object in the previous trial. We found that all these factors
519 support serial dependence in situations where several objects are encoded into WM. Specifically,
520 we observed a stronger serial dependence between items that shared the same task-relevant
521 context features across trials. Moreover, serial position partly facilitated serial dependence even
522 when it was the task-irrelevant context feature, whereas task-irrelevant color had no such effect.
523 Third, regardless of the context feature, the attractive bias was stronger toward the target item in the
524 previous trial. Together, our results show that serial dependence based on content-similarity is
525 enhanced between objects that share the same task-relevant context features and that are internally
526 selected as target objects.

527 In most previous studies on serial dependence between trials, only one item per trial had to be
528 encoded into WM. In contrast, the present study found that serial dependence also occurs when two
529 items per trial were attended and encoded into WM, replicating recent results from our laboratory
530 (Czoschke et al., 2019). Importantly, we also replicated the finding that serial dependence across
531 trials is particularly pronounced for target items that were retro-cued for report in the previous trial.
532 Retro-cueing implies that targets were internally selected into the focus of attention. In contrast,
533 previous studies have found enhanced serial dependence for pre-cued targets, i.e., as a result of
534 externally manipulating the attentional selection and encoding (Fischer & Whitney, 2014). Taken

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535 together, these findings show that both external and internal attention strongly promote serial
536 dependence. Interestingly, the present Experiment 2 with an increased number of subjects revealed
537 serial dependence also for non-targets, albeit with a clearly reduced amplitude compared to targets.
538 As both targets and non-targets from the previous trial were irrelevant for the current trial, this result
539 indicates that attentional prioritization in the previous trial strongly modulates the magnitude of serial
540 dependence, without being a necessary precondition for its occurrence.

541 Besides the influence of attention, another key property of serial dependence is that it operates
542 selectively between objects with similar contents, as reflected by the stereotypical tuning profile
543 observed for a range of different content features like orientation (Fischer & Whitney, 2014), faces
544 (Liberman et al., 2014), spatial position (Bliss et al., 2017), ensemble representations (Manassi et
545 al., 2017) or motion direction (Czoschke et al., 2019). Based on this property, Fischer and Whitney
546 (2014) suggested that serial dependence reduces small differences between consecutive content
547 features to support the impression of a coherent environment. The novel finding of the present study
548 was that, in addition to content similarity, context features also leave traces in WM and thus help to
549 relate corresponding objects across memory episodes. Specifically, we observed a stronger and
550 more broadly tuned serial dependence between motion directions with the same color (Experiment
551 1) or serial position (Experiment 2). Previous studies using only one stimulus per trial have yielded
552 contradictory results concerning the role of context features like spatial position for serial
553 dependence (Fischer & Whitney, 2014; Fritsche et al., 2017). The present design requiring the
554 selective report of one out of two items per trial should have increased the binding between content
555 and context features, thus enhancing the influence of context on serial dependence. This finding
556 corroborates the assumption that serial dependence indicates a continuity field in a changing
557 environment that promotes stability of object representations over time.

558 The observed modulation of serial dependence by both content similarity and context congruence
559 suggests that single features of an object are represented in WM as bound together to some degree.
560 This is in line with frameworks that assume a WM organization with integrated multi-feature objects
561 (Brady et al., 2011; Luck & Vogel, 1997; Oberauer & Lin, 2017). The definition of a WM item as a
562 combination of content and context features corresponds closely to the concept of object files
563 (Kahneman, Treisman, & Gibbs, 1992; Treisman, 1986). An object file contains the different features

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564 of an object that form a temporary representation, enabling us to track an object over time. The
565 object identity should remain stable and immune against small changes in object appearance,
566 caused, e.g., by movement or changing lighting conditions. While priming studies have shown that
567 object features are discriminated faster for previously presented objects (Noles, Scholl, & Mitroff,
568 2005), the mechanism enabling the tracking of objects over time has remained unknown. Fischer
569 and Whitney (2014) have proposed serial dependence as a mechanism underlying the continuity of
570 objects. However, across memory episodes with multiple relevant objects, serial dependence would
571 serve temporal integration only if it operated in an object-file fashion by relating corresponding
572 bundles of content and context features. Our findings show that context congruence of objects clearly
573 promotes serial dependence, thus supporting the interpretation that serial dependence is a
574 mechanism suited for temporal integration of object representations across time.

