

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20

**Dense and uniform displays facilitate the detection of salient targets.**

**Dirk Kerzel (ORCID: 0000-0002-2466-5221)**

**Martin Constant (ORCID: 0000-0001-9574-0674)**

Faculté de Psychologie et des Sciences de l'Éducation  
Université de Genève

Abstract: 184 words

Main text: 4939 words

Figures: 4

Tables: 0

Running head: Detection of salient targets

Address:

Dirk Kerzel

Faculté de Psychologie et des Sciences de l'Éducation

Université de Genève

40 Boulevard du Pont d'Arve, 1205 Genève, Switzerland

Tel: +41 (0) 22 / 37.99.132 / Fax: +41 (0) 22 / 37.99.129

Email: [dirk.kerzel@unige.ch](mailto:dirk.kerzel@unige.ch)

21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43

**Abstract**

Increasing the density or uniformity of nontarget stimuli appears to increase the saliency of singleton stimuli. Consequently, search times should be shorter. Surprisingly, however, effects of density or uniformity on search times were not always observed in detection tasks. We re-examined this finding with stimuli having two features, color and shape. Half of the participants indicated the presence or absence of a color singleton, and the other half indicated the presence or absence of a shape singleton. Density was changed by increasing the number of stimuli from 4 to 10. We found that effects of density were either limited to target-absent trials or to target-present trials, which may explain previous failures to observe these effects. When color was the target feature, we found shorter RTs to dense than sparse displays on target-absent trials, but no difference on target-present trials. When shape was the target feature, it was the opposite. Concerning the uniformity of the nontargets, we found shorter RTs with uniform than mixed displays and this difference was larger on target-absent than target-present trials. These results are mostly consistent with the Guided Search Model.

**Keywords**

visual search, attentional selection, saliency

**Public Significance Statement**

A unique color or shape appears more salient when it is surrounded by many stimuli of the same kind rather than by few stimuli of several kinds. However, there is only mixed experimental evidence for this intuition so far. Here, we provide evidence by re-examining a search task where observers judged the presence or absence of a salient stimulus.

44

## Introduction

45           The visual system is flooded with information each time we open our eyes. As we  
46 cannot treat the available information, we are forced to select only a few from the many  
47 stimuli for further processing. The question is how selection is controlled. Major theories  
48 agree that visual selection is driven by both top-down and bottom-up signals (Desimone &  
49 Duncan, 1995; Eimer, 2014; Luck et al., 2021; Schneider, 2013; Wolfe, 2021). Top-down  
50 signals arise from the goals of the observer and implicit memory processes, such as inter-  
51 trial priming or reward learning. For instance, attention in a grocery store may be guided  
52 toward red stimuli because we are currently looking for strawberries (our current goal) or  
53 because we just searched for tomatoes (our former goal). Bottom-up signals arise from  
54 stimulus saliency (Duncan & Humphreys, 1989; Koch & Ullman, 1985; Nothdurft, 1993).  
55 Saliency is largely determined by local feature contrast along basic dimensions such as color,  
56 orientation, or size. For instance, a misplaced tomato on a pile of lemons is salient because  
57 of its color contrast. A classic finding is that search RTs for salient shape, orientation, and  
58 letter targets do not increase when the number of nontarget stimuli is increased (Egeth et  
59 al., 1972; Nothdurft, 1993; Sagi & Julesz, 1985; Treisman & Gelade, 1980). Surprisingly, the  
60 detection of oriented lines or gratings was even found to improve with the number of  
61 nontargets (Sagi, 1990; Zhaoping & Frith, 2011). For color, the situation is similar or even  
62 more complicated. Some studies found RTs with salient color targets to be unaffected by set  
63 size (Nothdurft, 1993; Treisman & Gelade, 1980), while others found RTs to increase  
64 logarithmically (Buetti et al., 2016; Buetti et al., 2019), and yet others found RTs to decrease  
65 (Bravo & Nakayama, 1992; Rangelov et al., 2017; Song & Nakayama, 2006).

### 66 **Elusive effects of set size in detection tasks**

67           The different results may be partially explained by the different tasks and designs  
68 that were employed. In a classic study, Bravo and Nakayama (1992) used a task where  
69 participants searched for a stimulus in a color different from the remaining stimuli. In some  
70 blocks of trials, the color of this singleton and the color of the nontargets was fixed. With  
71 fixed colors, the target feature remained the same from one trial to the next and attention  
72 may have been guided to the target by perceptual priming (Ramgir & Lamy, 2021).  
73 Therefore, RTs were short and set size did not play a role. In other blocks, singleton and  
74 nontarget colors were swapped randomly. With random targets, there was no perceptual  
75 priming. Rather, perceptual grouping (Duncan & Humphreys, 1989) was necessary to

76 separate the singleton from the nontarget stimuli (Song & Nakayama, 2006). Reliance on  
77 perceptual grouping made search susceptible to effects of set size. Interestingly, RTs  
78 decreased with large set sizes (see also Rangelov et al., 2013), probably because perceptual  
79 grouping works better for dense stimuli (Julesz, 1986; Koch & Ullman, 1985).

80 Further, decreasing RTs with increasing set size and color targets were reliably  
81 observed with discrimination tasks, but not with detection tasks (Bravo & Nakayama, 1992;  
82 Rangelov et al., 2017; Song & Nakayama, 2006). In detection tasks, it is sufficient to indicate  
83 the presence or absence of a target feature whereas discrimination tasks require decisions  
84 about which target feature is present. RTs are typically longer in discrimination than  
85 detection tasks because attention has to be focused on the target (Chan & Hayward, 2009;  
86 Nakayama & Mackeben, 1989; Treisman & Gelade, 1980) (but see Töllner et al., 2012). Thus,  
87 in Bravo and Nakayama (1992), decreasing RTs with increasing set size only occurred when  
88 there was no inter-trial priming and attention needed to be focused on the target (i.e., with  
89 random targets and a discrimination task). In contrast, RTs remained unchanged with inter-  
90 trial priming and mere detection of a feature discontinuity (i.e., with fixed targets and a  
91 detection task). The latter result is surprising because improved perceptual grouping with  
92 larger set sizes is expected to directly affect the magnitude of the feature discontinuity and  
93 should speed its detection.

