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1 **Inversion of pop-out for a distracting feature dimension in monkey visual cortex**

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24 Draft Preparation, Writing – Review & Editing, Visualization; J.A.M. Lorteije: Conceptualization, Investigation,
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29 **Abstract**

30 During visual search, it is important to reduce the interference of distracting objects in the scene. The
31 neuronal responses elicited by the search target stimulus are typically enhanced. However, it is equally
32 important to suppress the representations of distracting stimuli, especially if they are salient and capture
33 attention. We trained monkeys to make an eye movement to a unique ‘pop-out’ shape stimulus among an
34 array of distracting stimuli. One of these distractors had a salient color that varied across trials and differed
35 from the color of the other stimuli, causing it to also pop-out. The monkeys were able to select the pop-out
36 shape target with high accuracy and actively avoided the pop-out color distractor. This behavioral pattern
37 was reflected in the activity of neurons in area V4. Responses to the shape targets were enhanced, while the
38 activity evoked by the pop-out color distractor was only briefly enhanced, directly followed by a sustained
39 period of pronounced suppression. These behavioral and neuronal results demonstrate a cortical selection
40 mechanism that rapidly inverts a pop-out signal to ‘pop-in’ for an entire feature dimension thereby
41 facilitating goal-directed visual search in the presence of salient distractors.

42 **Keywords:** Visual search, V4, monkey, suppression, enhancement.

43

44 **Significance statement**

45 Goal-directed behaviors like visual search involve both the selection of behaviorally relevant targets and the
46 suppression of task-irrelevant distractors. This is especially important if distractors are salient and capture
47 attention. Here we demonstrate that non-human primates suppress a salient color distractor while searching
48 for a target that is defined by shape, i.e. another feature dimension. The neuronal activity of V4 neurons
49 revealed the temporal evolution of target selection and distractor suppression. The neuronal responses
50 elicited by the pop-out target stimuli were enhanced whereas responses elicited by salient pop-out color
51 distractors were suppressed, after an initial brief phase of response enhancement. Our results reveal a ‘pop-
52 in’ mechanism by which the visual cortex inverts an attentional capture signal into suppression to facilitate
53 visual search.

54 **Introduction**

55 Humans and animals usually need to select one of several stimuli for action. This selection process relies on
56 priority signals in the brain such as the salience of stimuli and the subject's goals (1–7). In the visual domain,
57 for example, one could be faced with the task of locating a target object among distractor objects, e.g., trying
58 to find one's keys on a cluttered desk (Fig. 1A). A combination of bottom-up and top-down processes often
59 solves this problem (3). If the keys have a high saliency because they are bright red, for example, they 'pop
60 out' from the background, which would be considered a bottom-up contribution. However, top-down factors
61 also play an important role. You may, for example, imagine the shape of your keychain or try to remember
62 where the keys most likely are. Visual search is therefore a very useful experimental paradigm to study the
63 role of bottom-up and top-down factors in visual selection.

64 In many bottom-up search paradigms, the target pops out, because it has a unique feature. For example, it is
65 the only bright red item among grey distractors, or it is the only circle in the display in which all other
66 elements are squares. There are versions of this paradigm in which subjects do not know beforehand what
67 they will be looking for, but only that it is the unique item. For example, the display might have either one
68 square among circle distractors or one circle among square distractors. The search for items with unique
69 properties is usually parallel, which means that the time to find an item does not depend strongly on the total
70 number of distractors in a search display (7). Previous studies on the neuronal correlates of pop-out search
71 demonstrated that the responses elicited by pop-out stimuli are stronger in the visual, parietal, and frontal
72 cortex than the responses to stimuli that do not pop-out (8–18). In top-down search paradigms, the subject
73 looks for a specific item known as 'search-template' (19, 20)). The search template represents a top-down
74 influence on visual selection (1, 21)) and the representations of the items in the display that match the search
75 template are also enhanced in areas of the visual, parietal, and frontal cortex (19, 22–29).