575 While task-relevant context features consistently enhanced serial dependence, the effect of the task-
576 irrelevant context feature differed between experiments. In Experiment 1, we found that task-
577 irrelevant serial position changed the tuning width of serial dependence. In contrast, in Experiment
578 2 there was no such effect for task-irrelevant color. One explanation might be that serial position is
579 more automatically integrated into an object representation than color, even though the latter one is
580 a more salient visual feature. This relates to the importance of spatiotemporal information for the
581 definition of an object (Treisman, 1986). Furthermore, it reflects the importance of serial position as
582 a context feature regardless its task-relevance. The sequential order of events, i.e., stimulus
583 presentations, determines the serial position of an item and thus defines the temporal structure of a
584 trial. Therefore, temporal information might be of crucial relevance for item representations,
585 particularly in the case of sequentially presented items at the same spatial position (Schneegans &
586 Bays, 2018). Taken together, future studies should investigate the role of temporal position for WM
587 representations in greater depth.

588 Furthermore, we observed different effects of task-relevance on the amplitude of the bias for both
589 context features. For color, our results indicate that serial dependence was suppressed between
590 differently colored items when it was task-relevant (amplitude = 0.87°) compared to when it was task-
591 irrelevant (amplitude = 1.93°) whereas it was quite similar for items of the same color when it was
592 task-relevant or task-irrelevant (amplitudes of 2.32° and 2.06° , respectively). For serial position in

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593 contrast, task-relevance enhanced the amplitude of serial dependence between items with the same
594 serial position (amplitude = 2.33°) in contrast to when it was task-irrelevant (amplitude = 1.56°) and
595 was similar for items with different serial positions when it was task-relevant or task-irrelevant
596 (amplitudes of 1.82° and 1.76° , respectively). This indicates that task-relevance enhanced the
597 amplitude between items with the same serial position whereas it suppressed the amplitude between
598 items of different colors. This further strengthens the interpretation that color and serial position might
599 be two qualitatively different context features.

600 A large body of research on WM has shown that when a probe did not form part of the currently
601 memorized set but of the set presented on the previous trial, reaction times were longer and
602 recognition accuracy was reduced (see Jonides & Nee, 2006, for an overview). This phenomenon
603 is termed proactive interference and has been investigated most commonly using verbal stimuli (e.g.,
604 Jonides, Smith, Marshuetz, Koeppel & Reuter-Lorenz, 1998; Keppel & Underwood, 1962). Proactive
605 interference has been observed also for visual features like colors or shapes. Here it was particularly
606 pronounced when past and current items were presented at the same spatial location (Makovski &
607 Jiang, 2008). Similarly, in serial recall tasks participants often incorrectly reported items from
608 previous lists (so-called intrusions) at the same recall position across trials (e.g., Henson, 1999).
609 Proactive interference and serial dependence both describe effects of previous WM episodes on
610 current ones, which has led to the assumption that both could arise from the same underlying
611 mechanism (Kiyonaga et al., 2017). Our results demonstrate that serial dependence is supported by
612 corresponding context features across trials. As the same is true for proactive interference (Henson,
613 1999; Makovski & Jiang, 2008), this supports the possibility that serial dependence and proactive
614 interference reflect the same mechanism. On the other hand, this hypothesis is challenged by
615 important differences between both phenomena. Proactive interference effects arise because an
616 item from a previous trial is mistakenly assigned to the item set of the current trial. This indicates
617 that the binding between the item and its trial context was incorrect. In contrast, serial dependence
618 describes an integration of a previous into a current content feature of an object that is promoted by
619 content similarity and context congruence, rather than the erroneous recall of a previous object.
620 Furthermore, in most studies on proactive interference, the observed effects stemmed from
621 previously encoded but not tested items, i.e., non-targets. Bäuml and Kliegl (2013) even showed