94 In the present contribution, we re-examine the mixed results observed in detection  
95 tasks. To this end, we manipulated two variables (see Figure 1). First, we manipulated the set  
96 size between 4 and 10 stimuli. With 10 stimuli, density was higher and perceptual grouping  
97 is expected to be improved (Julesz, 1986; Koch & Ullman, 1985; Sagi, 1990). Therefore,  
98 search RTs are expected to decrease from set size 4 to 10, which would mean that search  
99 slopes are negative. Second, we manipulated the uniformity of the nontargets because  
100 similar grouping mechanisms are at play as in manipulations of set size. Nontarget stimuli  
101 group more easily when the irrelevant feature is uniform because of increased similarity  
102 (Duncan & Humphreys, 1989). Therefore, search RTs are expected to be shorter with  
103 uniform than mixed search displays. It should be mentioned that grouping by proximity  
104 (resulting from increased set size) and similarity (resulting from uniformity) has also been  
105 conceived as iso-feature suppression (Li, 1999), which makes similar predictions as grouping  
106 by similarity and proximity. Note, however, that the following analysis shows that effects of  
107 set size and uniformity may be different for target-present and target-absent trials.

**108 The Guided Search Model**

109 To re-examine the mixed results observed in detection tasks, the Guided Search  
110 Model (Chun & Wolfe, 1996; Wolfe, 1994) is ideally suited because it has applied ideas from  
111 signal detection theory to visual search. That is, it was conceived to model performance  
112 specifically in detection tasks. Importantly, Guided Search can accommodate both efficient  
113 (parallel) and inefficient (serial) search even though it has been mostly applied to inefficient  
114 search. Figure 2 shows an adapted version of the model where search is efficient. The model  
115 assumes that nontarget and target stimuli result in variable activations, which can be  
116 summarized by two normal distributions, one for nontarget stimuli and the other for target  
117 stimuli. The large separation between the distributions indicates that the target is salient  
118 and can be detected irrespective of the number of nontarget stimuli (i.e., flat search slopes).  
119 In serial search, the two distributions would be closer together, and search RTs would  
120 increase with the number of nontargets (i.e., search slopes larger than zero). According to  
121 the model, search slopes on target-absent and target-present trials are determined by the  
122 activation threshold and the average target activation, respectively. The activation threshold  
123 corresponds to the minimal activation of a nontarget stimulus that triggers inspection of this  
124 item. On target-absent trials, these items need to be inspected to reach the decision that the  
125 target is indeed absent. On target-present trials, nontarget stimuli with activations larger  
126 than the average target activation need to be inspected to make sure that they are not the  
127 target.

128 In the model, the proportion of the distribution to the right of the activation  
129 threshold determines the search slopes on target-absent trials, whereas the proportion of  
130 the distribution to the right of the average target activation determines the search slopes on  
131 target-present trials (see Figure 4 in Wolfe, 1994). That is, these slopes would typically  
132 determine how much RTs increase from set size 4 to 10. Here, we expect RTs to decrease  
133 from set size 4 to set size 10, which would mean search slopes are negative. These negative  
134 search slopes cannot be explained by a single distribution of nontarget activations because  
135 the proportion to the right of the activation threshold or average target activation cannot be  
136 negative. Therefore, we suggest that nontarget activations are lower with set size 10 or  
137 uniform stimuli. The resulting shift of the distribution of nontarget activations would  
138 decrease the proportion to the right of the activation threshold or average target activation,  
139 which explains the shorter search times with dense or uniform stimuli. Thus, a shift of the

140 distribution of nontarget activations is proposed as an explanation for negative search  
141 slopes.

## 142 **Hypotheses**

143 Inspection of Figure 2 shows that the presumed shift of the distribution of nontarget  
144 activations affects target-absent decisions more strongly than target-present decisions. The  
145 reason is that the part of the distribution of nontarget activations is larger to the right of the  
146 activation threshold than to the right of the average target activation. Therefore, target-  
147 absent decisions are expected to be more sensitive to shifts in the distribution of nontarget  
148 activations. That is, we expect stronger effects of set size or uniformity on target-absent  
149 than target-present trials, which should be visible in interactions of target presence  $\times$  set size  
150 and target presence  $\times$  uniformity.

151 We tested these predictions for two feature dimensions using combined shape-color  
152 stimuli. In the color task, we presented search displays where the target singleton was  
153 defined by color, and shape was irrelevant. In the shape task, it was the other way around.  
154 Both color and shape singletons are expected to result in efficient search, but previous  
155 works using similar stimuli found search times to be slower for shape than color singletons  
156 (Kerzel & Schonhammer, 2013; Theeuwes, 1992). As can be seen in Figure 2, the target  
157 activations may be higher for color than shape. However, predictions regarding target-  
158 absent responses are the same because the separation of target and nontarget activations is  
159 still large.

## 160 **Experiment**

161 The task of the participants was to indicate whether a singleton was present or  
162 absent. The stimuli in the search arrays had two features: color and shape. In the color task,  
163 color was relevant, and participants indicated whether there was a color singleton. In the  
164 shape task, shape was relevant, and participants indicated whether there was a shape  
165 singleton. The set size was either 4 or 10 stimuli. The irrelevant nontarget feature (i.e., shape  
166 in the color task and color in the shape task) could be either mixed or uniform. High set size  
167 and uniform nontargets are expected to facilitate grouping of nontargets, which should  
168 decrease the activation by nontarget stimuli. Therefore, we expect RTs to be shorter with  
169 high set size (i.e., negative search slopes) and uniform shapes. Importantly, effects of set size  
170 and uniformity are expected to be larger on target-absent than target-present trials.

## 171 **Methods**

172           **Participants.** First-year psychology students at the University of Geneva participated  
173 for class credit. We aimed at a sample size that would allow us to detect medium effect  
174 sizes. According to G\*Power 3.1 (Faul et al., 2009), a sample size of 32 was sufficient to find  
175 effect sizes with Cohen's  $d_z$  of 0.51 (power = .80, alpha = .05). Therefore, we aimed at 32  
176 participants per group of participants. In the group performing the color task, one dataset  
177 had to be removed because the overall error rate was much higher than in the remaining  
178 sample (12% vs.  $M = 3.8\%$ ,  $SD = 1.9$ ), leaving 31 datasets for analysis (2 men; age:  $M = 21$ ,  $SD$   
179 = 5). In the group performing the shape task, the data from two participants with very long  
180 RTs were replaced (826 and 836 ms vs.  $M = 519$  ms,  $SD = 40$ ) and one participant was  
181 removed because of a very high error rate (11% vs.  $M = 4.6\%$ ,  $SD = 1.8$ ), leaving 31 datasets  
182 for analysis (4 men; age:  $M = 20$ ,  $SD = 4$ ). All students reported normal or corrected-to-  
183 normal vision. The study was approved by the ethics committee of the Faculty of Psychology  
184 and Educational Sciences and was carried out in accordance with the Code of Ethics of the  
185 World Medical Association (Declaration of Helsinki). Informed consent was given before the  
186 experiment started.

