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Trial history contributes to the optimal tuning of attention

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Abstract

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In visual search tasks, targets are difficult to find when they are similar to the surrounding nontargets. In this scenario, it is optimal to tune attention to target features that maximize the difference between target and nontargets. We investigated whether the optimal tuning of attention is driven by biases arising from previously attended stimuli (i.e., trial history). Consistent with effects of trial history, we found that optimal tuning was stronger when a single target-nontarget relation was repeated than when two target-nontarget relations alternated randomly. Detailed analysis of blocks with random alternation showed that optimal tuning was stronger when the target-nontarget relation probed on the current trial matched the relation on the previous trial. We evaluated several mechanisms that may underlie effects of trial history, such as priming of attentional set, switch costs, and sensory adaptation. However, none of the accounts was able to fully account for the pattern of results.

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Keywords

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visual search, attentional capture, optimal tuning, sensory adaptation

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Public Significance Statement

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Visual search is a common everyday activity. For instance, we often look for objects in a particular color. This task is difficult when the color of the target is similar to the surrounding colors. Observers perform surprisingly well in this situation, suggesting that they adjust attention optimally to maximize the difference between the color of the target and the surrounding colors. However, we show that this adjustment breaks down when observers attempt to find more than a single target. Therefore, to optimize performance, it may best to search for only one object at a time.

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Introduction

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Navalpakkam and Itti (2007) illustrated the optimal tuning of attention using an image where a tiger is mostly hidden in high grass. Because of the importance of spotting the predator, attention should be optimally tuned to detect its features. An analysis of the color statistics of the image revealed that the color of the grass ranged from yellow to green, whereas the color of the tiger ranged from yellow to orange. To increase the chances of finding the tiger, it would not be optimal to look for the average yellow-orange color of the tiger's coat, because the grass is also yellow, and the overlap would result in a poor signal to noise ratio. Instead, it would be optimal to look for orange because orange is not contained in the color of the grass. To provide evidence for the optimal tuning of attention, Navalpakkam and Itti (2007) asked their participants to search for a color target among nontargets in a slightly different color. The search trials were interspersed with probe trials, where participants were shown several colors and had to select the color corresponding to the target. Participants did not choose the true target color most frequently, but a color that was shifted away from the nontarget color. Navalpakkam and Itti's results show that the nontarget color in the search task modified the memory representation of the target color. This memory error has been replicated in numerous experiments (Chapman et al., 2023; Hamblin-Frohman & Becker, 2021; Jung et al., 2021; Kerzel, 2020; Maith et al., 2021; Scolari & Serences, 2009; Yu & Geng, 2019).

Navalpakkam and Itti (2007) did not comment on the origins of optimal tuning, but the literature suggests that there are at least three possibilities. Like attentional selection in general, optimal tuning may be goal-driven, stimulus-driven, or history-driven (e.g., Awh et al., 2012; Liesefeld et al., 2024). Because the memory representation of the target was shifted, it may be that optimal tuning is goal-driven because memory representations are

71 used to set the search goals of the observer (Carlisle et al., 2011; Duncan & Humphreys,
72 1989; Eimer, 2014; Huynh Cong & Kerzel, 2021; Schneider, 2013). In contrast, a stimulus-
73 driven origin is unlikely because the shift is not a characteristic of the stimulus, but a change
74 in the observer's representation of the stimulus. In the current study, however, we explore
75 contributions from trial history, which have not been considered so far.

76 **Mixed vs. fixed target-nontarget relations**

77 The potential role of trial history emerges from a series of studies reporting
78 conflicting results. First, Scolari and Serences (2009) measured contrast detection thresholds
79 to masked stimuli. If attentional selection was biased away from the nontargets, contrast
80 thresholds should be lower for stimuli shifted away from the nontargets because of
81 attentional enhancement (Carrasco, 2011). However, there was no behavioral evidence for
82 this prediction, even though a later brain imaging study found some support (Scolari et al.,
83 2012). Importantly, Scolari and Serences (2009) randomly mixed the target and nontarget
84 features to avoid sensory adaptation (see p. 11941). Second, Kerzel (2020) measured cueing
85 effects. Cueing effects are largest for cue colors corresponding to the search goals of the
86 observer (Folk & Remington, 1998). Kerzel (2020) found the largest cueing effects for colors
87 shifted away from the nontargets, providing evidence for optimal tuning. Third, Hamblin-
88 Frohman and Becker (2021) measured oculomotor capture by distractors shown
89 simultaneously with target and nontarget stimuli. Oculomotor capture is strongest for
90 stimuli that correspond to the search goals of the observer (Wu & Remington, 2003).
91 Hamblin-Frohman and Becker (2021) found more oculomotor capture by distractors shifted
92 away from the nontargets, again providing support for optimal tuning. Importantly, target
93 and nontarget colors were fixed across trials in the two studies reporting support for optimal
94 tuning. As a result, the target-nontarget relation was repeated throughout the experiment.

95 In contrast, the study by Scolari and Serences (2009) did not find support for optimal tuning
96 when the target-nontarget relations were randomly mixed.

97 Thus, it appears that the optimal tuning of attention depends on trial history and only
98 occurs when a fixed target-nontarget relation is repeated, but previous studies did not
99 directly address this question. Applied to the example of the tiger in the grass, we may only
100 be able to optimally tune attention to the tiger if we repeatedly look at the grasslands. If we
101 switch between the grasslands with the tiger and a muddy pond with an almost submerged
102 hippo, we may not be able to optimally tune attention to both targets. For the tiger, the
103 optimally tuned target is “more orange” in a yellowish scene. For the hippo, the skin around
104 the hippo’s eyes is red-brown and the pond is brown. The optimally tuned target is therefore
105 “redder” in a brownish scene. The question is whether the optimally tuned targets are
106 available when we switch between the grasslands and the pond or whether they are only
107 available when we continuously look at one of the two scenes. In other words, does optimal
108 tuning occur with fixed and mixed target-nontarget relations or is it limited to fixed
109 relations?

110 **The contingent capture paradigm**

111 To answer this question, we used the contingent capture paradigm developed by Folk
112 et al. (1992). In the contingent capture paradigm, spatial cues are shown briefly before the
113 target (see Figure 1A). Cues at the target location are referred to as valid, and cues at a
114 nontarget location as invalid. Although the cues do not predict the target location, valid cues
115 result in shorter RTs than invalid cues. However, these cueing effects only occur when the
116 cue color corresponds to the target color. In contrast, cueing effects are absent when the
117 color of the cue does not match the color of the target, suggesting that only matching cues
118 capture attention (e.g., Becker et al., 2019; Carmel & Lamy, 2015; Folk & Remington, 1998;

119 Goller et al., 2020; Kim et al., 2019; Rigsby et al., 2023; Ruthruff et al., 2020; Schönhammer
120 et al., 2020; Zivony & Lamy, 2018).