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622 that testing items of a previous list eliminated proactive interference on a subsequent list. On the
623 other hand, serial dependence mainly arises from the target of a previous trial, as shown by our
624 results together with previous ones (Czoschke et al., 2019; Fischer & Whitney, 2014). Moreover,
625 proactive interference is usually interpreted as a malfunction that has to be overcome whereas serial
626 dependence is considered a beneficial temporal smoothing mechanism. Our results support the idea
627 that the mechanism underlying serial dependence is a beneficial one, because it relates objects over
628 time by reducing small differences between their representations. While this would be useful in
629 natural environments, it may lead to harmful outcomes in artificial settings, leading to systematic
630 errors or reduced performance in studies of serial dependence or proactive interference,
631 respectively. Notably, proactive interference has been found to correlate negatively with both WM
632 capacity (Mecklinger, Weber, Gunter, & Engle, 2003) and intelligence (Braver, Gray, & Burgess,
633 2007). If interference effects result from a generally beneficial mechanism, individuals with higher
634 WM capacity or fluid intelligence might be better at strategically controlling this mechanism. Taken
635 together, proactive interference and serial dependence differ with regard to their conceptual
636 explanation and whether they arise from previous targets or non-targets, but both describe an
637 influence from past memory events on current ones, which can be modulated by context congruence
638 of objects across time. Therefore, more research is needed to disentangle if and to which degree
639 those phenomena stem from the same underlying mechanism.

640 Until now, the processing stage at which serial dependence occurs has remained unclear. While
641 some studies have suggested a perceptual stage (Cicchini, Mikellidou, & Burr, 2017; Fischer &
642 Whitney, 2014; Fornaciai & Park, 2018; Manassi et al., 2017; St. John-Saaltink, Kok, Lau, & de
643 Lange, 2016), others have provided evidence for a memory- or decision-related process (Bliss et al.,
644 2017; Fritsche et al., 2017; Papadimitriou, Ferdoash, & Snyder, 2015; Pascucci et al., 2019). The
645 present findings support the hypothesis of serial dependence as a memory-based or decisional
646 mechanism. We observed that the impact of both investigated context features on serial dependence
647 relied heavily on task-relevance of the features. Furthermore, the purely visual context feature, i.e.
648 color, relied more strongly on task-relevance than serial position. Importantly, the latter feature is not
649 inherent in the visual presentation of a stimulus but only arises within the context of a trial. Taken
650 together, these observations argue against an exclusively perceptual basis of serial dependence.

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651 Future investigations of the neural underpinnings of this mechanism could elucidate the processing
652 stage at which serial dependence occurs.

653 Our study showed that representations in WM are biased towards previous representations,
654 specifically to those that were targets and had corresponding task-relevant context features. This
655 provides a new insight into the organization of object processing. Apparently, the binding of content
656 and context features is not completely erased after a memory episode, but to some extent is carried
657 over to subsequent episodes pointing toward a mechanism that selectively integrates corresponding
658 multi-feature object representations over time.