187           **Apparatus.** A 22.5-inch VIEWPixx Lite monitor (100 Hz, 1,920 × 1,200 pixels, standard  
188 backlight; VPixx Technologies Inc., Saint-Bruno, Canada) was used to present the stimuli.  
189 Color calibration was based on measurements with an i1Display Pro (VPixx Edition)  
190 colorimeter by X-Rite (Grand Rapids, Michigan, United States). Participants responded on a  
191 RESPONSEPixx Handheld 5-button response box (VPixx Technologies Inc., Saint-Bruno,  
192 Canada) using the left and right buttons. The experiment was run using the Psychtoolbox  
193 (Brainard, 1997; Kleiner et al., 2007).

194           **Stimuli.** Unless otherwise noted, a light gray fixation cross ( $0.5^\circ \times 0.5^\circ$ , 48.8 cd/m<sup>2</sup>)  
195 was shown in the center of the screen. The search displays consisted of 4 or 10 geometric  
196 shapes shown at an eccentricity of  $3.5^\circ$ . The shapes were equidistant but rotated randomly  
197 around fixation. The shapes were drawn in  $0.07^\circ$ -wide lines. The dimensions of the shapes  
198 were as follows. The circle and diamond had diameters of  $1.5^\circ$  and  $1.7^\circ$ , respectively. The  
199 triangle and square had side lengths of  $1.6^\circ$  and  $1.3^\circ$ , respectively. Color and luminance of  
200 the stimuli are indicated in CIE1931 xyY-coordinates. The xy-coordinates of the stimuli were  
201 red = (0.44, 0.27), yellow = (0.45, 0.48), green = (0.19, 0.39), and blue = (0.17, 0.18). The  
202 luminance was always  $Y = 48.8$  cd/m<sup>2</sup>. The four colors correspond to  $0^\circ$ ,  $90^\circ$ ,  $180^\circ$ , and  $270^\circ$

203 of rotation on a color wheel in a CIELAB-based color space with a luminance of  $L^* = 59$  and a  
204 saturation of 64. The background was gray = (0.31, 0.33) with a luminance of  $Y = 24.4 \text{ cd/m}^2$ .

205 **Procedure.** Trials started with a randomly determined fixation period of 750 – 1,250  
206 ms. Then, the search display was presented for 150 ms. Participants were asked to press one  
207 of two keys to indicate the presence or absence of a target singleton. They were told to  
208 respond as rapidly as possible while keeping the error rate below 10%. Performance  
209 feedback was given after blocks of 80 trials in a self-terminated break of at least 2,000 ms.  
210 Visual error feedback was given immediately after choice errors or RTs outside the response  
211 window of 2,000 ms.

212 **Design.** Three independent variables were within-participants, and one was between  
213 participants. For each participant, the target was either present or absent, the set size was  
214 either 4 or 10, and the irrelevant feature in the search display was either mixed or uniform.  
215 The eight conditions resulting from the combination of the three variables were presented  
216 once in each of 120 mini-blocks for a total of 960 trials. The task was manipulated between  
217 participants.

218 One group of participants searched for a color singleton and indicated its presence or  
219 absence. Target and nontarget colors were opponents in color space (i.e., red-green, green-  
220 red, yellow-blue, blue-yellow). The irrelevant shape feature could be either mixed or  
221 uniform. On trials with mixed shapes, each of the four shapes (circle, square, diamond,  
222 triangle) was presented once when the set size was four and 2-3 times when the set size was  
223 ten. On trials with uniform shape, all stimuli were the same shape.

224 Another group of participants searched for a shape singleton and indicated its  
225 presence or absence. To maximize the difference between target and nontarget shapes, we  
226 created four shape pairs, in analogy to the opponent colors (i.e., circle-diamond, diamond-  
227 circle, triangle-square, square-triangle). The irrelevant color feature could be either mixed or  
228 uniform. On trials with mixed colors, each of the four colors (red, green, yellow, blue) was  
229 presented once when the set size was four and 2-3 times when the set size was ten. On trials  
230 with uniform color, all stimuli were the same color.

231 The irrelevant feature on uniform trials, the distribution of irrelevant features on  
232 mixed trials, and the target position on target-present trials were random with the indicated  
233 constraints. Finally, the mapping of the left and right response keys to target-absent and -



234 present responses was counterbalanced across participants. At least 40 practice trials were  
235 performed before the experiment started.

## 236 Results

237 The data are available in the Open Science Framework at <https://osf.io/m87qj/>. We  
238 removed trials with false alarms (color task: 3.8%, shape task: 4.4%), misses (color task:  
239 3.5%, shape task: 4.8%) and RTs outside the response window of 2,000 ms (color task: 0.1%,  
240 shape task: 0.1%). Because the analysis of RTs with shape targets was susceptible to outlier  
241 removal criteria, we used medians instead of means for all RT analyses. Error percentages  
242 were below 5% and were analyzed separately. For these analyses, we considered only the  
243 mean percentage of choice errors. To correct the significance of multiple t-tests, we  
244 controlled for false discovery rate according to Benjamini and Hochberg (1995). For clarity,  
245 we report the uncorrected  $p$ -values. Significant results remain significant after correction  
246 unless otherwise noted.

247 **Reaction times.** We conducted a 2 (task: color, shape)  $\times$  2 (target presence: present,  
248 absent)  $\times$  2 (set size: 4, 10)  $\times$  2 (uniformity of nontargets: mixed, uniform) mixed ANOVA. We  
249 predicted that effects of set size and uniformity should affect target-absent responses more  
250 strongly than target-present responses. Statistical support for this hypothesis would come  
251 from the following two-way interactions: (1) the interaction between target presence and  
252 set size (2) the interaction between target presence and uniformity of the nontargets.

