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4 Behavioral and Computational Evidence for Simultaneous Guidance of Attention by Multiple  
5 Working Memory Items

6 Cherie Zhou, Monique M. Lorist, Sebastiaan Mathôt

7 University of Groningen

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#### Author Note

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Cherie Zhou<sup>1</sup>, Monique M. Lorist<sup>1,2</sup>, Sebastiaan Mathôt<sup>1</sup>,

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<sup>1</sup>Department of Experimental Psychology, University of Groningen,

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<sup>2</sup>University of Groningen, Faculty of Medical Sciences, Biomedical Sciences of Cells

16

& Systems, Neurosciences, Neuroimaging Center, Groningen, The Netherlands

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Correspondence concerning this article should be addressed to Cherie Zhou,

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Department of Experimental Psychology, University of Groningen, Grote Kruisstraat 2/1, 9712

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TS, Groningen. E-mail: [xiaoyi.zhou@rug.nl](mailto:xiaoyi.zhou@rug.nl)

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## Abstract

24

During visual search, task-relevant representations in visual working memory (VWM), known as attentional templates, are assumed to guide attention. A main debate over this VWM-based guidance concerns whether only one (Single-Item-Template hypothesis, or SIT) or multiple (Multiple-Item-Template hypothesis, or MIT) items can serve as attentional templates simultaneously. The current study was designed to test these two hypotheses. Participants memorized two colors, prior to a visual-search task where the target and the distractor could match or not match the colors held in VWM. Robust attentional guidance was observed when one of the memory colors was presented as the target (reduced response times [RTs] on target-match trials) or the distractor (increased RTs on distractor-match trials). We then constructed two drift-diffusion models that implemented the MIT and SIT hypotheses, which are similar in their predictions about overall RTs, but differ in their predictions about RTs on individual trials. Critically, simulated RT distributions revealed a better match of the MIT hypothesis to the observed data. Taken together, our findings provide behavioral evidence for the concurrent guidance of attention by multiple items in VWM.

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*Keywords:* visual working memory, attentional template, visual search, attentional

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guidance, attentional capture

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### Significance statement

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Theories differ in how many items within visual working memory can guide attention at the

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same time. This question is difficult to address, because multiple- and single-item-template

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theories make very similar predictions about average response times. Here we model response

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times at an individual level. Crucially, we find that multiple-item-template theories predict

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human behavior much better than single-item-template theories; that is, we find behavioral and

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computational evidence for multiple attentional templates that are simultaneously active.

48 Simultaneous Guidance by Multiple Attentional Template

49 Internal representations of task-relevant information, or *attentional templates*, stored in  
50 visual working memory (VWM), guide attention in visual search (Bundesen, 1990; Bundesen,  
51 Habekost, & Kyllingsbæk, 2005). For example, when you are looking for a chocolate cake, all  
52 dark items in a bakery will be more likely to draw your attention. In other words, VWM  
53 contents guide attention towards memory-matching items in a top-down manner to optimize  
54 visual search (Chelazzi, Miller, Duncan, & Desimone, 1993; Chelazzi, Duncan, Miller, &  
55 Desimone, 1998).

56 Although multiple representations can be maintained in VWM simultaneously, there is  
57 debate about the number of VWM items that can simultaneously serve as attentional templates.  
58 The Single-Item-Template hypothesis (SIT; Houtkamp & Roelfsema, 2006; Olivers, Peters,  
59 Houtkamp, & Roelfsema, 2011) proposes a functional division within VWM: While one item  
60 actively interacts with visual processing to guide attentional selection towards matching items,  
61 other items are shielded from visual sensory input, and thus cannot guide attention.

62 Studies demonstrating a switch cost between templates are often interpreted as evidence  
63 for the SIT model. In a study by Dombrowe, Donk, and Olivers (2011), participants made a  
64 sequence of two eye movements towards two spatially separated target items which were  
65 indicated by arrows. In the switch condition, the two targets had different colors, and thus  
66 required a switch between two templates; in the no-switch condition, both targets had the same  
67 color, and thus required only one attentional template. Crucially, eye movements that were  
68 correctly aimed at the second target were delayed by about 250ms – 300ms in the switch  
69 condition, compared to the no-switch condition. This cost associated with switching between  
70 templates is in line with the SIT hypothesis, suggesting that only one template can be active at  
71 one time.

72 In contrast to the SIT hypothesis, other researchers propose that multiple VWM items  
73 can guide attention simultaneously (Beck, Hollingworth, & Luck, 2012). Although, according  
74 to this Multiple-Item-Template (MIT) hypothesis, holding multiple items in VWM reduces the  
75 memory quality of each item, thus reducing memory-driven guidance (Bays & Husain, 2008;  
76 Kristjánsson & Kristjánsson, 2018). But unlike the SIT hypothesis, the MIT hypothesis does  
77 not pose a strict limitation on the number of items that can serve as attentional templates  
78 simultaneously. Recent work by Hollingworth and Beck (2016) supported the MIT hypothesis.  
79 They asked participants to memorize one or two colors, followed by a visual-search task in  
80 which participants had to report the orientation of a target among distractors. The distractors  
81 were either unrelated to the VWM colors (Match 0); matched one of the VWM colors (Match  
82 1); matched both of the VWM colors (Match 2); or were gray (i.e. no colored distractor). When  
83 two colors were held in VWM, stronger distraction was found on Match 2 trials, compared to  
84 Match 1 trials. This suggests that multiple items can guide attention at the same time.

85 However, the results of Hollingworth and Beck (2016) (see also, Frătescu,  
86 Van Moorselaar, & Mathôt, in press) can also be explained by the SIT hypothesis. If only one  
87 of the two memorized colors served as an attentional template on any given trial, then this color  
88 will match a distractor color on all trials (100%) in the Match 2 condition, but only half of all  
89 trials (50%) in the Match 1 condition. Therefore, average distraction would be stronger in the  
90 Match 2 condition than in the Match 1 condition. In other words, even the SIT hypothesis  
91 would predict slower reaction times in the Match 2 condition, compared to the Match 1  
92 condition. Put differently, because we generally look at averages across many trials when  
93 looking at behavioral data, it is difficult to make inferences about attentional guidance on  
94 individual trials. However, by modelling behavioral data at the level of individual trials, we  
95 can make such inferences, and doing so is one of the key contributions of the current study.