121 Previous research showed that effects of trial history on cueing effects depend on the
122 search task. In a relevant study, Folk and Remington (2008) presented a colored target
123 among white nontargets (i.e., a color singleton). Because it was not necessary to know the
124 target color and the target color varied unpredictably between green and red, participants
125 may have looked for any color singleton instead of looking for a particular color. Consistent
126 with singleton search, cueing effects were observed regardless of the match between cue
127 and target color. Further, cueing effects were larger when the cue color on the current trial
128 matched the target color on the previous trial. When the task was changed to favor search
129 for a particular color, however, these effects of trial history disappeared. Thus, effects of
130 trial history on cueing effects occur when participants search for singletons, but not when
131 they searched for a particular feature.

132 These results are important because participants in previous studies on optimal
133 tuning also searched for singletons, albeit with color differences that were much smaller
134 than in Folk and Remington (2008). Therefore, it appears likely that optimal tuning is also
135 susceptible to trial history. Possibly, optimal tuning is stronger if the cue on the current trial
136 matches the target-nontarget relation on the previous trial.

137 We used cueing effects as a diagnostic tool to assess optimal tuning. If optimal tuning
138 occurs, larger cueing effects are expected for cue colors that are shifted away from the
139 nontarget color compared with cue colors that are shifted toward the nontarget color (see
140 Figure 1B). Distances between colors are measured in degrees of rotation on an isoluminant
141 color wheel. Based on prior work (Kerzel, 2020), the optimal tuning was estimated to be
142 about -15° away from the nontarget color with these colors. The tuning of attention can be

143 quantified by the difference between cueing effects for cue colors shifted away (-15°) and
144 toward (+15°) the nontarget color, which we refer to as tuning scores (see Figure 1C). The
145 larger the tuning scores, the stronger the optimal tuning. In contrast, tuning scores of zero
146 would indicate that optimal tuning is absent, and that attention is tuned to the exact target
147 feature. Finally, negative tuning scores would indicate tuning towards the nontarget color,
148 which is the opposite of optimal tuning.

149 **Hypotheses**

150 Effects of trial history on optimal tuning were evaluated in two different ways. First,
151 we compared fixed and mixed blocks of trials. In fixed blocks, there was only one target-
152 nontarget relation that was repeated on every trial. In mixed blocks, there were two target-
153 nontarget relations in random order, resulting in some trials where the target-nontarget
154 relation was repeated and others where it changed. If optimal tuning was history-based and
155 depended on the match between the cue on the current trial and the target-nontarget
156 relation on the previous trial, stronger optimal tuning should occur in fixed than in mixed
157 blocks. Second, in mixed blocks, we analyzed optimal tuning separately for trials where the
158 target-nontarget relation was repeated and where it changed. If optimal tuning was history-
159 based, stronger optimal tuning is expected on trials where the target-nontarget relation was
160 repeated because the cue on the current trial matches the target-nontarget relation on the
161 previous trial. In our experiments, the cue always matched the target-nontarget relation on
162 the current trial, but similar results are expected for nonmatching cues because participants
163 performed singleton search (see above presentation of Folk & Remington, 2008).

164 Our main hypotheses were about effects of trial history on optimal tuning with two
165 target-nontarget relations. With two target-nontarget relations, several second-order
166 relations are possible. We did not have specific hypotheses about these second-order

167 relations but distinguished three which we decided to explore (see Figure 2). Either the two
168 target-nontarget relations shared the same nontarget color (Experiment 1), they shared no
169 color at all (Experiment 2), or they shared the same target color (Experiment 3). Each of
170 these second-order relations is illustrated by a real-world scenario in the introduction to the
171 respective experiment. We expect that the manipulation of second-order relation would
172 shed some light on the processes underlying potential effects of trial history.

173 **Experiment 1**

174 In Experiment 1, the nontarget color was fixed and the target color varied by +/- 30°
175 around this color, thereby creating two target-nontarget relations. In the example from the
176 introduction, this situation corresponds to a search for two different animals in the same
177 yellow-green grasslands. In addition to the tiger, which is more orange than the grass, there
178 may be a green snake, which is greener than the grass. Of note, these target-nontarget
179 relations are opposite. That is, one is more orange, and the other is greener than the same
180 yellow-green grasslands.

181 Effects of trial history should result in larger optimal tuning in fixed blocks with one
182 target-nontarget relation than in mixed blocks with two target-nontarget relations.
183 Moreover, in mixed blocks, larger optimal tuning is expected when the target-nontarget
184 relation repeats compared to when it changes because the cue on the current trial matches
185 the target-nontarget relation on the previous trial.

186 **Method**

187 **Transparency and Openness Promotion.** The number of participants was partially
188 determined by the counterbalancing demands described below. To fulfill these
189 requirements, 24 undergraduate psychology students participated (0 male; age: $M = 20.5$
190 years, $SD = 2.3$). In a related study by Kerzel (2020), the sample size was between 18 - 21 and

191 the η_p^2 for tuning scores was between .428 - .592, which would require only five
192 participants. In the current study, however, we were interested in modulations of tuning
193 scores by intertrial transition. We mostly performed the critical comparisons by paired t-test.
194 G*Power 3.1 (Faul et al., 2009) indicated that we could detect effect sizes as small as $d_z =$
195 0.66 with a sample size of 20 (two-tailed, alpha = .05, power = .8). None of the experiments
196 reported in this article was formally preregistered. The data are available at
197 <https://osf.io/xqwb9/> and requests for the program code can be sent via email to DK. Data
198 management, aggregation and plots were performed with MatLab 2022a (The Mathworks,
199 Natick, MA) and inferential statistics with IBM SPSS 27 (IBM, Armonk, NY). DK was supported
200 by grant No. 100019_182146 from the Swiss National Science Foundation. The authors
201 declare that they have no conflict of interest. Students participated for class credit and
202 reported normal or corrected-to-normal vision. The study was approved by the ethics
203 committee of the Faculty of Psychology and Educational Sciences at the University of Geneva
204 and was carried out in accordance with the Code of Ethics of the World Medical Association
205 (Declaration of Helsinki). Informed written consent was given before the experiment started.
206 Data were collected between 2021 and 2023.

207 **Apparatus.** The stimuli were displayed on a 22.5-inch LCD monitor (100 Hz, 1,920 ×
208 1,200 pixels, standard backlight; VPixx Technologies Inc., Saint-Bruno, Canada). Colors were
209 measured with an i1Display Pro (VPixx Edition) colorimeter by X-Rite (Grand Rapids,
210 Michigan, United States). Head position was stabilized with a chin/forehead rest at a viewing
211 distance of 66 cm. Responses were collected on a RESPONSEPixx Handheld 5-button
212 response box (VPixx Technologies Inc., Saint-Bruno, Canada), which had four buttons

213 arranged in a diamond shape and one button in the center. The Psychtoolbox (Brainard,
214 1997; Kleiner et al., 2007) controlled stimulus presentation and response collection.