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663 **References**

- 664 Bäuml, K.-H. T., & Kliegl, O. (2013). The critical role of retrieval processes in release from
665 proactive interference. *Journal of Memory and Language*, *68*(1), 39–53.
666 <https://doi.org/10.1016/j.jml.2012.07.006>
- 667 Bays, P. M., Wu, E. Y., & Husain, M. (2011). Storage and binding of object features in visual
668 working memory. *Neuropsychologia*, *49*(6), 1622–1631.
669 <https://doi.org/10.1016/j.neuropsychologia.2010.12.023>
- 670 Bliss, D. P., Sun, J. J., & D'Esposito, M. (2017). Serial dependence is absent at the time of
671 perception but increases in visual working memory. *Scientific Reports*, *7*(1).
672 <https://doi.org/10.1038/s41598-017-15199-7>
- 673 Brady, T. F., Konkle, T., & Alvarez, G. A. (2011). A review of visual memory capacity: Beyond
674 individual items and toward structured representations. *Journal of Vision*, *11*(5), 4–4.
675 <https://doi.org/10.1167/11.5.4>
- 676 Braver, T. S., Gray, J. R., & Burgess, G. C. (2007). Explaining the many varieties of working
677 memory variation: Dual mechanisms of cognitive control. In *Variation in working memory*
678 (pp. 76–106). New York, NY, US: Oxford University Press.
- 679 Cicchini, G. M., Mikellidou, K., & Burr, D. (2017). Serial dependencies act directly on perception.
680 *Journal of Vision*, *17*(14), 6. <https://doi.org/10.1167/17.14.6>
- 681 Czoschke, S., Fischer, C., Beitner, J., Kaiser, J., & Bledowski, C. (2019). Two types of serial
682 dependence in visual working memory. *British Journal of Psychology*, *110*(2), 256–267.
683 <https://doi.org/10.1111/bjop.12349>
- 684 Fischer, J., & Whitney, D. (2014). Serial dependence in visual perception. *Nature Neuroscience*,
685 *17*(5), 738–743. <https://doi.org/10.1038/nn.3689>
- 686 Fornaciai, M., & Park, J. (2018). Attractive Serial Dependence in the Absence of an Explicit Task.
687 *Psychological Science*, 095679761773738. <https://doi.org/10.1177/0956797617737385>
- 688 Fritsche, M., Mostert, P., & de Lange, F. P. (2017). Opposite Effects of Recent History on
689 Perception and Decision. *Current Biology*, *27*(4), 590–595.
690 <https://doi.org/10.1016/j.cub.2017.01.006>

CONTEXT INFORMATION SUPPORTS SERIAL DEPENDENCE OF MULTIPLE OBJECTS

- 691 Griffin, I. C., & Nobre, A. C. (2003). Orienting Attention to Locations in Internal Representations.
692 *Journal of Cognitive Neuroscience*, 15(8), 1176–1194.
693 <https://doi.org/10.1162/089892903322598139>
- 694 Henson, R. N. A. (1999). Coding Position in Short-term Memory. *International Journal of*
695 *Psychology*, 34(5–6), 403–409. <https://doi.org/10.1080/002075999399756>
- 696 Jonides, J., & Nee, D. E. (2006). Brain mechanisms of proactive interference in working memory.
697 *Neuroscience*, 139(1), 181–193. <https://doi.org/10.1016/j.neuroscience.2005.06.042>
- 698 Jonides, J., Smith, E. E., Marshuetz, C., Koeppe, R. A., & Reuter-Lorenz, P. A. (1998). Inhibition in
699 verbal working memory revealed by brain activation. *Proceedings of the National Academy*
700 *of Sciences*, 95(14), 8410–8413. <https://doi.org/10.1073/pnas.95.14.8410>
- 701 Kahneman, D., Treisman, A., & Gibbs, B. J. (1992). The reviewing of object files: Object-specific
702 integration of information. *Cognitive Psychology*, 24(2), 175–219.
703 [https://doi.org/10.1016/0010-0285\(92\)90007-O](https://doi.org/10.1016/0010-0285(92)90007-O)
- 704 Kang, M.-S., & Choi, J. (2015). Retrieval-Induced Inhibition in Short-Term Memory. *Psychological*
705 *Science*, 26(7), 1014–1025. <https://doi.org/10.1177/0956797615577358>
- 706 Keppel, G., & Underwood, B. J. (1962). Proactive inhibition in short-term retention of single items.
707 *Journal of Verbal Learning and Verbal Behavior*, 1(3), 153–161.
708 [https://doi.org/10.1016/S0022-5371\(62\)80023-1](https://doi.org/10.1016/S0022-5371(62)80023-1)
- 709 Kiyonaga, A., Scimeca, J. M., Bliss, D. P., & Whitney, D. (2017). Serial Dependence across
710 Perception, Attention, and Memory. *Trends in Cognitive Sciences*, 21(7), 493–497.
711 <https://doi.org/10.1016/j.tics.2017.04.011>
- 712 Landman, R., Spekreijse, H., & Lamme, V. A. F. (2003). Large capacity storage of integrated
713 objects before change blindness. *Vision Research*, 43(2), 149–164.
714 [https://doi.org/10.1016/S0042-6989\(02\)00402-9](https://doi.org/10.1016/S0042-6989(02)00402-9)
- 715 Liberman, A., Fischer, J., & Whitney, D. (2014). Serial Dependence in the Perception of Faces.
716 *Current Biology*, 24(21), 2569–2574. <https://doi.org/10.1016/j.cub.2014.09.025>
- 717 Luck, S. J., & Vogel, E. K. (1997). The capacity of visual working memory for features and
718 conjunctions. *Nature*, 390(6657), 279–281. <https://doi.org/10.1038/36846>