96           In the current study we investigate the attentional guidance of memory items in a visual-  
97 search task based on the additional-singleton paradigm (Theeuwes, 1992). Crucially, we  
98 compare not only the average RTs, but also the RT distributions of trials in different conditions.  
99 Moreover, we will extend our analyses by simulating individual trials based on the predictions  
100 of MIT and SIT hypotheses by means of a drift-diffusion model (Ratcliff & McKoon, 2008)  
101 and compare the simulated data to the obtained data. Participants first kept two colors in  
102 working memory, after which they searched for a colored target shape among a colored  
103 distractor shape and, in one experiment (Experiment 1), a grey distractor shape. The color of  
104 the target and the (colored) distractor was manipulated to match or not match the memorized  
105 colors.

106           Overall, both the SIT and MIT hypotheses predict faster reaction times (RTs) on target-  
107 match trials (i.e., only the target color matches one of the memory colors), and slower RTs on  
108 distractor-match trials (i.e., only the distractor color matches one of the memory colors).  
109 However, the SIT and MIT hypotheses make different predictions about what happens on  
110 individual trials. Specifically, when the target matches a VWM color, then the MIT hypothesis  
111 predicts that attention is always guided toward the target; in contrast, the SIT hypothesis  
112 predicts that attention is only guided toward the target on 50% of trials, because there's only a  
113 50% chance that the target color serves as an attentional template.

114           Furthermore, we also manipulated the congruency between the target and the distractor  
115 to investigate whether both memory colors guide attention. Inside the target, the orientation of  
116 a line-segment was either congruent, or incongruent, with a line-segment inside the (colored)  
117 distractor. The MIT hypothesis predicts the strongest congruency effect on both-match trials  
118 (i.e., both the target and the distractor match the memory colors), because attention is  
119 simultaneously guided towards both the target and the distractor. Therefore, when the line-

120 segment orientations of target and distractor are congruent, it is easier to report the orientation  
121 even though attention is partly drawn to the distractor, resulting in reduced RTs and error rates.  
122 In contrast, in the incongruent condition, there is more cognitive conflict caused by the different  
123 orientation of the matching distractor, resulting in increased RTs and error rates. The SIT  
124 hypothesis does not predict that attention is guided simultaneously towards the target and the  
125 distractor and therefore does not predict an especially strong congruency effect on both-match  
126 trials.

127         When it comes to the RT distribution of individual trials, the MIT hypothesis predicts  
128 that the distribution for both-match and non-match (i.e., neither the target nor the distractor  
129 match the memory colors) trials are the same, or at least very similar: On both-match trials,  
130 attention is guided toward both the target and the distractor, and the resulting facilitation and  
131 interference should cancel each other out, resulting in an RT distribution that is similar to the  
132 condition where no color matches the VWM items. In contrast, under the SIT hypothesis, on  
133 both-match trials, attention is guided either toward the target, resulting in fast RTs, or toward  
134 the distractor, resulting in slow RTs, but never to both at the same time. Thus, the distribution  
135 for both-match trials is expected to be wider than that for non-match trials. We built drift-  
136 diffusion models of individual trials to simulate the two hypotheses' predictions about RT  
137 distributions, and compared these with the collected data.

138         To foresee the results: The data by-and-large favor the predictions of the MIT  
139 hypothesis over the SIT hypothesis.

140

## Experiment 1

141 **Method**

142 **Participants**

143 Thirty-five first-year psychology students (aged from 18 to 23 years old; 18 female, 17  
144 male) from the University of Groningen participated in exchange for course credits. All  
145 participants had normal or corrected-to-normal acuity and color vision. We set our sample size  
146 to a minimum of thirty participants, so that our statistical power would be considerable higher  
147 than is standard in the field. The exact number of participants depended on how many  
148 participants signed up for our study. The study was approved by the local ethics review board  
149 of the University of Groningen (18123-S). Participants provided written informed consent.

150 **Stimuli, design and procedure**

151 Participants were seated in a dimly lit, sound-attenuated testing booth, behind a  
152 computer screen on which the stimuli appeared, at a viewing distance of approximately 62 cm.  
153 Each trial started with a 500ms fixation display, followed by a 1,000ms memory display,  
154 consisting of two color disks placed in the middle of the screen to the left and the right of the  
155 fixation dot (*Figure 1*). The memory colors were randomly drawn from a color circle with full  
156 brightness and saturation (luminance ranged between 49 cd/m<sup>2</sup> and 90 cd/m<sup>2</sup>), with the  
157 restriction that colors were at least 30° away from each other on the color circle. Participants  
158 were instructed to remember the exact colors of the items.

159 Following a 200ms fixation display, the search display was presented and remained  
160 visible until a response was given. The search display consisted of three shapes (1.3° visual  
161 angle): one diamond-shaped, colored target; one square-shaped, colored distractor and another  
162 square-shaped, gray distractor, all placed around the fixation dot, with a 200px radius (5.4°

163 visual angle). The colors of the target (diamond) and the colored distractor (square) either  
164 matched or did not match the remembered color depending on the *Target-Color-Match* (Match,  
165 Non-Match) and *Distractor-Color-Match* condition (Match, Non-Match), resulting in four  
166 types of trials: Non-Color-Match (short for: Target-Color-Match: Non-Match; Distractor-  
167 Color-Match: Non-Match), Target-Color-Match (short for: Target-Color-Match: Match;  
168 Distractor-Color-Match: Non-Match), Distractor-Color-Match (short for: Target-Color-Match:  
169 Non-Match; Distractor-Color-Match: Match), and Both-Color-Match (short for: Target-Color-  
170 Match: Match; Distractor-Color-Match: Match). All shapes in the search display contained a  
171 line segment ( $1.1^\circ$  visual angle) that was tilted  $22.5^\circ$  clockwise or counterclockwise from a  
172 vertical orientation. The line segments in the target and the colored distractor were tilted in the  
173 same (Congruent) or a different (Incongruent) direction depending on the *Orientation-*  
174 *Congruency* condition. The line segment inside the grey distractor was chosen randomly, and  
175 will not be analyzed.

176 Participants indicated the left or right orientation of the line segment within the diamond  
177 by clicking either the left or right mouse button, respectively, as quickly and accurately as  
178 possible. Feedback was given for 500ms immediately following the response: a green dot for  
179 a correct response, or a red dot for an incorrect response. Each trial ended with a memory test,  
180 in which participants selected the exact color they memorized in the color circle. They did this  
181 twice, once for each memorized color. Visual feedback followed, comparing the colors they  
182 selected with those that they actually saw.