215 **Stimuli.** There was a placeholder, a cue, and a target display (see Figure 1A). A central
216 fixation cross (0.2° radius, 0.07° linewidth) was shown throughout. The placeholders were
217 four outline rings shown to the left, right, above and below the fixation cross. The center-to-
218 center distance between the fixation cross and the rings was 3° . To create the outline rings,
219 a large and a slightly smaller circle were drawn with a linewidth of 1 pixel or 0.02° . The radii
220 of the circles were 1.4° and 1.2° . In the cue display, all outline rings were filled. One ring was
221 filled in the cue color while the remaining three rings were filled with the same light gray as
222 the placeholders. In the target display, a letter T tilted by 90° to the left or right was shown
223 inside each placeholder. The bars making up the tilted Ts were 1° long and 0.2° thick. One of
224 the Ts was the target color and the remaining Ts were the nontarget color.

225 Colors are described in xyY with Y in cd/m^2 . The background was dark gray, xyY =
226 (0.312, 0.332, 24.3) while the placeholders and the gray cues were light gray (0.312, 0.332,
227 48.8). The cue, target and nontarget colors were sampled along an isoluminant color wheel
228 in a CIELAB -space where distances reflect perceived color differences (Fairchild, 2005). In
229 CIELAB-space, the isoluminant color wheel had a lightness of $L^* = 59$ (corresponding to a
230 luminance of 48.8 cd/m^2) and a saturation of 64.

231 The nontarget color was fixed for each participant and the two target colors differed
232 by -30° or 30° of rotation from the nontarget color. The possible nontarget colors were at a
233 rotation of 0° , 45° , 90° , 135° , 180° and 315° on the color wheel. Figure 1B shows colors at
234 rotations from 0° to 360° from left right. The cue colors deviated by -15° or $+15^\circ$ from the
235 target color. The cue was always drawn from the same target-nontarget relation as the
236 subsequent search display. In trial blocks with one target-nontarget relation, there were 32

237 combinations resulting from crossing cue color (-15°, +15°), cue position (left, right, top,
238 bottom), and target position (left, right, top, bottom). The 32 combinations were shown
239 once in each mini-block and there were eight mini-blocks for a total of 256 trials per block. In
240 trial blocks with two target-nontarget relations, the 64 combinations resulting from crossing
241 target-nontarget relation, cue color (-15°, 15°), cue position (left, right, top, bottom), and
242 target position (left, right, top, bottom) were shown once in a mini-block. There were four
243 mini-blocks for a total of 256 trials per block. Trial blocks with fixed or mixed target-
244 nontarget relations alternated to have two of each. There were four possible block orders.
245 Half of the participants started with a fixed block, and the other half started with a mixed
246 block. For fixed blocks, the order of the two possible target-nontarget relations was
247 counterbalanced. The four possible block orders were crossed with the six possible
248 nontarget colors, requiring 24 participants to counterbalance these variables. Every
249 participant worked through 1,024 trials, except for one who terminated the experiment 64
250 trials too early. Because the number of lost trials was small, we decided to keep this dataset.

251 **Procedure.** A trial started with the presentation of the placeholder display for 700
252 ms. Then, the cue display was shown for 50 ms, followed by the placeholder display for 100
253 ms and the target display for 50 ms. The resulting SOA between cue and target was 150 ms.
254 The placeholder display was shown until a key was pressed. Participants responded to a T
255 rotated counterclockwise by a left button press and to a T rotated clockwise by a right
256 button press. They were instructed to respond as rapidly and accurately as possible while
257 ignoring the cue display. Trials with choice errors, anticipations and late responses were
258 followed by visual feedback. We considered trials with RTs longer than 1,500 ms as late.
259 Every 64 trials, the percentage of correct responses and the median RTs in the preceding
260 trial block were displayed for at least 3,000 ms during a self-terminated pause.

261 **Results**

262 In the analyses of RTs, we successively excluded trials with late responses (0.2%),
263 choice errors (4.2%), and trials with RTs longer than 2.5 *SDs* above the respective condition
264 mean (2.2%). Cueing effects were calculated by subtracting RTs with valid cues from RTs
265 with invalid cues. We calculated tuning scores by subtracting cueing effects with +15° cue
266 colors from cueing effects with -15° cue colors. Positive numbers indicate tuning away from
267 the nontarget color, which is consistent with optimal tuning. Mean absolute RTs, cueing
268 effects and tuning scores are shown in Figures 3 and 4, but our focus was on the analysis of
269 tuning scores. Significant tests remained significant after controlling for false discovery rate
270 (Benjamini & Hochberg, 1995) and we therefore report the uncorrected *p*-values.

271 We evaluated differences in tuning scores between trial blocks with fixed or mixed
272 target-nontarget relations (see Figure 3). Consistent with an effect of trial history on optimal
273 tuning, tuning scores were larger with fixed than mixed target-nontarget relations (45 vs. 15
274 ms), $t(23) = 4.99, p < .001$, Cohen's $d_z = 1.02$. This difference corresponds to the significant
275 three-way interaction in the ANOVA with all relevant factors shown in Table 1. One-sample
276 *t*-tests showed that both tuning scores were significantly different from zero, $t_s > 3.49, p_s <$
277 $.002$, Cohen's $d_z > 0.71$.

278 Next, we evaluated effects of intertrial transition in blocks with mixed target-
279 nontarget relations (see Figure 4). We separated trials where the cue matched the previous
280 target-nontarget relation from trials where it did not match. Tuning scores were larger when
281 the cue matched the previous target-nontarget relation than when it did not match (29 vs. 3
282 ms), $t(23) = 2.77, p = .011$, Cohen's $d_z = 0.57$. This difference corresponds to the significant
283 three-way interaction in the ANOVA with all relevant factors shown in Table 2. One-sample
284 *t*-tests showed that tuning scores were significantly different from zero when the cue

285 matched the previous target-nontarget relation (29 ms), $t(23) = 4.31$, $p < .001$, Cohen's $d_z =$
286 0.88, but not when it did not match (3 ms), $t(23) = 0.49$, $p = .628$, Cohen's $d_z = 0.10$.

287 We also evaluated whether optimal tuning in fixed blocks was different from trials in
288 mixed blocks where the cues matched the previous target-nontarget relation. In mixed
289 blocks, cues were preceded by as few as one matching target-nontarget relation, whereas
290 there were many more repetitions in fixed blocks. Tuning scores tended to be larger in fixed
291 blocks than in matching trials of mixed blocks (42 vs. 29 ms), $t(23) = 2.04$, $p = .053$, Cohen's
292 $d_z = 0.42$. Thus, repetition of the same target-nontarget relation throughout a block of trials
293 tended to increase optimal tuning relative to repetitions occurring randomly in mixed blocks.

294 Finally, we performed the same analyses on the proportion of choice errors to rule
295 out speed-accuracy tradeoff. We found no significant differences between tuning scores, ps
296 $> .689$, but tuning scores were significantly different from zero in fixed blocks (1.9%), $t(23) =$
297 2.71, $p = .012$, Cohen's $d_z = 0.55$, and approached significance in mixed blocks (1.7%), $t(23) =$
298 2.03, $p = .054$, Cohen's $d_z = 0.42$. In mixed blocks, tuning scores approached significance on
299 matching trials (2.1%), $t(23) = 1.91$, $p = .069$, Cohen's $d_z = 0.39$, but not on nonmatching trials
300 (1.4%), $p = .225$. Because tuning scores in choice errors were not opposite to those in RTs,
301 there is no evidence for speed-accuracy tradeoff.