76 Many displays contain salient distractors that interfere with visual search. This is the case in Figure 1 for the
77 green parrot, which captures attention, making it more difficult to find the keys. Researchers have debated
78 the degree of automaticity of attentional capture, with some researchers arguing that it is mandatory (30)
79 whereas others arguing that it can be prevented by sufficiently strong top-down signals (31). Importantly,
80 conditions exist under which salient display items do not appear to interfere with visual search (32, 33) or
81 cause even less interference than regular, non-salient distractors (34–37).

82 The mechanism by which salient distractors can be suppressed is not yet fully understood and there are
83 contrasting views (38). One possibility is that salient distractors initially capture attention, but that it is
84 rapidly curtailed by top-down suppression mechanisms (39). Support for such reactive suppression comes
85 from human EEG studies employing markers of distractor selection and suppression (40–43). The signal
86 suppression hypothesis (35–37) proposed another account, in which a top-down influence prevents the
87 capture of attention by salient distractors so that there is no need for disengagement. This viewpoint received

87 support from behavioral studies (34, 35, 44) and other human EEG studies (34, 36, 37, 45, 46). We note,
88 however, that the relation between this putative suppressive signal and its EEG signatures is under dispute
89 (43, 47).

90 The degree to which salient distractors attract attention and, hence the need for disengagement, depends on
91 how predictable they are. Salient distractors are more efficiently suppressed if their features are predictable,
92 for example, because they are the same across trials or are known in advance (48, 49). Bichot et al. (50)
93 demonstrated that the representations of stimuli that consistently appear as distractors, across many days, are
94 strongly suppressed in the frontal cortex of monkeys. Like distractor predictability, foreknowledge about the
95 target also decreases the influence of salient distractors. If the subject knows the target, a search template can
96 be established before the display appears and the influence of salient distractors is weaker than in pop-out
97 search in which the target properties are not specified. Researchers proposed that pop-out search demands a
98 special ‘singleton detection mode’ (32). If subjects search for a salient target with unknown features, they are
99 more susceptible for interference by salient distractors. The degree of interference by the distractor depends
100 on the relation between the features of the target and the distractor (35, 36, 38, 51, 52). Interference is strong
101 if the target and salient distractor are defined on the same feature dimension, e.g., if they both have an
102 orientation that differs from that of all other distractors. Interference is weaker if they are defined on a
103 different feature dimension, e.g., the target differs in orientation from the other items whereas the salient
104 distractor differs in color. In this situation, the features can be weighted. The target dimension receives a
105 higher weight than the salient distractor so that the degree of distraction can be diminished (40, 52–54).

106 Two previous studies have examined the neuronal mechanisms for the suppression of salient distractors
107 during visual search. Ipata et al. (55) had monkeys searching for a black target shape among black
108 distractors. They added a salient distractor, which was green and bright, and recorded neurons in the lateral
109 intraparietal area (LIP) of the parietal cortex. As expected, targets elicited stronger neuronal responses than
110 the black distractors, but the activity elicited by the salient green items was even weaker than that elicited by
111 the regular black distractors. Hence, the representation of the salient distractor is efficiently suppressed in the
112 parietal cortex. A later study by Cosman et al. (56) replicated this finding in the frontal eye fields (FEF) in a
113 task where the monkeys searched for a white target letter while the salient distractor was colored. Again, the
114 target letter elicited strongest activity, followed by the regular distractors and the salient distractor elicited
115 weakest activity. These results are in accordance with those of Bichot et al. (50) showing the effective
116 suppression of a specific feature that is always distracting in the frontal cortex. (57, 58). However, parietal
117 and frontal cortex are relatively high up in the cortical processing hierarchy and activity elicited by salient
118 distractors might still be enhanced in the visual cortex, even after extensive training. The representation of
119 salient distractors in visual cortex remains to be investigated.