183 The three factors (*Target-Color-Match*, *Distractor-Color-Match*, *Orientation-*  
184 *Congruency*) were mixed randomly within blocks. Participants completed eight blocks of 32  
185 trials each (256 trials in total), preceded by one practice block of 32 trials which was excluded

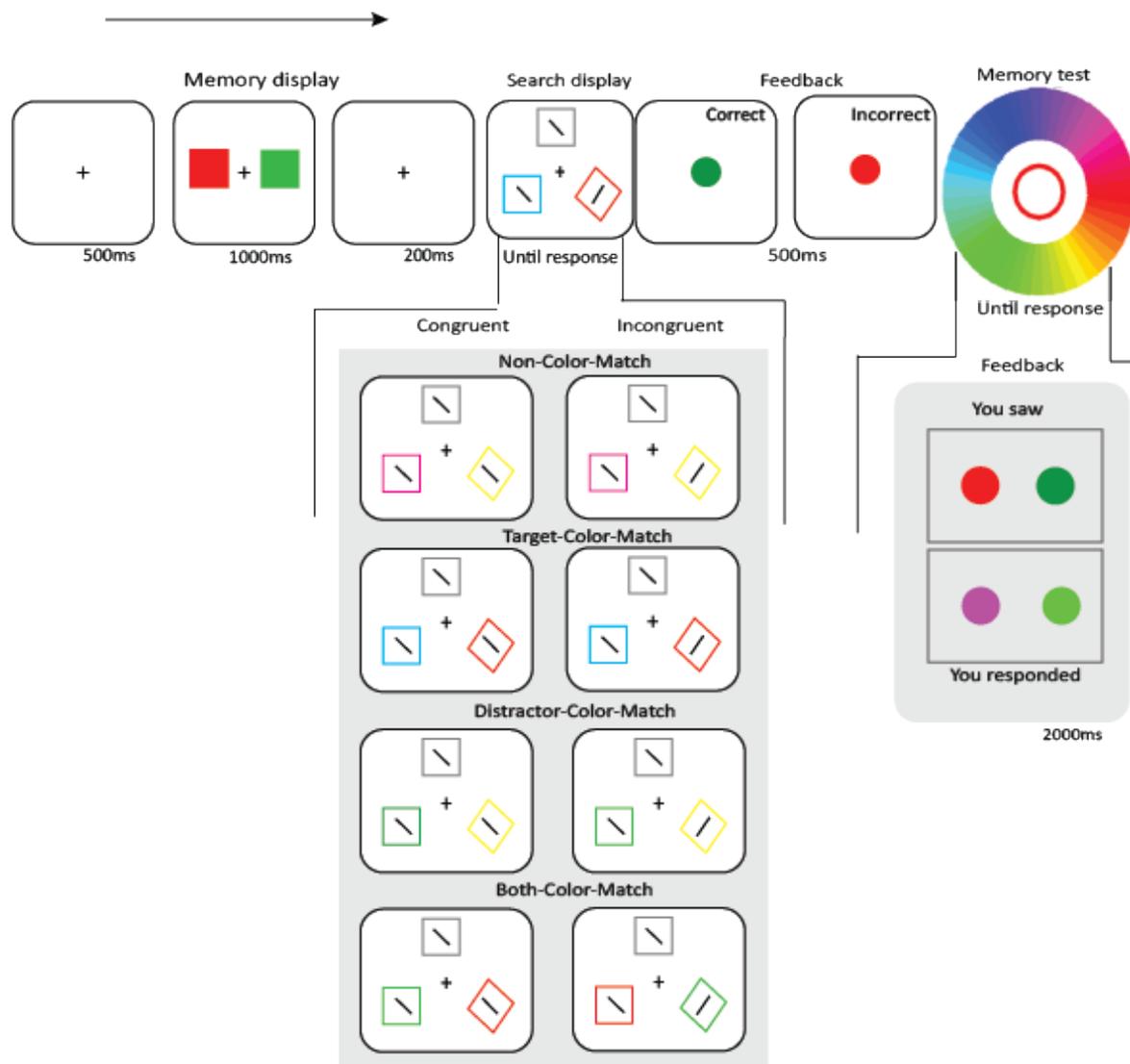
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186 from analysis. Stimulus presentation and response collection were controlled with  
187 OpenSesame version 3.2 (Mathôt, Schreij, & Theeuwes, 2012).

188 A detailed pre-registration of the experiment is available at <https://osf.io/sy7n8/>.

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190

191 *Figure 1.* Sequence of events in a trial of *Experiment 1*. All Target-Color-Match and Distractor-  
192 Color-Match conditions in the search display for both Congruent and Incongruent trials are  
193 illustrated.

10

194 **Data processing**

195 Trials with RTs shorter than 200ms and longer than 2,000ms were excluded.  
196 Furthermore, participants were excluded from analysis if their mean RT for deviated more than  
197 2.5 SD from the grand mean RT of all participants, or if his/her accuracy rate in the search task  
198 was less than 0.7. Only RT data of correct trials were analyzed. Thirty participants and 7478  
199 trials (of 8960) remained for further analysis.

200 **Data analysis**

201 The data were analyzed using the JASP software package (version 0.9; JASP Team,  
202 2018) with the default settings, with *Target-Color-Match* (Match, Non-Match), *Distractor-*  
203 *Color-Match* (Match, Non-Match), and *Orientation-Congruency* (Congruent, Incongruent) as  
204 factors. Inclusion Bayes Factor based on matched models were used to quantify evidence for  
205 effects (Rouder, Speckman, Sun, Morey, & Iverson, 2009).