302 Discussion

303 In Experiment 1, the target-nontarget relations were opposite around the same
304 nontarget color. Tuning scores were larger in fixed than in mixed blocks, and in mixed blocks,
305 tuning scores were larger when the cue color matched the previous target-nontarget
306 relation. These results suggest that trial history played an important role. In fact, tuning
307 scores were not significantly different from zero for cues that did not match the previous
308 target-nontarget relation. Therefore, optimal tuning does not occur simultaneously in

309 opposite directions from the same nontarget color, but only in the direction of the previous
310 target-nontarget relation. In the example with two animals in the grasslands, it would not be
311 possible to tune attention optimally when switching between the tiger and snake, but only
312 when repeatedly searching for the same animal.

313 **Experiment 2**

314 In Experiment 2, the two target-nontarget relations were separated by at least 90°
315 from each other, resulting in large differences between the colors. In the example from the
316 introduction, this situation corresponds to two different scenes with two different animals.
317 For instance, the observer may switch between looking for a tiger in the grasslands and
318 looking for an almost submerged hippo in a pond. Thus, the target-nontarget relations are
319 independent. One is more orange than the yellow-green grasslands and the other is redder
320 than the brown pond.

321 **Method**

322 The method was as in Experiment 1 with the following exceptions. The two nontarget
323 colors for each participant were separated by at least 90° to create two independent target-
324 nontarget relations. The five possible pairs of nontarget colors were 0°/90°, 45°/135°,
325 90°/180°, 135°/315°, and 315°/45°. These pairs were crossed with four possible block orders,
326 requiring 20 participants (3 male; age: $M = 21.4$ years, $SD = 3.7$). Data from one participant
327 was replaced because the percentage of errors was excessive compared to the rest of the
328 sample (16% vs. $M = 4.8\%$, $SD = 2.6\%$).

329 **Results**

330 Before calculating individual mean RTs per condition, we successively excluded trials
331 with late responses (0.1%), choice errors (4.0%), and trials with RTs longer than 2.5 SD s
332 above the respective condition mean (2.0%). Tuning scores were larger with fixed than

333 mixed target-nontarget relations (50 vs. 30 ms), $t(19) = 3.29$, $p = .004$, Cohen's $d_z = 0.74$. This
334 difference corresponds to the significant three-way interaction in the ANOVA with all
335 relevant factors (see Table 1). One-sample t-tests showed that both tuning scores were
336 significantly different from zero, $t_s > 5.79$, $p_s < .001$, Cohen's $d_z > 1.29$.

337 However, optimal tuning did not differ between trials where the cue matched the
338 previous target-nontarget relation and trials where it did not (35 vs. 26 ms), $t(19) = 0.90$, $p =$
339 $.382$, Cohen's $d_z = 0.20$. The Bayes factor was 4.01 for this comparison, which provides
340 moderate evidence for the null hypothesis. This comparison corresponds to the non-
341 significant three-way interaction in the ANOVA with all relevant factors (see Table 2). One-
342 sample t-tests showed that tuning scores were significantly different from zero when the cue
343 matched the previous target-nontarget relation (35 ms), $t(19) = 4.88$, $p < .001$, Cohen's $d_z =$
344 1.09 , and when it did not (26 ms), $t(19) = 4.18$, $p < .001$, Cohen's $d_z = 0.93$.

345 Further, tuning scores were larger in fixed blocks than in matching trials of mixed
346 blocks (50 vs. 35 ms), $t(19) = 2.62$, $p = .017$, Cohen's $d_z = 0.59$, suggesting that repetitions of
347 the same target-nontarget relation throughout a block of trials resulted in stronger optimal
348 tuning than repetitions occurring randomly in mixed blocks.

349 Finally, we performed the same analyses on the proportion of choice errors but
350 found no significant differences between tuning scores, $p_s > .209$. However, tuning scores
351 were significantly different from zero in fixed blocks (3.0%), $t(19) = 2.78$, $p = .012$, Cohen's d_z
352 $= 0.62$, and approached significance in mixed blocks (1.5%), $t(19) = 2.09$, $p = .050$, Cohen's d_z
353 $= 0.47$. In mixed blocks, tuning scores were significant on matching trials (2.4%), $t(19) = 2.19$,
354 $p = .041$, Cohen's $d_z = 0.49$, but not on nonmatching trials (0.5%), $p = .726$. Because tuning
355 scores in choice errors were not opposite to those in RTs, there is no evidence for speed-
356 accuracy tradeoff.

357 Discussion

358 As in Experiment 1, tuning scores were reduced in mixed compared to fixed blocks,
359 but analysis of mixed blocks showed no difference between cues matching or not matching
360 the previous target-nontarget relation. In addition, tuning scores were significant for
361 nonmatching cues, which was not the case in Experiment 1. Thus, attention could be
362 simultaneously tuned to two target-nontarget relations. In the example with two animals in
363 two different scenes, it would be possible to tune attention optimally to the tiger in the
364 grasslands and the hippo in the pond, albeit less optimally than to a single target.

365 Experiments 3

366 In Experiment 3, the target color was fixed and the nontarget colors were opposite.
367 This situation corresponds to the search for a tiger in two different scenes. For instance,
368 there may be one tiger in the yellow-green grasslands and another in an orange-red clay pit.
369 When the two scenes switch randomly, optimal tuning of attention is not warranted because
370 the optimal tuning to one scene may make the target harder to see in the other scene. In the
371 grasslands, attention is optimally tuned to “more orange”, but looking for “more orange” is
372 not useful in the orange-red clay pit, where it would be best to look for “yellower”.

373 Method

374 The target color was fixed for each participant and the two nontarget colors differed
375 by -30° or 30° . The possible target colors were 0° , 45° , 90° , 135° , 180° and 315° . The four
376 possible block orders were crossed with the six possible target colors, requiring 24
377 participants (3 male; age $M = 23.4$ years, $SD = 7.2$).

378 Results

379 Before calculating individual mean RTs per condition, we successively excluded trials
380 with late responses (0.1%), choice errors (4.7%), and trials with RTs longer than 2.5 SDs

381 above the respective condition mean (2.0%). Tuning scores were larger in fixed than mixed
382 blocks (31 vs. -6 ms), $t(23) = 4.48$, $p < .001$, Cohen's $d_z = 0.91$. This difference corresponds to
383 the significant three-way interaction in the ANOVA with all relevant factors (see Table 1).
384 One-sample t-tests showed that the tuning scores in fixed blocks were significantly different
385 from zero, $t(23) = 5.73$, $p < .001$, Cohen's $d_z > 0.71$, but not in mixed blocks (-6 ms), $t(23) =$
386 1.15 , $p = .261$, Cohen's $d_z = 0.23$.