120 In the present study we tested the generality of the suppression mechanisms by asking three questions: (1)
121 Are salient distractors suppressed in the visual cortex? (2) Is the efficient suppression of a salient distractor

122 stimulus also possible when its features vary across trials? (3) Can salient distractor suppression occur when
123 the subject searches for a pop-out stimulus on a different feature dimension?

124 We trained monkeys in a task in which they carried out a pop-out search for a shape while we presented a
125 salient color distractor with a color that varied across trials. They had to select the shape singleton as target
126 for an eye movement to obtain a juice reward. As expected, the shape singleton elicited stronger V4 activity
127 than the distractors with a different shape. Remarkably, the V4 representation of salient color singleton was
128 briefly enhanced followed by a period of pronounced suppression below the level of representation of the
129 regular non-pop-out distractors, even though its color was unpredictable. At a behavioral level, the monkeys
130 also selected the salient distractor less often than the regular distractors, indicating active avoidance. We
131 conclude that after extensive training, the neuronal mechanisms for visual search can exploit the presence of
132 a color singleton if it is always a distractor, and rapidly cause it to ‘pop-in’ instead of pop-out, thus avoiding
133 capture and promoting efficient goal-directed behavior.

134 **Results**

135 Two monkeys were extensively trained to perform a visual search task (Fig. 1B,C) in which they had to
136 select a single odd-shape-out (target) from an array of six stimuli. On any given trial, the target could either
137 be a circle among squares, or a square among circles. To study whether V4 neurons show suppression of
138 salient distractors, one of the distractor stimuli had a different color than the others (either green among red,
139 or red among green) (Fig. 1B, bottom). The shapes, colors, and locations of the target and salient distractor
140 were randomly assigned on each trial so that the animal could not predict the shape or color of the target and
141 salient distractor. As a result, consecutive trials could have the same shape and colors assigned to the target
142 and distractor, both could change, or one of the feature assignments could stay the same while the other
143 changed. Moreover, to examine a previously reported interaction between stimulus salience and reward in
144 human visual search behavior (59), we randomly rewarded correct responses with either small or large juice
145 rewards (with the large reward being approximately four times the small reward amount). After an initial
146 training phase to learn the task, both monkeys were extensively trained to reach high performance levels (22
147 training sessions for M1, 56 for M2).

148 We recorded 34,543 trials in monkey 1 (M1) and 13,815 trials in monkey 2 (M2) in 28 and 16 sessions,
149 respectively. Both monkeys displayed similar eye movement patterns (Fig. 1D), most often choosing the
150 target stimulus (M1: 69%, M2: 78% of choices), followed by non-salient distractors (M1: 29%, M2: 20%),
151 and only rarely choosing the salient distractor stimulus (M1: 2%, M2: 2%). The lower probability of
152 choosing a salient distractor than a non-salient distractor remained when we accounted for the fact that there
153 were four non-salient distractors and only one salient distractor (see Fig. 1D insets, corrected for prevalence).
154 The probability of choosing the target was much higher than chance (one-tailed t-test, M1: $t(26) = 87.4$, $p <$
155 0.001 ; M2: $t(15) = 53.5$, $p < 0.001$). On error trials, both animals were significantly less likely to choose the
156 salient distractor than a non-salient distractor (prevalence-corrected, one-tailed paired t-test, M1: $t(26) = -$

157 51.6, $p < 0.001$; M2: $t(15) = -21.6$, $p < 0.001$).