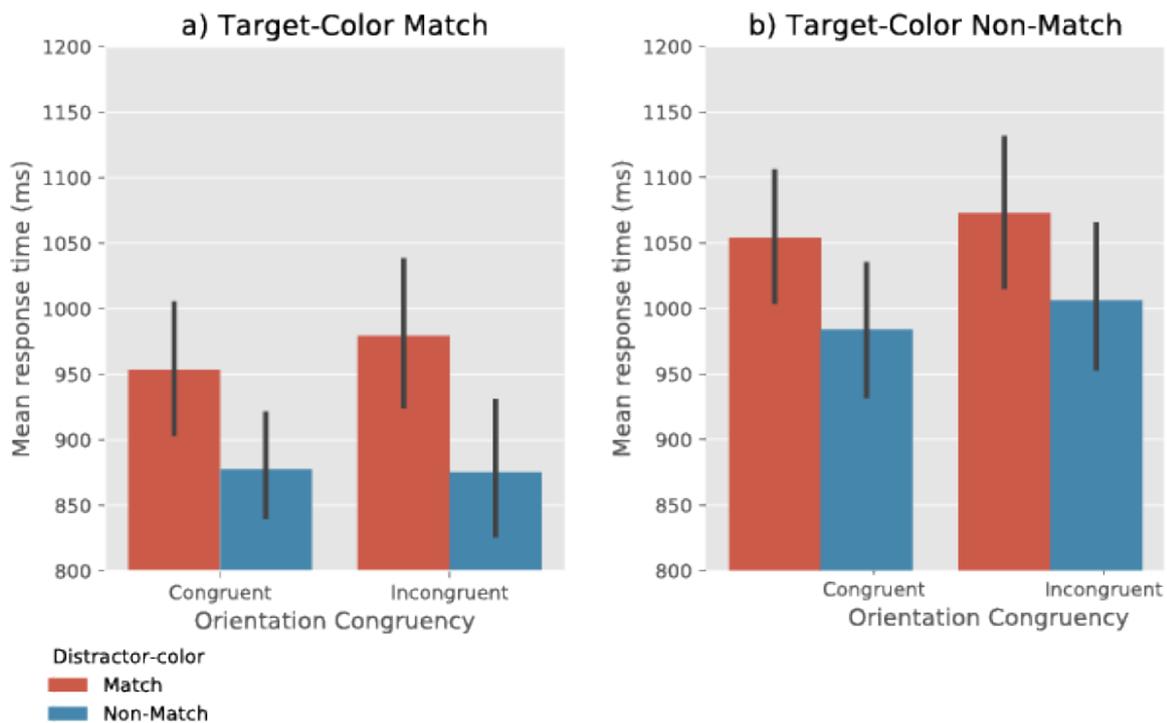
206 Following Wetzels et al. (2011), we consider Bayes factors (*BFs*) between 3 and 10 or  
207 between .1 and .33 are indicators of “substantial” evidence in favor of the alternative ( $H_1$ ) or  
208 the null hypothesis ( $H_0$ ), respectively; *BFs* between 10 and 30 or between .03 and .1 are  
209 indicators of “strong” evidence; and *BFs* between 30 and 100 or between .01 and .03 are  
210 indicators of “very strong” evidence of  $H_1$  or  $H_0$ .

211 **Results and Discussion**

212 **Search RTs**

213 A Bayesian Repeated-Measure ANOVA revealed very strong evidence for memory-  
214 based guidance in the Target-Color-Match ( $BF_{10} = 3.301 \times 10^{24}$ ) and Distractor-Color-Match  
215 ( $BF_{10} = 4.074 \times 10^{15}$ ) conditions, suggesting that the overall search performance was faster

216 when the target matched the memory color, and slower when the distractor matched the  
217 memory color (*Figure 2*). Moreover, the results showed substantial evidence for the effect of  
218 Orientation-Congruency on RTs ( $BF_{10}=7.187$ ), indicating that RT were faster on congruent  
219 trials than incongruent trials. No interaction effect between the factors was found (all  $BF_{10} <$   
220  $.06$ ).



221  
222 *Figure 2.* Mean response time as a function of Target-Color-Match, Distractor-Color-Match,  
223 and Orientation-Congruency.

### 224 **RT distributions**

225 To test whether only one of the color items maintained in working memory served as  
226 attentional template (i.e., SIT), or both of the two color items guided attention (i.e., MIT) in  
227 the visual search task, we analyzed the RT distributions for the Both-Color-Match and Non-  
228 Color-Match trials. According to the SIT hypothesis, on Both-Color-Match trials, attention is  
229 guided by the target on some trials, which leads to faster RTs, while on other trials attention is  
230 guided by the distractor which leads to slower RTs. Therefore, the Both-Color-Match trials

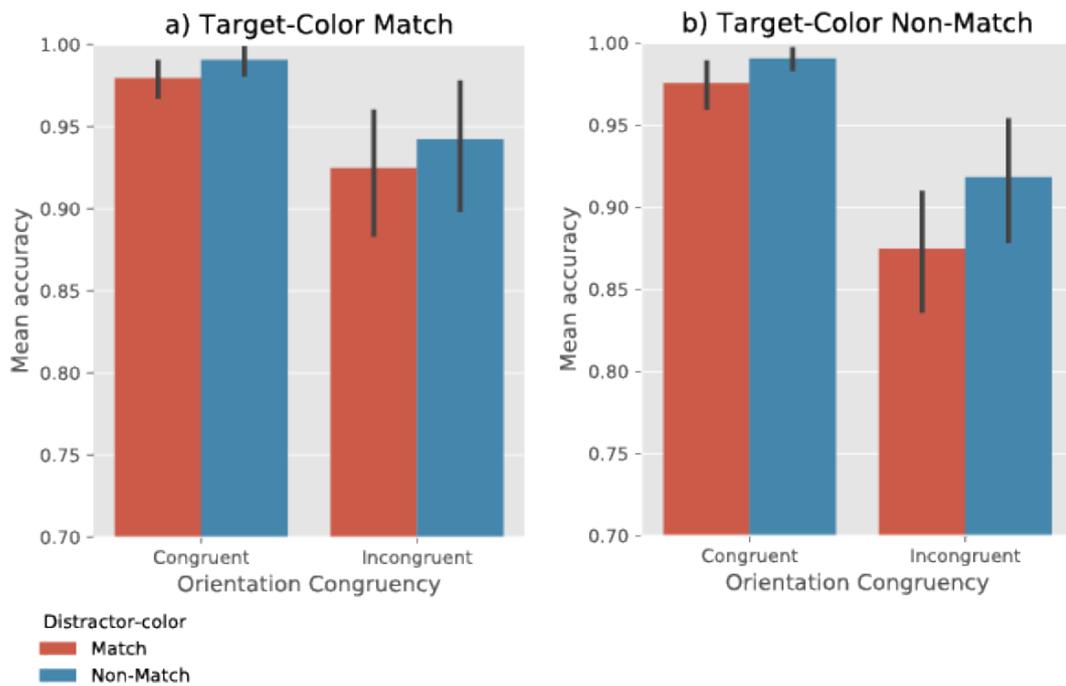
231 should result in a bimodal distribution (i.e. wider than that of the Non-Color-Match trials)  
232 according to the SIT hypothesis. In contrast, the MIT hypothesis predicts that on Both-Color-  
233 Match trials, both the target and the distractor guide attention, thus resulting in a unimodal  
234 distribution (i.e. resembling that of the Non-Color-Match trials).

235 To test this, an Inverse Gaussian distribution was fit to the RTs per condition for each  
236 participant. The scale parameter, which reflects the width of the distributions was analyzed  
237 using a two-tailed Bayesian Repeated-Measure T-test. We found substantial evidence that the  
238 RT distributions for the Both-Color-Match and the Non-Color-Match trials were equally wide  
239 ( $BF_{10} = 4.046$ ), as predicted by the MIT hypothesis.