253 Unexpectedly, the nature of the two-way interaction between target presence and  
254 set size changed with the task, as evidenced by a significant three-way interaction (see  
255 Figure 3),  $F(1, 60) = 14.62, p < .001, \eta_p^2 = .196$ . In the color task, RTs were about the same for  
256 set size 4 and 10 when the target was present (475 vs. 476 ms),  $t(30) = 0.44, p = .660$ ,  
257 Cohen's  $d_z = 0.08$ , but were 7 ms longer with set size 4 than 10 when the target was absent  
258 (478 vs. 471 ms),  $t(30) = 3.52, p = .001, d_z = 0.63$ . Stronger effects of set size on target-absent  
259 than target-present trials are consistent with predictions of the Guided Search Model. In the  
260 shape task, however, RTs were about the same for set sizes 4 and 10 when the target was  
261 absent (507 vs. 508 ms),  $t(30) = 0.47, p = .640, d_z = 0.09$ , but were 6 ms longer with set size 4  
262 than 10 when the target was present (531 vs. 526 ms),  $t(30) = 2.46, p = .020, d_z = 0.44$ . This  
263 pattern is opposite to predictions of the Guided Search Model. Thus, effects of set size were  
264 expected to be more pronounced on target-absent than -present trials, but we found this  
265 pattern only for the color task and the opposite pattern for the shape task.

266 The two-way interaction of target presence and uniformity of the nontargets was  
 267 significant (see Figure 4),  $F(1, 60) = 4.92, p = .030, \eta_p^2 = .076$ . Unlike in the preceding analysis,  
 268 the two-way interaction was not further qualified by task,  $F(1, 60) = 1.17, p = .284, \eta_p^2 = .019$ .  
 269 On target-present trials across both tasks, RTs were 6 ms longer with mixed than uniform  
 270 nontargets (505 vs. 499 ms),  $t(61) = 5.00, p < .001, d_z = 0.55$ . This difference was greater (12  
 271 ms) on target-absent trials (497 vs. 485 ms),  $t(61) = 6.09, p < .001, d_z = 0.77$ , which is  
 272 consistent with predictions from the Guided Search Model.

273 In addition to the results speaking to our experimental hypotheses, there were  
 274 several other results. The effect of target presence,  $F(1, 60) = 10.86, p = .002, \eta_p^2 = .153$ , was  
 275 modulated by task,  $F(1, 60) = 8.56, p = .005, \eta_p^2 = .125$ . In the color task, RTs were about the  
 276 same on target-present and -absent trials (475 vs. 474 ms),  $t(30) = 0.23, p = .819, d_z = 0.04$ . In  
 277 contrast, in the shape task, RTs were 22 ms shorter on target-absent than -present trials  
 278 (507 vs. 529 ms),  $t(30) = 4.72, p < .001, d_z = 0.85$ , which is odd as RTs are typically longer on  
 279 target-absent than -present trials. We will return to this result in the General Discussion.  
 280 Further, RTs in the color task were shorter than in the shape task (476 vs. 519 ms),  $F(1, 60) =$   
 281  $14.05, p < .001, \eta_p^2 = .190$ , which is visible in the smaller offset of the y-axis in Figure 3. Also,  
 282 RTs with set size 4 were longer than with set size 10 (499 vs. 496 ms),  $F(1, 60) = 6.12, p =$   
 283  $.016, \eta_p^2 = .093$ . Note that the main effects of set size and task as well as the two-way  
 284 interaction of task and target presence were further qualified by the three-way interaction  
 285 of task, set size, and target presence, which we described above (see also Figure 3). Further,  
 286 there was an effect of nontarget uniformity (see also Figure 4),  $F(1, 60) = 62.97, p < .001, \eta_p^2 =$   
 287  $.512$ , which was modulated by task,  $F(1, 60) = 19.38, p < .001, \eta_p^2 = .244$ . In the color task,  
 288 RTs were 3 ms longer on trials with mixed than uniform nontargets (477 vs. 474 ms),  $t(30) =$   
 289  $2.79, p = .009, d_z = 0.50$ . In the shape task, this difference increased to 14 ms (526 vs. 512  
 290 ms),  $t(30) = 7.71, p < .001, d_z = 1.38$ .

291 **Choice Errors.** To check for speed-accuracy tradeoff, we conducted the same ANOVA  
 292 as above on the percentage of choice errors. We found that effects on error percentages  
 293 were small and mostly mirrored RTs. The relevant three-way interaction of task, set size, and  
 294 target presence, which we observed in RTs, was not significant in the analysis of errors,  $F(1,$   
 295  $60) = 0.75, p = .390, \eta_p^2 = .012$ , ruling out speed-accuracy tradeoff. Concerning the relevant  
 296 two-way interaction of nontarget uniformity and target presence, we confirmed the same  
 297 interaction in error percentages as in RTs,  $F(1, 60) = 4.90, p = .031, \eta_p^2 = .075$ . Error

298 percentages on target-present trials were about the same with mixed and uniform  
 299 nontargets (4.1% vs. 4.3%),  $t(61) = 1.05$ ,  $p = .300$ ,  $d_z = 0.13$ , but on target-absent trials, error  
 300 percentages were higher with mixed than uniform nontargets (4.4% vs. 3.8%),  $t(61) = 2.18$ ,  $p$   
 301  $= .033$ ,  $d_z = 0.28$ .

302 In addition to the results speaking to our hypothesis, there were several other  
 303 results. Consistent with the analysis of RTs, error percentages tended to be lower in the  
 304 color than in the shape task (3.6% vs. 4.6%),  $F(1, 60) = 4.63$ ,  $p = .036$ ,  $\eta_p^2 = .072$ . The  
 305 interaction of target presence and set size,  $F(1, 60) = 20.09$ ,  $p < .001$ ,  $\eta_p^2 = .251$ , showed that  
 306 error percentages on target-present trials were lower with set size 4 than 10 (3.7% vs. 4.7%),  
 307  $t(61) = 3.64$ ,  $p < .001$ ,  $d_z = 0.46$ , but on target-absent trials, error percentages were higher  
 308 with set size 4 than 10 (4.6% vs. 3.6%),  $t(61) = -3.15$ ,  $p < .001$ ,  $d_z = 0.40$ . The interaction of  
 309 task and nontarget uniformity,  $F(1, 60) = 6.88$ ,  $p = .011$ ,  $\eta_p^2 = .103$ , showed that in the color  
 310 task, error percentages were about the same with mixed and uniform shapes (3.5% vs.  
 311 3.8%),  $t(30) = 1.15$ ,  $p = .258$ ,  $d_z = 0.21$ , whereas in the shape task, error percentages were  
 312 higher with mixed than uniform colors (4.9% vs. 4.4%),  $t(30) = 2.61$ ,  $p = .014$ ,  $d_z = 0.47$ .