158 Swapping the colors of the target and salient distractor on successive trials did not affect accuracy for either
159 animal as indicated by a two-way ANOVA with color-swap and reward quantity as independent variables
160 (all p s > 0.48). It did slow down M1 by a few milliseconds (Fig. 1E; $F(1, 12210) = 38.8$, $p < 0.001$), but had
161 no effect on M2's reaction time ($F(1, 7484) = 1.59$, $p = 0.83$). A change of the target shape had a much more
162 pronounced effect of performance. It decreased the accuracy of both animals and increased the reaction times
163 (Fig. 1E; all $p < 0.001$). There were no interactions between the effects of color and shape changes. These
164 results imply a shape-based priming of pop-out effect across trials (60), but an absence of color-based
165 priming, which is consistent with the animals being in 'shape-searching' mode due to extensive training on
166 the 'odd-shape-out' search task. Unlike previous work in humans (59), we did not observe any main or
167 interaction effects of reward quantity on visual search performance (SI Appendix, Fig. S1).

168 What happened when the monkeys made an error? They predominantly selected the distractor stimulus that
169 was adjacent to the target in the search array (Fig. 1F), a pattern that was neither influenced by the location
170 of the salient distractor, nor by the saccadic reaction time (comparing the 30% fastest and 30% slowest
171 saccades) (squares and diamonds in Fig. 1F). The distribution of erroneous saccades relative to the target
172 position was the same for salient and non-salient distractors (red and grey symbols in Fig. 1F), which
173 indicates that the probability of choosing the salient distractors was decreased uniformly (Fig. 1D) with little
174 influence of the target location.

175 Whereas the signal suppression hypothesis (34) proposes that a salient distractor can be proactively
176 suppressed to avoid attentional capture, the stimulus-driven rapid-disengagement account suggests that
177 capture does temporarily occur but that it is then quickly suppressed. The latter scenario should be associated
178 with a brief period of pop-out for the salient distractor followed by a sustained period of distractor
179 suppression. Because visually guided saccades can occur at very low latencies in both humans and monkeys
180 (61–65), especially after prolonged training (66), and fast saccades tend to be more strongly influenced by
181 stimulus salience (67–69), we wondered whether an early neuronal pop-out of the salient distractor would
182 result in very rapid saccadic responses to the salient distractor before the distractor suppression could have
183 manifested. To investigate this possibility, we compared the distributions of saccade reaction times (SRTs;
184 SI Appendix, Fig. S2) for target and salient distractor choices. A larger proportion of the salient distractor
185 choices than the target choices occurred at the shortest reaction times in both monkeys (Fig. 2A). We
186 calculated the proportion of salient distractor choices ($p_{SD} = n_{SD}/n_{ALL}$) as function of SRT (Fig. 2B). In both
187 animals, the proportion SD choices was significantly higher for the 12.5% shortest SRTs (first octile) than
188 for SRTs in the 2nd-4th octiles (chi-squared test, M1: $X^2(1) = 8.55$, $p < 0.01$; M2: $X^2(1) = 21.41$, $p < 0.001$). In
189 M1 there was even a brief epoch in which the salient distractor was chosen more often than the target, but
190 saccades to the salient distractor were strongly suppressed for longer SRTs. Also, in M2 the salient distractor
191 choices decreased for longer SRTs, but the target was always chosen with the highest probability (SI

192 Appendix, Fig. S2). This result indicates that the distractor pops out in an early interval after stimulus
193 presentation, but that the pop-out signal is rapidly suppressed to prevent erroneous choices.

194 Next, we compared the neuronal responses in V4 elicited by target stimuli, non-salient distractor stimuli and
195 salient distractor stimuli on correct trials (Fig. 3A, top panels). We pooled the data across animals (Fig. 3,
196 left panels) because the results were similar for M1 and M2 (Fig. 3, middle and right panels). The late V4
197 response elicited by target stimuli was stronger than that elicited by non-salient distractor stimuli (time
198 window 150-200 ms after stimulus onset, $t(34) = 8.9$, $p < 0.001$; M1: $t(9) = 5.6$, $p < 0.001$; M2: $t(24) = 7.0$, p
199 < 0.001). The response elicited by the salient distractor stimulus was weaker than that elicited by the target
200 stimulus and, importantly, also weaker than that elicited by the non-salient distractor stimulus ($t(34) = -9.9$, p
201 < 0.001 ; M1: $t(9) = -5.4$, $p < 0.001$; M2: $t(24) = -9.1$, $p < 0.001$). This ordering of response strength was very
202 consistent among recording sites (SI Appendix, Fig. S3).