#### 240 **Accuracy**

241 The same analysis for RTs was conducted on mean accuracy. We found substantial  
242 evidence for the effect of Target-Color-Match ( $BF_{10} = 3.022$ ) and Distractor-Color-Match ( $BF_{10}$   
243  $= 6.577$ ), revealing that the overall search accuracy was higher when the target matches the  
244 memory color, and lower when the distractor matches the memory color (*Figure 3*). Moreover,  
245 a strong overall Orientation-Congruency effect was found ( $BF_{10} = 4.496 \times 10^{13}$ ), showing that  
246 search performance was more accurate when the orientation of the line-segment in a target was  
247 congruent with that in a distractor than when they were incongruent. No evidence for any  
248 interaction effect between the factors was found (all  $BF_{10} < 2.0$ ).

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250 *Figure 3.* Mean accuracy rate as a function of Target-Color-Match, Distractor-Color-Match,  
251 and Orientation-Congruency.

252 In summary, we found that the search performance increased (i.e. became faster and  
253 more accurate) when the target matched one of the colors held in VWM, but decreased when  
254 the distractor matched the VWM item. Moreover, the RT distribution for both-match trials and  
255 no-match trials are similar, which suggests that both color items that were maintained in the  
256 VWM draw attention. These results are consistent with the assumptions of the MIT hypothesis.  
257 Unlike we predicted, however, we did not find evidence that the effect of Orientation-  
258 Congruency is larger when both the target and the distractor matched, compared to other  
259 conditions. We suspected that the presence of the grey (unrelated) color might affected the  
260 processing of the target and the distractor in visual search. Therefore, in the follow-up  
261 experiment, we removed the grey color in the search display.

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## Experiment 2

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In Experiment 2, we removed the grey color item (the unrelated item) from the search display. We reasoned that this would increase the strength of the Orientation-Congruency effect, because there were now only two line segments in the display, thus providing a stronger test of our prediction that the effect of Orientation-Congruency should be strongest when both the distractor and the target matched the VWM colors. Furthermore, we wanted to replicate the main results of Experiment 1.

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### Method

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#### Participants

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Thirty-six first-year psychology students (aged from 18 to 25 years old; 20 female, 16 male) from the University of Groningen participated in exchange for course credits. All participants had normal or corrected-to-normal acuity and color vision.

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#### Stimuli, design and procedure

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The method was the same as in Experiment 1 except for the following. The search display consists of one diamond-shaped, colored target, and one square-shaped, colored distractor, placed on an imaginary circle around the fixation with equal space between them (see *Figure 4*).

279

#### Data processing

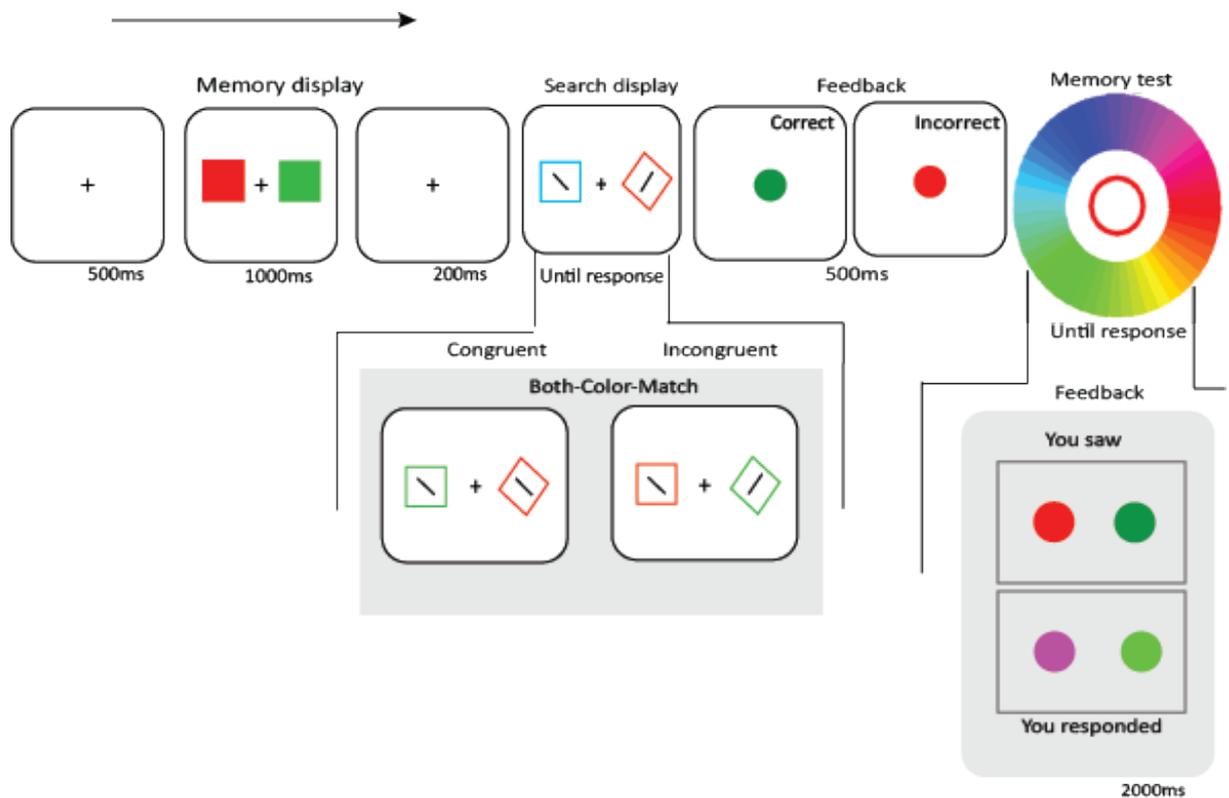
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The same trimming criteria and analyses were used as in Experiment 1. Thirty participants and 7548 trials (of 9216) remained for further analysis. A detailed pre-registration of the experiment is available at <https://osf.io/xpzhy/>.