387 In mixed blocks, tuning scores were larger on trials where the cue matched the
388 previous target-nontarget relation than when it did not (2 vs. -19 ms), $t(23) = 2.94$, $p = .007$,
389 Cohen's $d_z = 0.60$. This difference corresponds to the significant three-way interaction in the
390 ANOVA with all relevant factors (see Table 2). One-sample t-tests showed that the tuning
391 scores with matching cues were not significantly different from zero (2 ms), $t(23) = 0.33$, $p =$
392 $.742$, Cohen's $d_z = 0.07$, whereas they were significantly below zero with nonmatching cues (-
393 19 ms), $t(23) = 2.98$, $p = .007$, Cohen's $d_z = 0.61$.

394 Further, tuning scores were larger in fixed blocks than in matching trials of mixed
395 blocks (31 vs. 2 ms), $t(23) = 3.03$, $p = .006$, Cohen's $d_z = 0.62$, suggesting that repetitions of
396 the same target-nontarget relation throughout a block of trials resulted in stronger optimal
397 tuning than repetitions occurring randomly in mixed blocks.

398 Finally, we performed the same analyses on the proportion of choice errors. Tuning
399 scores tended to be larger in fixed than mixed blocks (2.5% vs. 0.4%), $t(23) = 2.00$, $p = .057$,
400 Cohen's $d_z = 0.41$, and tuning scores were significantly different from zero in fixed blocks
401 (2.5%), $t(23) = 4.14$, $p < .001$, Cohen's $d_z = 0.85$. None of the remaining differences was
402 significant, $ps > .188$. Because tuning scores in choice errors were not opposite to those in
403 RTs, speed-accuracy tradeoff is unlikely.

404 **Discussion**

405 As in the previous experiments, optimal tuning was larger in fixed than in mixed
406 blocks, even compared to those trials in mixed blocks where the cue matched the previous
407 target-nontarget relation. While these results are as in Experiment 1, the magnitude of
408 optimal tuning was smaller. With cues matching the previous target-nontarget relation,
409 tuning scores were not significantly different from zero, and with nonmatching cues, tuning
410 scores were significantly below zero. The tuning scores of zero with cues matching the
411 previous target-nontarget relation are surprising because positive tuning scores were
412 observed in these conditions in Experiments 1 and 2. Further, the inverted tuning scores
413 suggest that attention was tuned **toward** the nontarget color, which is non-adaptive because
414 it makes the target more difficult to see.

415 **General Discussion**

416 We evaluated effects of trial history in the optimal tuning of attention. Optimal
417 tuning of attention refers to changes in the target representation that decrease the overlap
418 between target and nontarget features. That is, participants do not search for the true target
419 color, but for a color that is shifted away from the nontarget color. Previous research has
420 established that the memory representation of the target is biased (Chapman et al., 2023;
421 Hamblin-Frohman & Becker, 2021; Jung et al., 2021; Kerzel, 2020; Maith et al., 2021; Scolari
422 & Serences, 2009; Yu & Geng, 2019). Because memory representations are the basis for
423 goal-driven search (Carlisle et al., 2011; Duncan & Humphreys, 1989; Eimer, 2014; Huynh
424 Cong & Kerzel, 2021; Schneider, 2013), the bias may suggest that optimal tuning is a goal-
425 driven process. However, goal-driven processes may not be the only drivers of optimal
426 tuning. The current study investigated effects of trial history by comparing trial blocks with

427 fixed and mixed target-nontarget relations and by evaluating effects of the match between
428 the current cue color and the previous target color in mixed blocks.

429 To measure optimal tuning, we used cueing effects. If attention was tuned away from
430 the nontarget color, larger cueing effects are expected for cue colors shifted away from the
431 nontarget color compared with cue colors shifted toward. We refer to the difference
432 between cueing effects as tuning scores. Larger tuning scores reflect stronger optimal
433 tuning. We compared fixed blocks with a single target-nontarget relation to mixed blocks
434 where two target-nontarget relations varied randomly (see Figure 3).

435 In three experiments, we found that tuning scores were larger in fixed than mixed
436 blocks. Thus, trial history is important for optimal tuning. The reduced optimal tuning in
437 mixed blocks was observed regardless of the nature of the target-nontarget relation. That is,
438 the reduction was found with a fixed nontarget color and two opposite target colors
439 (Experiment 1), with two target-nontarget relations that were far apart (Experiment 2), and
440 with a fixed target color and two opposite nontarget colors (Experiment 3).

441 Further, the analysis of intertrial transitions in mixed blocks (see Figure 4) showed
442 that optimal tuning was larger if the cue matched the previous target-nontarget relation, at
443 least in Experiments 1 and 3. With target colors that were far apart (Experiment 2), there
444 was evidence that intertrial transitions did not affect optimal tuning. Nonetheless, the
445 overall conclusion of the current study is that trial history contributes substantially to the
446 optimal tuning of attention. It appears that optimal tuning is strongest if the cue matches
447 the previous target-nontarget relation and weaker or even absent if it does not.

448 Finally, optimal tuning was larger in fixed blocks than in matching trials of mixed
449 blocks, suggesting that optimal tuning increases with repetition of the same target-
450 nontarget relation. Which process underlies these results?

451 **Underlying Processes**

452 **Priming of attentional set.** Folk and Remington (2008) observed reduced cueing
453 effects on trials where the cue was different from the previous target. However, this
454 reduction only occurred when participants looked for color singletons, not when they looked
455 for a particular color. Folk and Remington suggested that the previous target would prime an
456 attentional control setting for a particular color, but only if participants had not established
457 an attentional set for a particular color to begin with (see also results from dual-target
458 search, Irons et al., 2012; Kerzel & Grubert, 2022; Kerzel & Witzel, 2019). Because
459 participants searched for singletons in the current study, it may be that there was priming of
460 optimal tuning. That is, cues matching the target-nontarget relation from the previous trial
461 showed optimal tuning because the respective target-nontarget relation was primed. The
462 problem with this account is that it predicts effects of intertrial transition for all types of
463 target-nontarget relations. However, differences between matching and nonmatching cues
464 were absent in Experiment 2 and there was no optimal tuning with cues matching the
465 previous target-nontarget relation in mixed blocks of Experiment 3.

466 **Switch costs.** In mixed blocks, the target-nontarget relation switched randomly and
467 there were costs associated with these switches. The ANOVAs in Table 2 show significant
468 effects of the previous target-nontarget relation in Experiments 1 and 3. That is, RTs were
469 significantly longer when the previous target-nontarget relation was different from the
470 current relation compared to when it was the same. These switch costs amounted to 16 and
471 12 ms in Experiments 1 and 3, respectively. It may be that switching to a new target
472 interfered with the optimal tuning of attention. Instead, we have argued that optimal tuning
473 was reduced because the cue did not match the previous target-nontarget relation. In fact,
474 the two cannot be dissociated because on switch trials, the cue was always nonmatching

475 with respect to the previous target-nontarget relation. Thus, the question is whether the
476 modestly longer RTs on switch trials may account for the reduced optimal tuning. We think
477 that this is unlikely. First, cueing effects result from shifts of attention preceding the search
478 display and are therefore unrelated to processing of the search display. Second, cueing
479 effects have been shown to increase with longer RTs (Ruthruff et al., 2020), but optimal
480 tuning decreased with longer RTs on switch trials. Third, attentional control settings can be
481 rapidly changed without reducing cueing effects (Lien et al., 2010). Fourth, and most
482 importantly, the magnitude of the switch costs does not follow the tuning scores. For
483 instance, switch costs were similar in Experiments 1 and 3, yet the tuning scores were much
484 smaller or inverted in Experiment 3. Nonetheless, there is also evidence supporting the role
485 of switch costs. The absence of switch costs in Experiment 2 was accompanied by the
486 absence of intertrial effects in mixed blocks. However, when taken together, the results do
487 not provide a clear picture regarding the relation between switch costs and optimal tuning.