### 313 Discussion

314 We examined effects of set size and uniformity on singleton search. Perceptual  
 315 grouping of nontargets is facilitated with high set size because of increased density (Julesz,  
 316 1986; Koch & Ullman, 1985) and with uniformity because of increased similarity (Duncan &  
 317 Humphreys, 1989). As a result, search times should decrease with high set size or uniform  
 318 nontargets. However, these effects were not always observed in detection tasks. To better  
 319 understand the mixed results, we derived more detailed predictions about target-present  
 320 and -absent trials from the Guided Search Model (Chun & Wolfe, 1996; Wolfe, 1994).

321 We started from the assumption that the expected decrease of RTs with high set size  
 322 was accounted for by a shift of the distribution of nontarget activations. That is, nontarget  
 323 activations are expected to be lower with set size 10 than 4, possibly because of iso-feature  
 324 suppression (Li, 1999). Similarly, nontarget activations are expected to be lower with  
 325 uniform than mixed nontargets. According to the Guided Search Model, the effects of a shift  
 326 in the distribution of nontarget activations should be stronger on target-absent than target-  
 327 present trials (see Figure 2). That is, RTs are expected to decrease with set size 10 or with  
 328 uniform nontargets, but more strongly so when the target is absent. Our results were mostly  
 329 consistent with this prediction. For nontarget uniformity, we found shorter RTs with uniform

330 than mixed nontargets and consistent with our predictions, this difference was more  
331 pronounced on target-absent than -present trials. For effects of set size, however, the  
332 results were mixed and depended on the task. In the color task, we found shorter RTs with  
333 set size 10 on target-absent trials, but not on target-present trials, which is consistent with  
334 our predictions. In the shape task, however, shorter RTs with set size 10 were observed for  
335 target-present trials, but not for target-absent trials, which is inconsistent with our  
336 predictions. Thus, predictions derived from the Guided Search Model were confirmed with  
337 one exception, which is that, in the shape task, the effect of set size was observed on target-  
338 present and not on target-absent trials (see Figure 3).

339 While at odds with the model presented in Figure 2, there may be an explanation  
340 related to an anomaly in the search RTs. As reported above, RTs were shorter on target-  
341 absent than target-present trials in the task producing the inconsistent result. Shorter RTs on  
342 target-absent than -present trials are surprising because if anything, previous research found  
343 RTs to be longer on target-absent trials (e. g., Treisman & Gelade, 1980; Wolfe, 1994).  
344 Possibly, target-present responses in the shape task required an additional processing stage,  
345 namely identification (Eimer, 2014; Wolfe, 2021), contrary to the typical requirements of a  
346 detection task. That is, the selected shape singleton had to be compared to an internal  
347 template of the target to decide that it was indeed a shape singleton. As a result, RTs  
348 increased on target-present trials. Target identification may have been necessary because  
349 the color variations in mixed displays were very salient (see lower part of Figure 1). To avoid  
350 false positive responses to variations in color, the shape singleton in the shape task may  
351 have been more thoroughly inspected than the color singleton in the color task. If  
352 identification is admitted as an explanation for the longer RTs on target-present trials, then  
353 the effect of set size on these trials may result from facilitated identification of the shape  
354 singleton in dense compared to sparse displays. Possibly, this is the reason why predictions  
355 of the Guided Search Model were not confirmed, but the exact mechanisms remain unclear.

### 356 **Relation to the attentional window account**

357 Further, our results are of interest to the attentional window account. The  
358 attentional window account was proposed by Theeuwes (2004) in the context of the  
359 additional singleton paradigm. In the original version of the additional singleton paradigm  
360 (Theeuwes, 1992), color-shape stimuli as in the current experiment were used. Participants  
361 searched for a shape singleton and on some trials, an irrelevant color singleton was

362 presented. Search RTs were found to be longer on trials with a color singleton, suggesting  
363 that it captured attention (Theeuwes, 2010). However, interference from the color singleton  
364 disappeared when features on the relevant shape dimension were mixed (Bacon & Egeth,  
365 1994), which is referred to as feature search.

366         The difference between uniform and mixed shapes suggests that interference from  
367 the color singleton was restricted to singleton search. However, it may be that feature  
368 search was less efficient. That is, the number of stimuli that can be inspected simultaneously  
369 may be reduced and the color singleton would be frequently outside the “attentional  
370 window”, thereby reducing capture (Theeuwes, 2004). However, search slopes were found  
371 to be about equal for singleton and feature search (Kerzel & Barras, 2016; see also test  
372 phase in Leber & Egeth, 2006) and when singleton and feature search displays appeared  
373 unpredictably, search slopes were the same (Kerzel & Huynh Cong, 2022). In the current  
374 experiment, features could be mixed on the irrelevant dimension and were always uniform  
375 on the relevant dimension whereas in Bacon and Egeth’s (1994) feature search, it was the  
376 other way around. Nonetheless, the current results confirm that search slopes for a  
377 singleton target are unaffected by uniformity on the irrelevant dimension. There was no  
378 increase in search slopes with mixed features, even if mixed features resulted in a large  
379 increase in RTs (i.e., shape task). Thus, search did not become more effortful even though  
380 additional time was needed to process the stimuli.

381         Finally, our results speak against the assumption that the saliency of color singletons  
382 increases with increasing set size (Stilwell et al., 2022). In the context of the Guided Search  
383 Model, this corresponds to a shift of the distribution of target activations to the right, which  
384 should decrease RTs to color targets (Töllner et al., 2011). However, we found no effect of  
385 set size on target-present trials in the color task. Therefore, our results do not provide  
386 support for the idea that denser displays increase the saliency of color singletons. Rather,  
387 dense displays facilitate grouping and result in shorter RTs on target-absent trials, at least  
388 with color singleton targets and shape as irrelevant dimension.

### 389 **Conclusions**

390         In sum, we investigated effects of set size and uniformity on the detection of color or  
391 shape singletons. In the color task, we found that RTs were unaffected on target-present  
392 trials but were shorter with large set size on target-absent trials. These results are consistent  
393 with the Guided Search model, which considers the difference between activations from

394 nontarget and target stimuli as decisive for search RTs. Subtle differences in the distribution  
 395 of nontarget activations may affect target-absent trials more strongly than target-present  
 396 trials. For the shape task, however, we found the opposite. Set size influenced target-  
 397 present instead of target-absent trials, which is not consistent with the Guided Search  
 398 Model. However, it may be that this effect is related to the overall increased RTs on target-  
 399 present trials in the shape task. Finally, we found that effects of uniformity were more  
 400 pronounced on target-absent than present trials for both tasks, which is again consistent  
 401 with the Guided Search Model.