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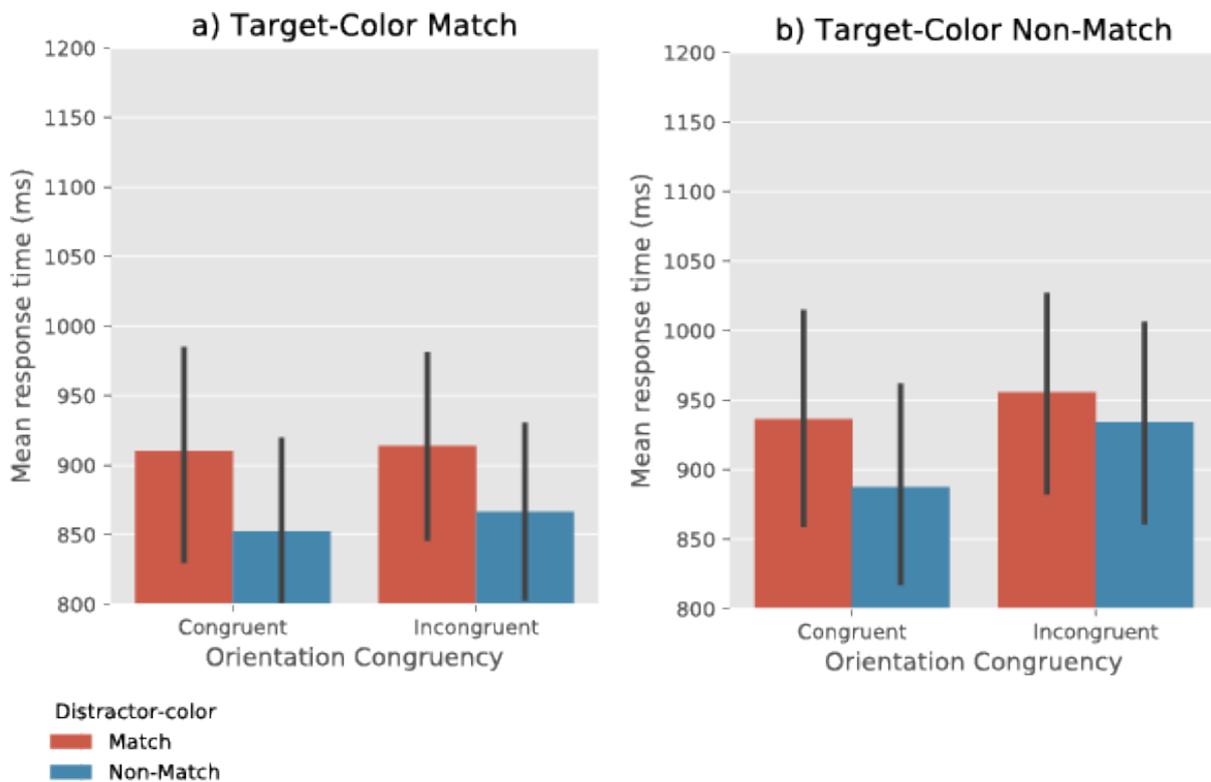
285 *Figure 4.* Sequence of events in a Distractor-Color-Match trial of *Experiment 2*.

## 286 Results and Discussion

### 287 Search RTs

288 A Bayesian Repeated-Measure ANOVA provided strong evidence for memory-based  
289 guidance of Target-Color-Match ( $BF_{10} = 2.152 \times 10^6$ ) and Distractor-Color-Match ( $BF_{10} =$   
290  $1.605 \times 10^6$ ). Moreover, there was very strong evidence for the effect of Orientation-  
291 Congruency on RTs ( $BF_{10} = 72.249$ ), reflecting that participants were faster on congruent trials  
292 than on incongruent trials. Crucially, the results showed a substantial evidence for a Target-  
293 Color-Match  $\times$  Orientation-Congruency interaction ( $BF_{10} = 3.689$ ). To further qualify this  
294 effect, we performed a two-tailed Bayesian Repeated-Measure T-test. When the target color  
295 did not match (*Figure 5b*), there was a very strong evidence for an effect of Orientation-  
296 Congruency ( $BF_{10} = 799.871$ ); in contrast, when target matched the memory color (*Figure 5a*),

297 there was substantial evidence against an effect of Orientation-Congruency ( $BF_{10} = 0.245$ ). No  
298 evidence for other interaction effects was found.



299

300 *Figure 5.* Mean response time as a function of Target-Color-Match, Distractor-Color-Match,  
301 and Orientation-Congruency

### 302 RT distributions

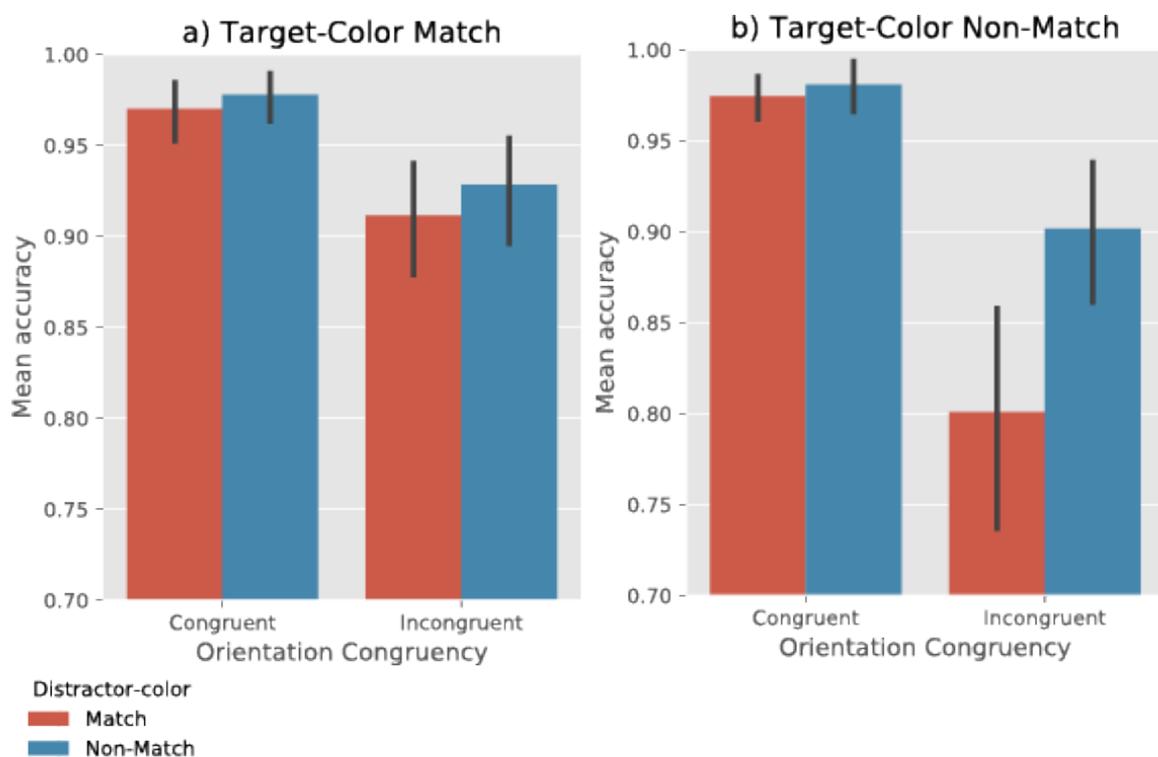
303 Similar to Experiment 1, the RT distribution of the Both-Target-Match trials was  
304 equally wide as that of the Non-Match trials ( $BF_{10} = 4.046$ ), as predicted by the MIT hypothesis.