488 **Sensory adaptation.** Another explanation of the results is in terms of sensory
489 adaptation (see p. 11941 in Scolari & Serences, 2009). Sensory adaptation to color is
490 sufficiently rapid (half-life of less than 25 ms, Rinner & Gegenfurtner, 2000) to allow for
491 changes after a single trial. Sensory adaptation may occur to the target and nontarget colors
492 in a search display, and additionally, to intermediate colors because they are not linearly
493 separable (Bauer et al., 1996; D'Zmura, 1991). Consequently, cues shifted from the target
494 toward the nontarget color are in the range of sensory adaptation and their processing may
495 be reduced. In contrast, the processing of cue colors shifted away from the nontarget color
496 does not suffer from sensory adaptation. As a result, their ability to capture attention may
497 be larger, resulting in increased cueing effects. Thus, sensory adaptation may explain optimal
498 tuning for a single target-nontarget relation, but it also explains some effects of intertrial

499 transition in mixed blocks. For instance, in Experiment 3, the target color was fixed and only
500 the nontarget color changed. In mixed blocks, optimal tuning was inverted if the cue did not
501 match the previous target-nontarget relation. In contrast to the other accounts, sensory
502 adaptation may provide an explanation. Because the target color was fixed, the same cue
503 colors appeared in both target-nontarget relations, but with different signs (see Figure 2C).
504 That is, the cue color shifted toward the nontarget (+) in one target relation was also the cue
505 color shifted away from the nontarget (-) in the other target-nontarget relation. On a switch
506 trial, the adapted cue color from the previous trial (+, e.g. in relation 1) becomes the cue
507 color shifted away (-, e.g. in relation 2) on the current trial. As a result, cueing effects are
508 reduced for the cue color shifted away, which is opposite to optimal tuning and results in
509 inverted tuning scores. However, sensory adaptation has difficulty explaining the results
510 from Experiment 1. In Experiment 1, optimal tuning was eliminated when the target-
511 nontarget relation changed. However, sensory adaptation predicts that cue colors from both
512 target-nontarget relations that deviate towards the nontarget color (+15°) should adapt.
513 Because adaptation was intermittent, sensory adaptation may be weaker on switch trials,
514 but should nonetheless be present, which was not the case. To obtain more direct evidence
515 for sensory adaptation, measurements of event-related potentials could evaluate sensory
516 adaptation by focusing on an early lateralized potential at posterior electrodes (Kerzel &
517 Huynh Cong, 2021; Schönhammer et al., 2020).

518 Overall, more research is required to clarify which process underlies effects of trial
519 history on optimal tuning. Note that our list of mechanisms may not be exclusive. In the
520 discrimination learning literature, a phenomenon with similar structure has received several
521 interpretations, but is also awaiting a conclusive explanation. When animals are rewarded
522 for responding to a colored light (S+), and not rewarded for responding to another colored

523 light (S-), they will respond most to colors on the opposite side of the S+ from the S-, which is
524 reminiscent of the larger cueing effects for cue colors shifted away from the nontarget
525 colors. Famously, the learning effects have been attributed to relational responding (Köhler,
526 1938) or gradients of excitation and inhibition (Spence, 1937). However, neither mechanism
527 was confirmed in more recent research (Lazareva et al., 2005), calling for more research and
528 new theories.

529 **Conclusions**

530 We asked whether trial history contributes to optimal tuning. Optimal tuning occurs
531 when participants search for a target that exaggerates the true relation between target and
532 nontarget colors to improve the signal-to-noise ratio. We observed that optimal tuning was
533 stronger in trial blocks with a fixed target-nontarget relation compared with trial blocks
534 where two target-nontarget relations were randomly mixed. Analysis of intertrial transitions
535 in mixed blocks showed that effects of trial history changed with the type of target-
536 nontarget relation. When the target-nontarget relations were opposite around the same
537 nontarget color (Experiment 1), optimal tuning only occurred when the cue matched the
538 previous target-nontarget, but not when it did not match. This difference was not observed
539 when the target-nontarget relations were far apart (Experiment 2). Finally, when the target-
540 nontarget relations were opposite around the same target color (Experiment 3), optimal
541 tuning did not occur with matching cues and was inverted with nonmatching cues. Taken
542 together, these results clearly show that optimal tuning depends on trial history. Several
543 mechanisms underlying these effects, such as priming of attentional set, switch costs and

544 sensory adaptation, are discussed. However, none of the mechanism can fully account for
 545 the results.

546 **Statement on the generality of findings**

547 The participants in the current study were mostly female first-year psychology
 548 students, which limits the generalizability of the current findings.

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679

680

681 **Table 1.** Results from repeated-measures ANOVAs on mean individual reaction times in
 682 Experiments 1-3.

683

factor	Experiment 1			Experiment 2			Experiment 3		
	<i>F</i>	<i>p</i>	η_p^2	<i>F</i>	<i>p</i>	η_p^2	<i>F</i>	<i>p</i>	η_p^2
- block	19.10	< .001	.454	10.36	= .005	.353	49.75	< .001	.684
- cue color	3.35	= .080	.127	7.91	= .011	.294	11.10	= .003	.325
- cue validity	109.27	< .001	.826	72.96	< .001	.793	12.30	= .002	.349
- block x cue color		-		3.58	= .074	.158	19.02	< .001	.453
- block x cue validity		-			-		7.16	= .013	.237
- cue color x cue validity	68.91	< .001	.750	67.21	< .001	.780	13.12	= .001	.363
- three-way interaction	24.90	< .001	.520	10.85	= .004	.363	20.07	< .001	.466

684

685

686 **Note.** The factorial design of the ANOVAs was 2 (block: fixed, mixed) × 2 (cue color: -15°, 15°)
 687 × 2 (cue validity: valid, invalid). The degrees of freedom were (1, 23) in Experiments 1 and 3,
 688 and (1, 19) in Experiment 2. Only significant effects or effects approaching significance (*p* <
 689 .100) are shown for clarity.

690

691 **Table 2.** Results from repeated-measures ANOVAs on mean individual reaction times in
 692 mixed blocks of Experiments 1-3.