#### 402 Acknowledgments

403 DK was supported by grant No. 100019\_182146 from the Swiss National Science  
 404 Foundation. We wish to thank Sydney Annézo, Julia Benitez, Inès Lepreux, Mathieu Zaugg  
 405 and Quentin Zongo for running the experiment.

#### 406 References

- 407 Bacon, W. F., & Egeth, H. E. (1994). Overriding stimulus-driven attentional capture. *Perception &*  
 408 *Psychophysics*, 55(5), 485-496. <https://doi.org/10.3758/BF03205306>
- 409 Benjamini, Y., & Hochberg, Y. (1995). Controlling the false discovery rate: A practical and powerful  
 410 approach to multiple testing. *Journal of the Royal Statistical Society. Series B*  
 411 *(Methodological)*, 57(1), 289-300.
- 412 Brainard, D. H. (1997). The Psychophysics Toolbox. *Spatial Vision*, 10, 433-436.  
 413 <https://doi.org/10.1163/156856897x00357>
- 414 Bravo, M. J., & Nakayama, K. (1992). The role of attention in different visual-search tasks. *Perception*  
 415 *& Psychophysics*, 51(5), 465-472. <https://doi.org/10.3758/bf03211642>
- 416 Buetti, S., Cronin, D. A., Madison, A. M., Wang, Z., & Lleras, A. (2016). Towards a better  
 417 understanding of parallel visual processing in human vision: Evidence for exhaustive analysis  
 418 of visual information. *Journal of Experimental Psychology: General*, 145(6), 672-707.  
 419 <https://doi.org/10.1037/xge0000163>
- 420 Buetti, S., Xu, J., & Lleras, A. (2019). Predicting how color and shape combine in the human visual  
 421 system to direct attention. *Scientific Reports*, 9(1), 20258. [https://doi.org/10.1038/s41598-](https://doi.org/10.1038/s41598-019-56238-9)  
 422 [019-56238-9](https://doi.org/10.1038/s41598-019-56238-9)
- 423 Chan, L. K., & Hayward, W. G. (2009). Feature integration theory revisited: Dissociating feature  
 424 detection and attentional guidance in visual search. *Journal of Experimental Psychology:*  
 425 *Human Perception and Performance*, 35(1), 119-132. [https://doi.org/10.1037/0096-](https://doi.org/10.1037/0096-1523.35.1.119)  
 426 [1523.35.1.119](https://doi.org/10.1037/0096-1523.35.1.119)
- 427 Chun, M. M., & Wolfe, J. M. (1996). Just say no: How are visual searches terminated when there is no  
 428 target present? *Cognitive Psychology*, 30(1), 39-78. <https://doi.org/10.1006/cogp.1996.0002>
- 429 Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annual Review of*  
 430 *Neuroscience*, 18, 193-222. <https://doi.org/10.1146/annurev.ne.18.030195.001205>
- 431 Duncan, J., & Humphreys, G. W. (1989). Visual search and stimulus similarity. *Psychological Review*,  
 432 96, 433-458. <https://doi.org/10.1037/0033-295x.96.3.433>
- 433 Egeth, H., Jonides, J., & Wall, S. (1972). Parallel processing of multielement displays. *Cognitive*  
 434 *Psychology*, 3(4), 674-698. [https://doi.org/10.1016/0010-0285\(72\)90026-6](https://doi.org/10.1016/0010-0285(72)90026-6)
- 435 Eimer, M. (2014). The neural basis of attentional control in visual search. *Trends in Cognitive Sciences*,  
 436 18(10), 526-535. <https://doi.org/10.1016/j.tics.2014.05.005>

- 437 Faul, F., Erdfelder, E., Buchner, A., & Lang, A.-G. (2009). Statistical power analyses using G\*Power 3.1:  
 438 Tests for correlation and regression analyses. *Behavior Research Methods*, 41(4), 1149-1160.  
 439 <https://doi.org/10.3758/brm.41.4.1149>
- 440 Julesz, B. (1986). Texton gradients: the texton theory revisited. *Biological Cybernetics*, 54(4-5), 245-  
 441 251. <https://doi.org/10.1007/bf00318420>
- 442 Kerzel, D., & Barras, C. (2016). Distractor rejection in visual search breaks down with more than a  
 443 single distractor feature. *Journal of Experimental Psychology: Human Perception and*  
 444 *Performance*, 42(5), 648-657. <https://doi.org/10.1037/xhp0000180>
- 445 Kerzel, D., & Huynh Cong, S. (2022). Search mode, not the attentional window, determines the  
 446 magnitude of attentional capture. *Attention, Perception, & Psychophysics*.  
 447 <https://doi.org/10.3758/s13414-022-02582-4>
- 448 Kerzel, D., & Schonhammer, J. (2013). Salient stimuli capture attention and action. *Attention,*  
 449 *Perception, & Psychophysics*, 75(8), 1633-1643. <https://doi.org/10.3758/s13414-013-0512-3>
- 450 Kleiner, M., Brainard, D. H., & Pelli, D. (2007). What's new in Psychtoolbox-3? *Perception*, 36, 14-14.
- 451 Koch, C., & Ullman, S. (1985). Shifts in selective visual attention: Towards the underlying neural  
 452 circuitry. *Human Neurobiology*, 4(4), 219-227.  
 453 <https://www.ncbi.nlm.nih.gov/pubmed/3836989>
- 454 Leber, A. B., & Egeth, H. E. (2006). It's under control: Top-down search strategies can override  
 455 attentional capture. *Psychonomic Bulletin & Review*, 13(1), 132-138.  
 456 <https://doi.org/10.3758/BF03193824>
- 457 Li, Z. (1999). Contextual influences in V1 as a basis for pop out and asymmetry in visual search.  
 458 *Proceedings of the National Academy of Sciences of the United States of America*, 96(18),  
 459 10530-10535. <https://doi.org/10.1073/pnas.96.18.10530>
- 460 Luck, S. J., Gaspelin, N., Folk, C. L., Remington, R. W., & Theeuwes, J. (2021). Progress toward  
 461 resolving the attentional capture debate. *Visual Cognition*, 29(1), 1-21.  
 462 <https://doi.org/10.1080/13506285.2020.1848949>
- 463 Nakayama, K., & Mackeben, M. (1989). Sustained and transient components of focal visual attention.  
 464 *Vision Research*, 29(11), 1631-1647. [https://doi.org/10.1016/0042-6989\(89\)90144-2](https://doi.org/10.1016/0042-6989(89)90144-2)
- 465 Nothdurft, H. C. (1993). Saliency effects across dimensions in visual search. *Vision Research*, 33(5-6),  
 466 839-844. [https://doi.org/10.1016/0042-6989\(93\)90202-8](https://doi.org/10.1016/0042-6989(93)90202-8)
- 467 Ramgir, A., & Lamy, D. (2021). Does feature intertrial priming guide attention? The jury is still out.  
 468 *Psychonomic Bulletin & Review*. <https://doi.org/10.3758/s13423-021-01997-8>
- 469 Rangelov, D., Müller, H. J., & Zehetleitner, M. (2013). Visual search for feature singletons: Multiple  
 470 mechanisms produce sequence effects in visual search. *Journal of Vision*, 13(3).  
 471 <https://doi.org/10.1167/13.3.22>
- 472 Rangelov, D., Müller, H. J., & Zehetleitner, M. (2017). Failure to pop out: Feature singletons do not  
 473 capture attention under low signal-to-noise ratio conditions. *Journal of Experimental*  
 474 *Psychology: General*, 146(5), 651-671. <https://doi.org/10.1037/xge0000284>
- 475 Sagi, D. (1990). Detection of an orientation singularity in gabor textures: Effect of signal density and  
 476 spatial-frequency. *Vision Research*, 30(9), 1377-1388. [https://doi.org/10.1016/0042-6989\(90\)90011-9](https://doi.org/10.1016/0042-6989(90)90011-9)
- 477 Sagi, D., & Julesz, B. (1985). "Where" and "What" in Vision. *Science*, 228(4704), 1217-1219.  
 478 <https://doi.org/10.1126/science.4001937>
- 479 Schneider, W. X. (2013). Selective visual processing across competition episodes: A theory of task-  
 480 driven visual attention and working memory. *Philosophical Transactions of the Royal Society*  
 481 *B: Biological Sciences*, 368(1628). <https://doi.org/10.1098/rstb.2013.0060>
- 482 Song, J.-H., & Nakayama, K. (2006). Role of focal attention on latencies and trajectories of visually  
 483 guided manual pointing. *Journal of Vision*, 6(9). <https://doi.org/10.1167/6.9.11>
- 484 Stilwell, B. T., Egeth, H., & Gaspelin, N. (2022). Electrophysiological evidence for the suppression of  
 485 highly salient distractors. *Journal of Cognitive Neuroscience*, 34(5), 787-805.  
 486 <https://doi.org/10.1162/jocn.a.01827>