### 305 Accuracy

306 Analysis showed very strong evidence for the effect of Target-Color-Match ( $BF_{10} =$   
307 39.973) and Distractor-Color-Match ( $BF_{10} = 53.291$ ), revealing that the overall accuracy was  
308 higher when the target matched the memory color, and lower when the distractor matched the  
309 memory color (*Figure 6*). Moreover, there was a main effect of Orientation-Congruency ( $BF_{10}$

310 =  $1.186 \times 10^6$ ), showing that search performance was more accurate when the line-segment  
311 orientation in a target was congruent with that in a distractor, compared to when they were  
312 incongruent.

313 In addition, the results revealed very strong evidence for a Target-Color-Match  $\times$   
314 Orientation-Congruency interaction ( $BF_{10} = 261.620$ ), and substantial evidence for Distractor-  
315 Color-Match  $\times$  Orientation-Congruency interaction ( $BF_{10} = 8.154$ ). However, no three-way  
316 interaction (Target-Color-Match  $\times$  Distractor-Color-Match  $\times$  Orientation-Congruency) was  
317 found ( $BF_{10} = 2.739$ ).



318

319 *Figure 6.* Mean accuracy rate as a function of Target-Color-Match, Distractor-Color-Match,  
320 and Orientation-Congruency.

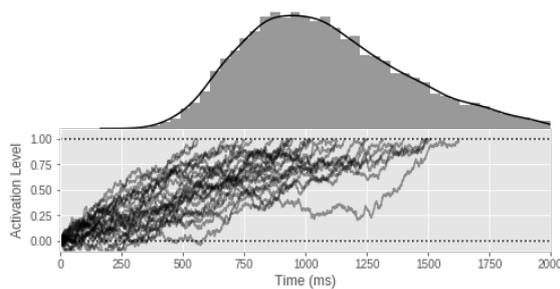
321 In this experiment, we observed faster overall RTs and stronger congruency effect than  
322 in Experiment 1. This suggests that the irrelevant (grey) distractor in Experiment 1 did attract  
323 attention, thus reducing overall performance. Nevertheless, we successfully replicated the

324 attentional guidance by the target and the distractor when they match the VWM colors.  
325 Importantly, we found that when the target matched the VWM item, the congruency effect  
326 largely disappeared. This robust guidance by the memory-matching item is in line with the  
327 MIT hypothesis.

### 328 **Drift-diffusion modeling**

329 As described above, the distribution of correct RTs is very similar for the Non-Color-  
330 Match and Both-Color-Match trials; this favors the Multiple-Item-Template (MIT) hypothesis  
331 over the Single-Item-Template (SIT) hypothesis. However, we wanted to compare the  
332 predictions that both hypotheses make about RT distributions more rigorously.

333 To do so, we used a one-sided drift-diffusion model to simulate RTs and to fit the  
334 distribution of correct RTs. The model simulates an Activation Level that changes over time,  
335 using four parameters: A Threshold, a Drift Rate, a Noise Level, and a Timeout. At time 0, the  
336 Activation Level is 0. At time 1, the Activation Level is incremented by the Drift Rate, as well  
337 as by a value that is randomly sampled from a normal distribution with a standard deviation  
338 that is equal to the Noise Level. Because we constrain the Drift Rate in our model to be a  
339 positive value, the Activation Level increases over time, although with an element of  
340 randomness. The point in time at which the Activation Level reaches the threshold is taken as  
341 the simulated RT. If the Activation Level has not reached a Threshold after a Timeout number  
342 of samples, the simulation is started again, until a valid RT is simulated. A higher Drift Rate  
343 results, on average, in lower simulated RTs. A higher Noise Level results in more variable  
344 simulated RTs.



345 *Figure 7.* An illustration of the single-sided drift-diffusion model. The lower part shows how  
346 the Activation Level evolves over time, until it exceeds a Threshold. The upper part shows  
347 the resulting distribution of simulated RTs.

348 The Threshold was set to a constant value of 1. The Timeout was set to a constant value  
349 of 2000, corresponding to the 2000ms timeout in our experiments. The Drift Rate and Noise  
350 Level were determined for each participant separately, by taking all the correct RTs for a given  
351 participant, and rank-ordering them from fast to slow. Next, we simulated the same number of  
352 RTs, using a candidate pair of values for the Drift Rate and Noise Level, and similarly rank-  
353 ordered these simulated RTs. We then took the residual sum of squares (RSS) of the real and  
354 simulated RTs. The Drift Rate and Noise Level were then chosen such that they minimized the  
355 RSS for a given participant.

356 Next, we constructed two models that embodied the predictions of the MIT and SIT  
357 hypotheses. To do so, we added one additional parameter, Drift Rate Change, which was added  
358 to the basic Drift Rate to simulate the reduced RTs (facilitation) when attention was guided by  
359 the Target, and subtracted from the basic Drift Rate to simulate the increased RTs (interference)  
360 when attention was guided by the Colored Distractor.

361 The MIT and SIT hypotheses make slightly different predictions about the Drift Rate  
362 in the different conditions (Table 1). In a nutshell, the MIT hypothesis predicts that a Target  
363 Match should result in facilitation on every trial, and that a Distractor Match should result in  
364 interference on every trial, and that the two should cancel each other out on Both Match trials.

363 In contrast, the SIT hypothesis predicts that a Target Match should result in facilitation on only  
 364 50% of trials, because only one of the two VWM items serves as an attentional template, and  
 365 thus the probability of the Target matching the attentional template is only 50%. For the same  
 366 reason, a Distractor Match should result in interference on only 50% of trials, and the Both  
 367 Match condition should be a mixture of 50% facilitation and 50% interference.

Table 1

*The Drift Rate in each condition as predicted by the MIT and SIT hypotheses. The percentages indicate the percentage of trials on which the Drift Rate has a particular value.*