693

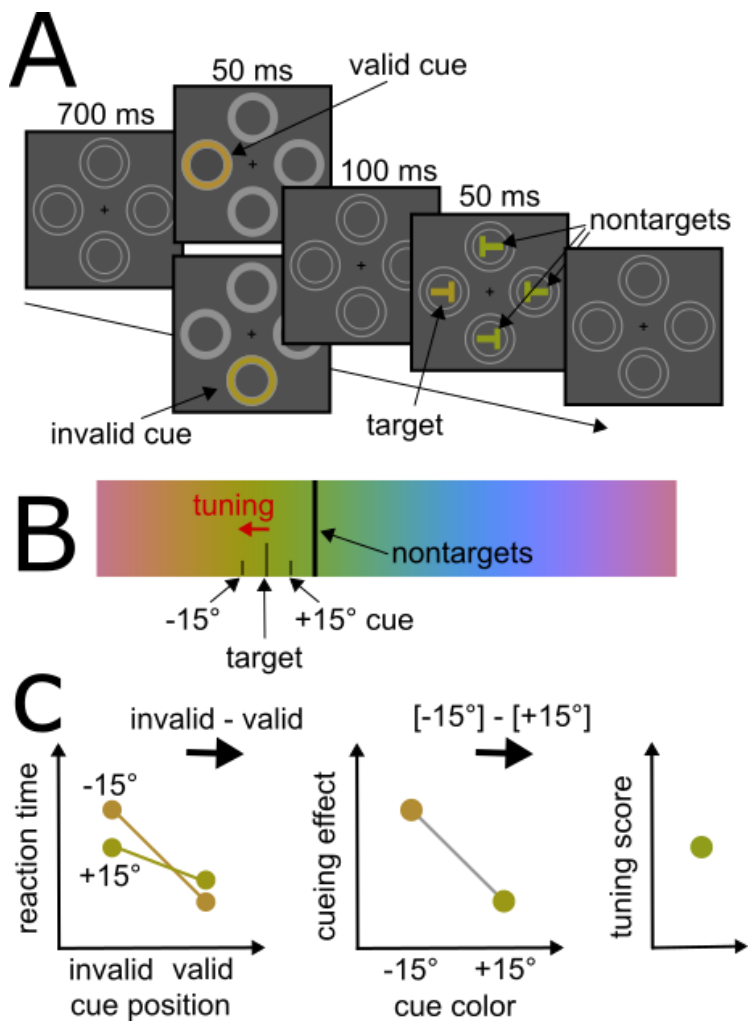
factor	Experiment 1			Experiment 2			Experiment 3		
	<i>F</i>	<i>p</i>	η_p^2	<i>F</i>	<i>p</i>	η_p^2	<i>F</i>	<i>p</i>	η_p^2
- previous TNR	13.19	< .001	.364	-	-	-	13.77	= .001	.375
- cue color		-			-		23.90	< .001	.510
- cue validity	91.07	< .001	.798	50.25	< .001	.726		-	
- previous TNR x cue color		-			-		7.32	= .013	.241
- cue color x cue validity	13.87	= .001	.376	45.13	< .001	.704		-	
- three-way interaction	7.67	= .011	.250	0.80	= .382	.040	8.64	= .007	.273

694

695

696 **Note.** The factorial design of the ANOVAs was 2 (previous target-nontarget relation: match,
 697 no match) \times 2 (cue color: -15° , 15°) \times 2 (cue validity: valid, invalid). The degrees of freedom
 698 were (1, 23) in Experiments 1 and 3, and (1, 19) in Experiment 2. Non-significant effects are
 699 omitted except for the three-way interaction in Experiment 2. TNR = target-nontarget
 700 relation

701

702 **Figure 1.**703 *Illustration of experimental stimuli and data analysis.*

704

705 *Note.* Panel A illustrates the time course of a trial. Panel B illustrates the selection of cue

706 colors. In a CIELAB-based color space, the cue colors deviated either away (-15°) or toward

707 (+15°) the nontarget color. Optimal tuning assumes that attention is tuned away from the

708 nontarget color. Panel C illustrates the data analysis. Subtracting valid from invalid cue trials

709 yields cueing effects. Subtracting cueing effects with the +15° cue color from the -15° cue

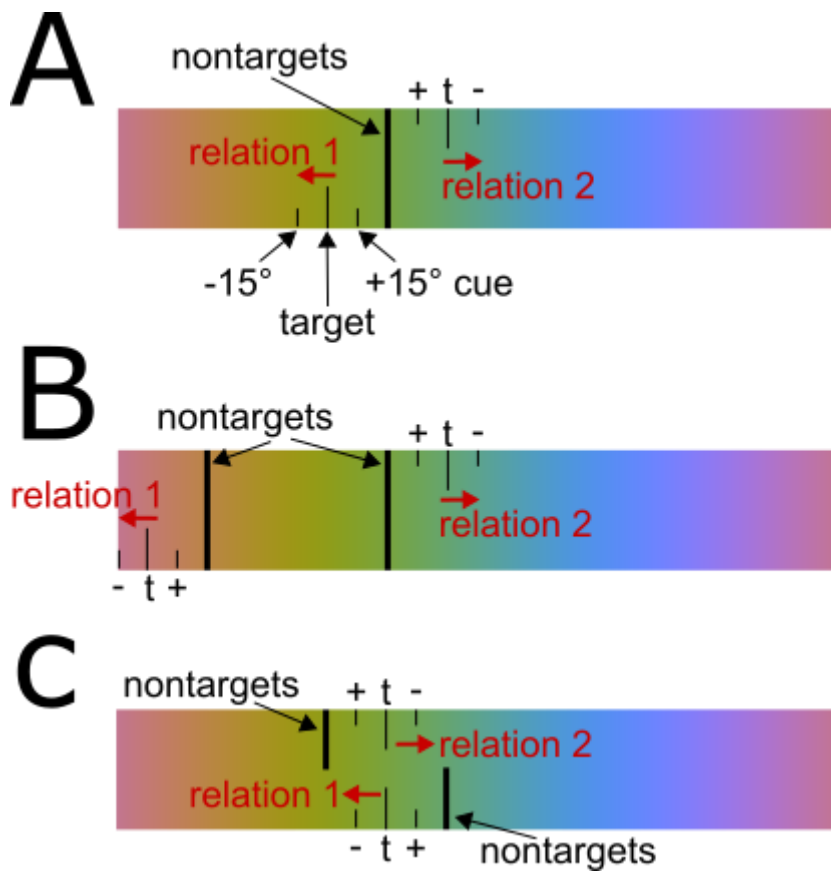
710 color yields tuning scores. Positive tuning scores indicate that the cueing effects were larger

711 for cues deviating away from the nontargets, as predicted by optimal tuning.