203 We examined the time-course of target enhancement and salient distractor suppression by subtracting V4
204 activity elicited by the non-salient distractor stimuli from the other two conditions (Fig. 3B). We measured
205 the latency of the enhancement and suppression of targets and salient distractors with a fitting procedure that
206 has been described before (70) (see Material and Methods and SI Appendix, Fig. S4). The latency of target
207 enhancement was 112 ± 9 ms (averaged across monkeys, standard deviation determined with bootstrapping)
208 and the latency of suppression of salient distractors was 158 ± 25 ms. This pattern was also present in
209 individual animals (M1_T: 124 ± 20 ms, M2_T: 108 ± 15 ms; M1_{SD}: 184 ± 14 ms, M2_{SD}: 159 ± 11 ms) and the
210 salient distractor suppression was significantly later than the target enhancement (paired t-test, M1: $t(75) = -$
211 26.3 , $p < 0.001$; M2: $t(72) = -22.1$, $p < 0.001$; Pooled data: $t(67) = -17.7$, $p < 0.001$). Thus, the pop-in effect
212 was expressed in area V4 as a decreased response to the irrelevant singleton, even though its color was
213 unpredictable.

214 The brief early epoch with an enhanced probability of saccades to the salient distractor suggests that the
215 distractor representation might be briefly enhanced in V4 (33, 35, 37) before it is suppressed. We therefore
216 examined the possibility of an early response enhancement. We observed that the salient distractor (Fig. 3B,
217 red bars) indeed caused a brief epoch of enhanced activity before suppression became evident, in a time-
218 window up to 100 ms after stimulus onset (Fig. 3B shows significant modulation in several 10 ms non-
219 overlapping time bins in both monkeys; t-tests at $p < 0.05$, Bonferroni corrected).

220 We also examined a possible influence of the behavioral priming effect, which occurred when the target
221 shape was the same on consecutive trials, on V4 activity. The priming effect did not have a consistent
222 influence on V4 activity (SI Appendix, Fig. S5), which suggests that the increase in SRT may originate in
223 downstream brain regions, as a post-selective process (54). Furthermore, V4 activity on error trials was more
224 variable than on correct trials (SI Appendix, Fig. S3).

225 **Discussion**

226 Goal-directed behaviors require a selection process that highlights relevant stimuli and suppresses
227 distractors. Here, we used a visual search paradigm to investigate the representations of relevant and
228 irrelevant pop-out stimuli (7) in area V4 of the monkey visual cortex. We presented a salient pop-out color
229 distractor with an unpredictable color while the monkeys searched for a singleton shape. Our results
230 demonstrate that the visual brain can suppress the representation of pop-out stimuli on an irrelevant feature
231 dimension while enhancing the representation of pop-out stimuli on a relevant feature dimension. A brief
232 neuronal activity enhancement preceded the suppression of distractor representations (Fig. 4), suggesting that
233 an initial pop-out process is required before it can invert into pop-in. To our knowledge, this is the first
234 demonstration of ‘pop-in’ for an irrelevant feature dimension, which presumably emerged during the
235 monkeys’ considerable training.