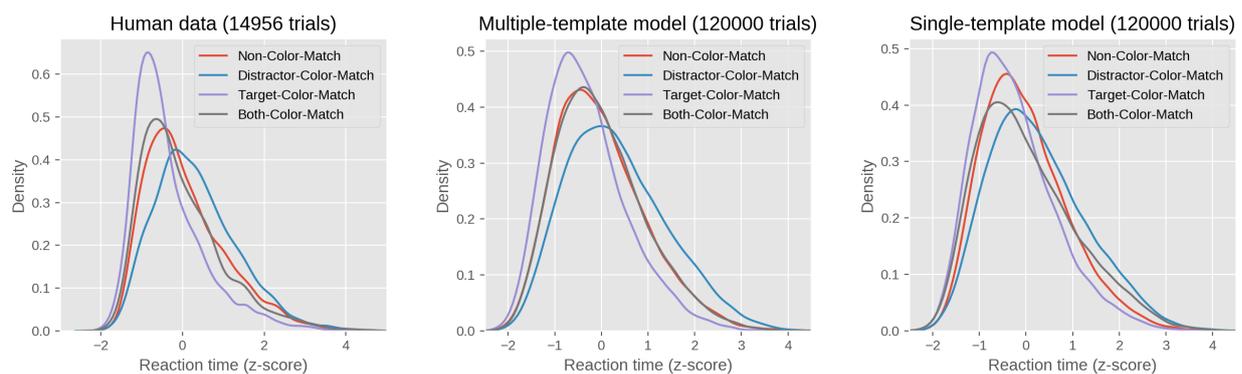
<b>Trial Type</b>	<b>MIT hypothesis</b>	<b>SIT hypothesis</b>
Non-Color-Match	100%: Drift Rate	100%: Drift Rate
Target-Color-Match	100%: Drift Rate + Drift Rate Change	50%: Drift Rate + Drift Rate Change 50%: Drift Rate
Distractor-Color-Match	100%: Drift Rate - Drift Rate Change	50%: Drift Rate - Drift Rate Change 50%: Drift Rate
Both-Color-Match	100%: Drift Rate	50%: Drift Rate + Drift Rate Change 50%: Drift Rate - Drift Rate Change

368

369 For each participant separately, and for the MIT and SIT hypotheses separately, we then  
 370 determined the Drift Rate Change parameter, while keeping the other parameters as previously  
 371 determined. This was done by taking all the correct RTs for a given participant, ordering them  
 372 first by trial type (Non-Color Match, Target Color-Match, Distractor-Color-Match, Both-Color-  
 373 Match) and then rank-ordering them from fast to slow within each Condition. We then  
 374 simulated the same number of RTs, using a candidate value for the Drift Rate Change, and

375 similarly ordered these simulated RTs. The Drift Rate Change was then chosen such that it  
376 minimized the RSS between the real and simulated RTs.

377 To test which hypothesis could best account for the data, we compared the RSS for the  
378 MIT hypothesis with the RSS for the SIT hypothesis with a default Bayesian two-sided paired-  
379 samples t-test. This revealed ‘extreme’ evidence ( $BF_{10} = 52,874$ ) in favor of the MIT  
380 hypothesis. To qualitatively compare the MIT and SIT hypothesis to the human data, we  
381 generated RT distributions, which were z-scored for each participant for visualization. As  
382 shown in *Figure 8*, the MIT hypothesis characterizes the human data much better than the SIT  
383 hypothesis does.



384 *Figure 8.* a) Distribution of correct RTs for the human participants (kernel-density estimates; z-  
scored per participant). b) Distribution of RTs simulated by the Multiple Item Template (MIT)  
385 hypothesis. c) Distribution of RTs simulated by the Single-Item-Template (SIT) hypothesis.

## 385 **General Discussion**

386 Here we report that multiple working-memory representations guide attention  
387 concurrently, thus providing crucial behavioral evidence for a long-standing debate in the field  
388 of visual working memory (VWM). In our experiments, participants remembered two colors.  
389 Next, they performed a visual-search task in which the color of the target and that of a distractor  
390 could match, or not match, a color in VWM. We found that search was faster when there was

391 a target-color match, showing that attention was guided towards memory-matching targets;  
392 similarly, we found that search was slower when there was a distractor-color match, showing  
393 that attention was (mis)guided towards memory-matching distractors.

394 To further test the predictions of the MIT and SIT hypotheses, the orientation of the  
395 line-segment inside the search target was manipulated to be either the same (i.e., congruent) or  
396 opposite (i.e., incongruent) to the line segment inside the distractor. Overall, this should result  
397 in an Orientation-Congruency effect, such that RTs are slowed on incongruent compared to  
398 congruent trials. However, the MIT and SIT hypotheses make different predictions about when  
399 this congruency effect should be strongest. Specifically, the MIT hypothesis predicts that the  
400 congruency effect should be strongest on both-match trials (i.e. when both the target and the  
401 distractor matched the memorized colors). This prediction follows because only in that case  
402 attention would be drawn simultaneously towards the distractor and the target, thus creating  
403 the strongest interference (and thus the strongest congruency effect) in that condition. The SIT  
404 hypothesis makes no such prediction, because on both-match trials, attention would be guided  
405 either by the target or by the distractor dependent on which of the colors was used as a template  
406 color, but not by both, and thus there is no reason to predict increased interference. Although,  
407 we did *not* find an increased congruency effect on both-match trials, we *did* find that the  
408 congruency effect was largely absent whenever there was a target match. This suggests that  
409 attention was guided towards the target on 100% of trials, so strongly even that interference by  
410 the orientation of the line-segment inside the distractor was largely absent. Although we did  
411 not predict this, it is consistent with the MIT hypothesis. However, this effect was present only  
412 in the RTs of Exp. 2, where the grey (irrelevant) distractor was removed. Therefore, this result  
413 should be interpreted with caution.

414           Additionally, we analyzed the RT distribution for both-match and no-match trials (i.e.  
415 when neither the target nor the distractor matched the memorized colors). The MIT hypothesis  
416 predicts that the distribution for both-match and no-match trials should be the same (or at least  
417 similar). This follows from the MIT hypothesis, because on both-match trials, the facilitation  
418 due to attention being guided towards the target and the interference due to attention being  
419 guided towards the distractor should cancel each other out. In contrast, the SIT hypothesis  
420 predicts a wider distribution for both-match trials than for no-match trials. This follows from  
421 the SIT hypothesis, because attention is guided either by the target or by the distractor in both-  
422 match trials (but never by both), thus resulting in a bimodal distribution that is wider than the  
423 distribution for no-match trials. Consistent with the MIT hypothesis, we found that the RT  
424 distribution for both-match trials resembled that for no-match trials. To confirm this  
425 conclusion, we simulated the individual trials of RTs based on the predictions of the MIT and  
426 the SIT hypothesis by means of a drift-diffusion model. Crucially, the observed data showed a  
427 better match to the simulated RTs based on the MIT hypothesis.

428           Taken together, our results provide evidence against the SIT hypothesis, which posits  
429 that there can only be one template active in working memory at one time to bias visual  
430 selection (van Moorselaar, Theeuwes, & Olivers, 2014; Olivers et al., 2011). And we show  
431 behavioral and computational evidence for simultaneous guidance of multiple VWM items,  
432 providing strong support for the MIT hypothesis.

433

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535 Availability of Data and Materials

536 All experimental data and materials can be found on the OSF (Open Science

537 Framework): <https://osf.io/knmu2/>

538