712

713 **Figure 2.**

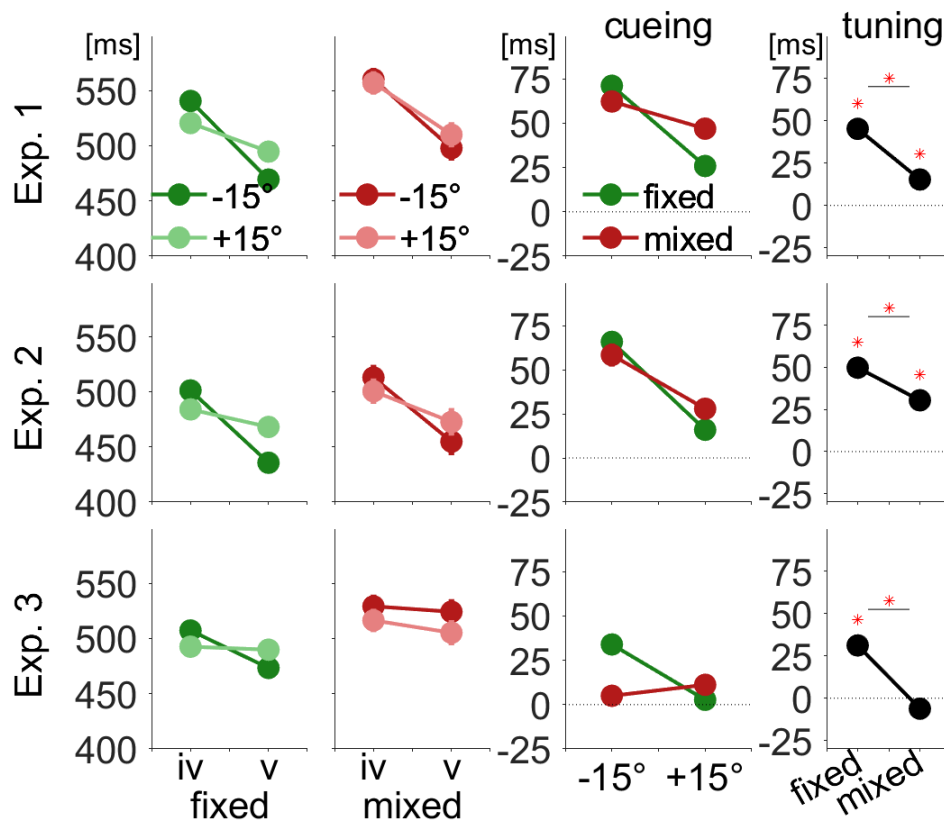
714 *Target-nontarget relations in Experiments 1-3.*



715

716 *Note.* In each Experiment, there were two target-nontarget relations. In Experiment 1, the
 717 nontarget color was fixed and the target color varied (panel A). In Experiment 2, the target-
 718 nontarget relations were far apart (panel B). In Experiment 3, the target color was fixed and
 719 the nontarget color varied (panel C). The signs indicate cue colors deviating away (-) or
 720 towards (+) the nontarget color. t = target.

721

722 **Figure 3.**723 *Results in blocks with fixed and mixed target-nontarget relations in Experiment 1-3.*

724

725 *Note.* The different dependent variables are shown column by column and the data from the

726 different experiments are shown row by row. In the first and second column, the y-axis

727 shows reaction times in milliseconds (ms). Data from trial blocks with fixed and mixed target-

728 nontarget relations are shown in the first and second column, respectively. Trials were

729 averaged as a function of cue color (-15°, +15°) and cue validity (iv = invalid, v = valid). The

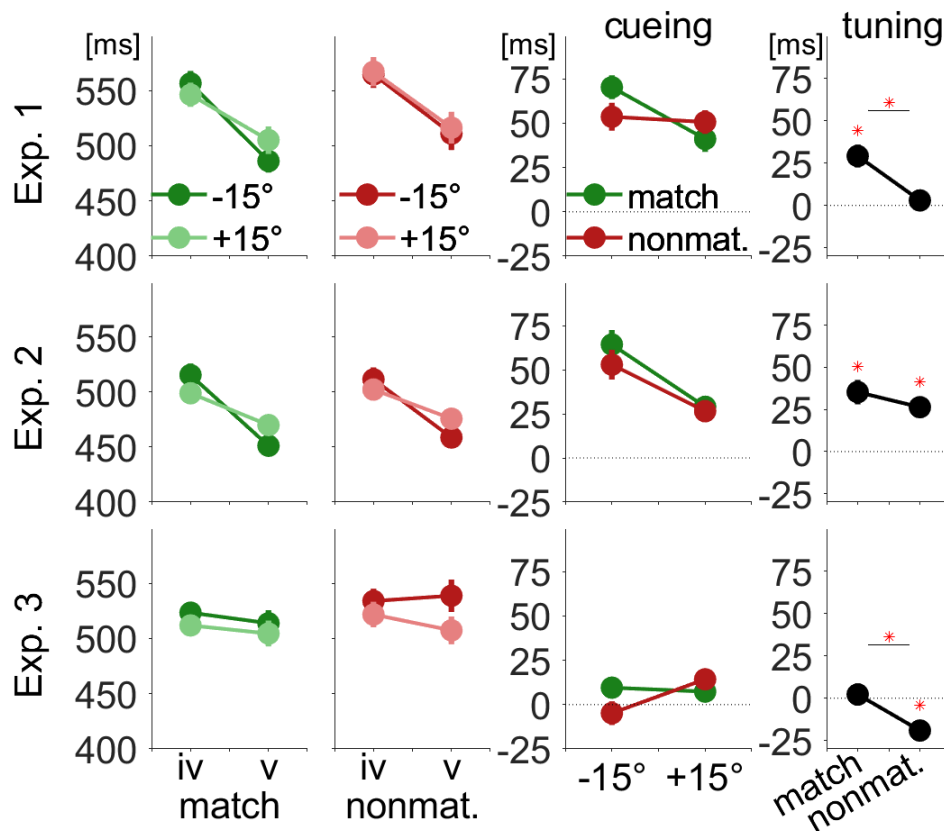
730 third column shows cueing effects (invalid - valid) in milliseconds on the y-axis. Cueing

731 effects are shown for each cue color in fixed and mixed blocks. The fourth column shows

732 attentional tuning scores in milliseconds on the y-axis. Tuning scores are shown for fixed and

733 mixed blocks. Error bars show the between-subject standard error. Error bars were mostly

734 smaller than the symbols. Red asterisks in the rightmost column indicate significant *t*-tests.

735 **Figure 4.**736 *Results from Experiment 1-3, data from blocks with mixed target-nontarget relations.*

737

738 *Note.* The different dependent variables are shown column by column and the data from the

739 experiments are shown row by row. In the first and second column, the y-axis shows

740 reaction times in milliseconds (ms). Data from trial blocks where the cue matched the

741 previous target-nontarget relation (match) and where it did not match (nonmatch) are

742 shown in the first and second column, respectively. Trials were averaged as a function of cue

743 color (-15°, +15°) and cue validity (iv = invalid, v = valid). The third column shows cueing

744 effects (invalid - valid) in milliseconds on the y-axis. Cueing effects are shown for each cue

745 color in matching and nonmatching trials. The fourth column shows attentional tuning

746 scores in milliseconds on the y-axis. Tuning scores are shown for matching and nonmatching

747 trials. Error bars show the between-subject standard error, but were often smaller than the

748 symbols. Red asterisks in the rightmost column indicate significant t-tests. nonmat. =

749 nonmatch