CONTEXT INFORMATION SUPPORTS SERIAL DEPENDENCE OF MULTIPLE OBJECTS

- 719 Makovski, T., & Jiang, Y. V. (2008). Proactive interference from items previously stored in visual
720 working memory. *Memory & Cognition*, 36(1), 43–52. <https://doi.org/10.3758/MC.36.1.43>
- 721 Manassi, M., Liberman, A., Chaney, W., & Whitney, D. (2017). The perceived stability of scenes:
722 serial dependence in ensemble representations. *Scientific Reports*, 7(1).
723 <https://doi.org/10.1038/s41598-017-02201-5>
- 724 Mecklinger, A., Weber, K., Gunter, T. C., & Engle, R. W. (2003). Dissociable brain mechanisms for
725 inhibitory control: effects of interference content and working memory capacity. *Cognitive*
726 *Brain Research*, 18(1), 26–38. <https://doi.org/10.1016/j.cogbrainres.2003.08.008>
- 727 Noles, N. S., Scholl, B. J., & Mitroff, S. R. (2005). The persistence of object file representations.
728 *Perception & Psychophysics*, 67(2), 324–334. <https://doi.org/10.3758/BF03206495>
- 729 Oberauer, K., & Lin, H.-Y. (2017). An interference model of visual working memory. *Psychological*
730 *Review*, 124(1), 21–59. <https://doi.org/10.1037/rev0000044>
- 731 Papadimitriou, C., Ferdoash, A., & Snyder, L. H. (2015). Ghosts in the machine: memory
732 interference from the previous trial. *Journal of Neurophysiology*, 113(2), 567–577.
733 <https://doi.org/10.1152/jn.00402.2014>
- 734 Pascucci, D., Mancuso, G., Santandrea, E., Della Libera, C., Plomp, G., & Chelazzi, L. (2019).
735 Laws of concatenated perception: Vision goes for novelty, decisions for perseverance.
736 *PLOS Biology*, 17(3), e3000144. <https://doi.org/10.1371/journal.pbio.3000144>
- 737 Schneegans, S., & Bays, P. M. (2018). New perspectives on binding in visual working memory.
738 *British Journal of Psychology*. <https://doi.org/10.1111/bjop.12345>
- 739 Souza, A. S., & Oberauer, K. (2016). In search of the focus of attention in working memory: 13
740 years of the retro-cue effect. *Attention, Perception, & Psychophysics*, 78(7), 1839–1860.
741 <https://doi.org/10.3758/s13414-016-1108-5>
- 742 St. John-Saaltink, E., Kok, P., Lau, H. C., & de Lange, F. P. (2016). Serial Dependence in
743 Perceptual Decisions Is Reflected in Activity Patterns in Primary Visual Cortex. *Journal of*
744 *Neuroscience*, 36(23), 6186–6192. <https://doi.org/10.1523/JNEUROSCI.4390-15.2016>
- 745 Treisman, A. (1986). Features and Objects in Visual Processing. *Scientific American*, 255(5), 114B
746 – 125.
- 747