236 The efficiency of visual search depends on bottom-up factors that determine the salience of stimuli, such as
237 brightness and local feature contrasts causing pop-out, and the top-down search template, the internal
238 representation of the item that the subject is searching for (1, 3, 4, 22). Researchers have hypothesized that
239 stimulus salience and goal-driven influences on the distribution of attention jointly determine a ‘priority
240 map’ of visual space (3–7, 71–73). There are multiple candidate brain regions for such a priority map,
241 including the LGN (71), pulvinar (74), superior colliculus (75, 76), V1 (77), V4 (66), the parietal (8, 10, 55)
242 and prefrontal cortex (11). Indeed, stimulus-driven pop-out signals have a widespread influence on the
243 neuronal firing rates in early visual cortex (12, 78, 79), parietal cortex (10), frontal cortex (11), and
244 subcortical structures like the superior colliculus (80). Similarly, the top-down influences of the search
245 template on firing rates also occur in most, if not all, of the same brain regions, including V1 (81, 82), V4
246 (15, 18), the parietal (55) and prefrontal cortex (11, 50, 56). It is conceivable that the relative contributions of
247 the multiple priority maps depend on the task, e.g., on the features that matter and on whether the subject
248 reports the location of the target with an eye or hand movement.

249 There are many instances in which the representation of visually salient items needs to be suppressed,
250 because task relevant items are less conspicuous, causing a conflict between bottom-up and top-down
251 factors. The signal suppression hypothesis (36, 37) proposed that top-down suppression signals can prevent
252 attentional capture by salient distractors if their features are known in advance (34–37, 44–46, 51, 56, 83–
253 85). An alternative possibility is that salient distractors attract attention, but that it is rapidly disengaged (39).
254 Previous electrophysiological studies in areas LIP and FEF of monkeys revealed that the neuronal activity
255 elicited by a salient distractor with a predictable color can indeed be suppressed below the activity elicited by
256 regular distractors (55, 56). The suppression of salient distractors has also been measured as a distractor
257 positivity (Pd) component in the EEG of humans (37, 38, 86) but a recent study using the steady-state
258 visually evoked potential (SSVEP) did not find evidence for suppression below the activity elicited by
259 regular distractors (47). This SSVEP study used displays with only few items, however, and it has been

260 suggested that such displays do not emphasize pop out but require other search processes ('clump scanning')
261 (41, 52, 87). The present study went beyond these previous studies by investigating whether suppressive
262 signals influence spiking activity in the visual cortex of monkeys. Furthermore, we used a new task in which
263 the features of the salient distractor were unpredictable, and the monkey was searching for a pop-out
264 stimulus on a different feature dimension.

265 Unlike the previous studies (55, 56), we found that the salient distractor elicited a brief enhancement of V4
266 activity that later inverted into sustained suppression. It seems likely that the early response enhancement
267 occurred because the color of the salient distractor was unpredictable so that it first needed to be registered
268 before it could be suppressed. We also observed a behavioral consequence of this brief pop-out phase
269 because a proportion of the early saccades landed on the salient distractor whereas it was less likely to be
270 selected than regular distractors at later time points, when pop-out has inverted into pop-in. This result
271 provides evidence for short-lived attentional capture, followed by rapid attentional disengagement (38, 39)
272 and goes against the proactive top-down suppression of attentional capture proposed by the signal
273 suppression theory.

274 In a previous study on the role of area V4 during visual search Ogawa and Komatsu (15) trained monkeys to
275 search for either shape or color singletons in displays that also included a singleton in the other dimension, as
276 a salient distractor. Unlike in the present study, however, the monkeys searched for shape and color
277 singletons in alternating blocks of trials. When they made an error, they selected the salient distractor more
278 often than regular distractors, which is also different from the current results. Accordingly, V4 activity
279 elicited by the target of search was strongest, V4 activity elicited by salient distractors was intermediate and
280 stronger than that elicited by regular distractors (15). In other words, in the previous study both the singleton
281 target and the singleton distractor popped out, while in the present study, the color singleton was never
282 relevant and its V4 representation was suppressed below the activity elicited by regular distractors.