- 488 Theeuwes, J. (1992). Perceptual selectivity for color and form. *Perception & Psychophysics*, 51(6),  
489 599-606. <https://doi.org/10.3758/Bf03211656>
- 490 Theeuwes, J. (2004). Top-down search strategies cannot override attentional capture. *Psychonomic*  
491 *Bulletin & Review*, 11(1), 65-70. <https://doi.org/10.3758/bf03206462>
- 492 Theeuwes, J. (2010). Top-down and bottom-up control of visual selection. *Acta Psychologica*, 135(2),  
493 77-99. <https://doi.org/10.1016/j.actpsy.2010.02.006>
- 494 Töllner, T., Rangelov, D., & Müller, H. J. (2012). How the speed of motor-response decisions, but not  
495 focal-attentional selection, differs as a function of task set and target prevalence.  
496 *Proceedings of the National Academy of Sciences*, 109(28), E1990–E1999.  
497 <https://doi.org/10.1073/pnas.1206382109>
- 498 Töllner, T., Zehetleitner, M., Gramann, K., & Müller, H. J. (2011). Stimulus saliency modulates pre-  
499 attentive processing speed in human visual cortex. *PLoS One*, 6(1), e16276.  
500 <https://doi.org/10.1371/journal.pone.0016276>
- 501 Treisman, A. M., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*,  
502 12(1), 97-136. [https://doi.org/10.1016/0010-0285\(80\)90005-5](https://doi.org/10.1016/0010-0285(80)90005-5)
- 503 Wolfe, J. M. (1994). Guided Search 2.0 A revised model of visual search. *Psychonomic Bulletin &*  
504 *Review*, 1(2), 202-238. <https://doi.org/10.3758/BF03200774>
- 505 Wolfe, J. M. (2021). Guided Search 6.0: An updated model of visual search. *Psychonomic Bulletin &*  
506 *Review*, 28(4), 1060-1092. <https://doi.org/10.3758/s13423-020-01859-9>
- 507 Zhaoping, L., & Frith, U. (2011). A clash of bottom-up and top-down processes in visual search: The  
508 reversed letter effect revisited. *Journal of Experimental Psychology-Human Perception and*  
509 *Performance*, 37(4), 997-1006. <https://doi.org/10.1037/a0023099>

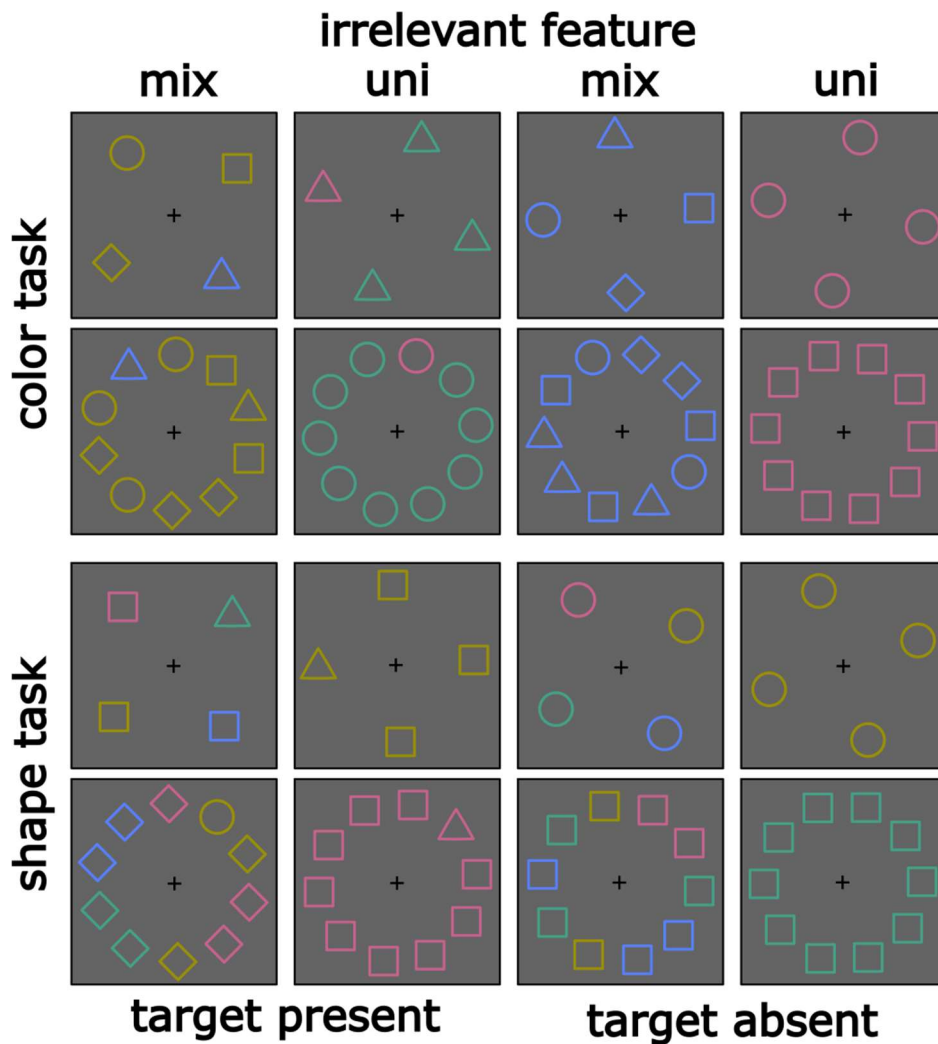
510



511 **Figure 1.**

512 *Illustration of the experimental stimuli.*

513



514

515

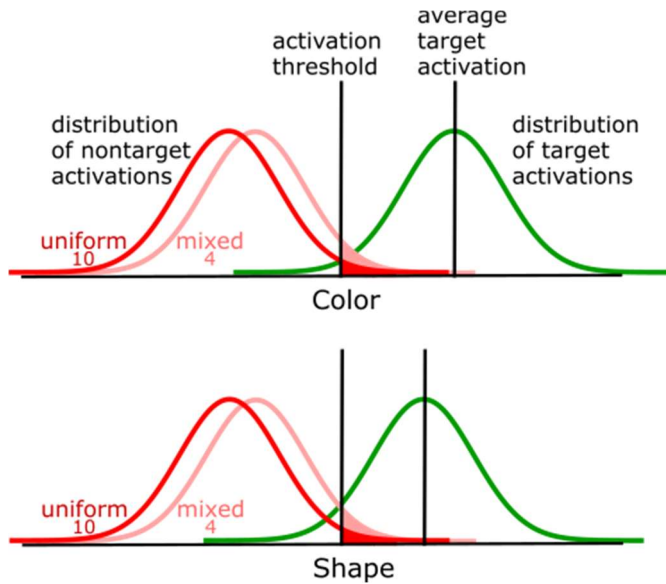
516 *Note.* Half of the participants searched for a color singleton and the other half for a shape  
 517 singleton (i.e., color and shape tasks). The irrelevant nontarget feature was shape in the  
 518 color task, and color in the shape task. The nontarget feature was either mixed or uniform.  
 519 The target was either present or absent and set size was either 4 or 10. mix = mixed, uni =  
 520 uniform.

521

522 **Figure 2.**

523 *Model of search reaction times for target-present and -absent trials (adapted from Chun &*  
 524 *Wolfe, 1996).*

525



526

527

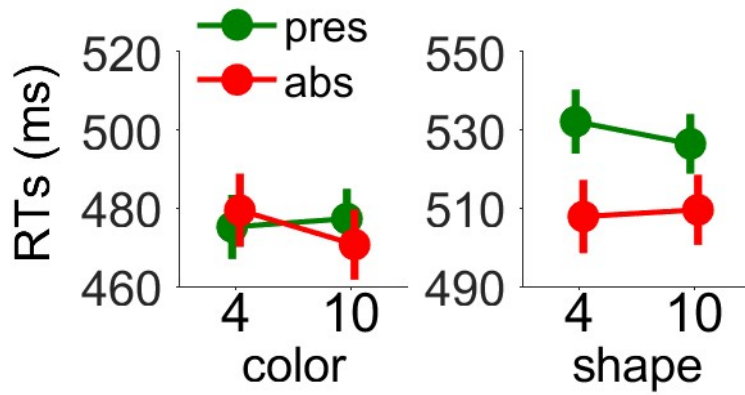
528 *Note.* Search RTs on target-absent trials are determined by the part of the distribution of  
 529 nontarget activations that lies to the right of the activation threshold. We assume that the  
 530 nontarget activations were lower for set size 10 than set size 4 and for uniform than mixed  
 531 shapes, which shifts the distribution to the left. The distance between nontarget and target  
 532 distributions may be larger in the color than the shape task (upper vs. lower panel). Note  
 533 that the model is simplified because the width of the distribution is likely to vary with the  
 534 activation level (Chun & Wolfe, 1996; Li, 1999; Wolfe, 1994).

535

536

537 **Figure 3.**

538 *The three-way interaction of task (color, shape), set size (4, 10), and target presence*  
 539 *(present, absent).*



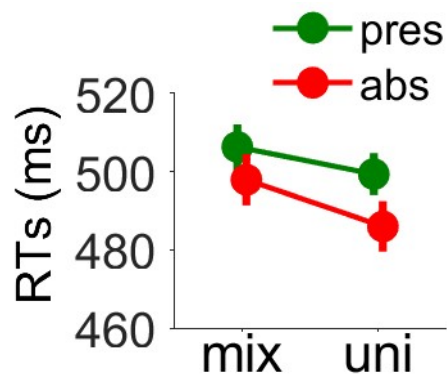
540

541 *Note.* The prediction was that reaction times (RTs) are longer with set size 4 than 10 and that  
 542 this difference is larger on target-absent than -present trials. We found this pattern only in  
 543 the color task (left graph). In the shape task (right graph), the longer RTs with set size 4 than  
 544 10 were observed on target-present trials, but not on target-absent trials. Error bars  
 545 represent one between-participant standard error. pres = present, abs = absent

546

547 **Figure 4.**

548 *The two-way interaction of uniformity of nontargets (mixed, uniform) with target presence*  
549 *(present, absent).*



550

551 *Note.* The prediction was that reaction times (RTs) are longer with mixed than uniform  
552 nontargets and that this difference is larger on target-absent than -present trials. The data  
553 confirm this prediction. Error bars represent one between-participant standard error. pres =  
554 present, abs = absent, mix = mixed, uni = uniform

555

556