283 Our results indicate that there are at least two processing steps in the present search task (Fig. 4). Initially,
284 there is pop-out in two feature dimensions: color and shape. Later in the trial, the activity elicited by the
285 shape singleton remains enhanced, whereas activity elicited by the color singleton is suppressed, indicating
286 that V4 could contribute to a priority map with enhanced target and suppressed distractor representations
287 (Fig. 4). The source of the suppressive pop-in signal is unknown, but it could rely on feedback projections
288 (88, 89) that might have been strengthened during training. In accordance with this view, microstimulation of
289 FEF interacts with stimulus driven activity in early visual cortex in a topographic manner, with an effect that
290 depends on stimulus strength and the presence of distractors (90). It is remarkable that the neuronal
291 mechanisms for the registration of the salient distractor and its later suppression can co-exist with the
292 mechanisms for pop-out on another feature dimension. Previous studies anticipated that the degree to which
293 different feature dimensions cause pop-out can be weighted (52–54). However, to our knowledge, these
294 theories did not anticipate that dimension weights could become negative, causing attentional repulsion of

295 singletons on a specific feature dimension. A limitation of our results is that we do not know whether the
296 activity elicited by the regular distractors, which we used as a reference to compute target modulation and
297 salient distractor modulation, changed during training (91, 92). Future studies could address this question by
298 including neutral distractors with a third color, which is always irrelevant for the task.

299 Previous studies demonstrated a profound influence of the recent history of trial types during visual search.
300 Repeatedly searching for the same stimulus features causes priming. It reduces an observer's reaction time,
301 improves accuracy, and increases the difference between the strengths of the neuronal representation of
302 targets and distractors (9, 18, 60, 93–97). We here observed a priming effect of shape. When the shape of the
303 search target remained the same on consecutive trials, the monkeys were faster and more accurate than when
304 it was different. Interestingly, we did not find a behavioral priming effect of color as was observed in
305 previous studies (9, 18, 93), in which the search target was a color singleton. It therefore seems likely that
306 priming only occurs for the feature dimension that defines the search goal.

307 Earlier studies also demonstrated an effect of reward quantity on visual search performance (59, 98–100). A
308 study in human subjects demonstrated that visual search is faster if a preceding trial with the same target and
309 distractor features gave rise to high, as opposed to low, reward (59). We did not replicate this effect in our
310 monkeys, where reward magnitude on the previous trial did not strongly affect performance. One possible
311 explanation is that the animals were highly trained, which may have reduced their sensitivity to reward
312 outcomes on individual trials. However, other explanations, including species differences, are also
313 conceivable.

314 In conclusion, our work shows parallel mechanisms of target enhancement and salient distractor suppression
315 during visual search in V4 that rapidly develop and manifest behaviorally as efficient distractor avoidance
316 and goal-directed target selection. It seems likely that the conversion of initial distractor enhancement into
317 functional and profound suppression that occurs round 150 ms after stimulus onset reflects a top-down
318 dynamic adjustment of the weights of individual feature dimensions. The extended training history, during
319 which the salient color never coincided with the search target, must have engaged plasticity mechanisms
320 inverting pop-out into pop-in, making the mechanisms of visual search more versatile than might have been
321 anticipated.

322 **Materials and Methods**

323 **Subjects.** All animal procedures complied with the NIH Guide for Care and Use of Laboratory Animals, and
324 were approved by the institutional animal care and use committee of the Royal Netherlands Academy of Arts
325 and Sciences. Two male macaque monkeys participated in the experiment. They were 5 (M1) and 8 (M2)
326 years old at the start of the experiments and weighted between 7-8 (M1) and 8-9 (M2) kg over the course of
327 the recordings. The monkeys were socially housed in pairs in a specialized primate facility with natural
328 daylight, controlled humidity and temperature. The home-cage was a large floor-to-ceiling cage that allowed
329 natural climbing and swinging behavior. The cage had a solid floor, covered with sawdust, and was enriched
330 with toys and foraging items. The diet consisted of monkey chow supplemented with fresh fruit. The access
331 to fluid was controlled, according to a carefully designed regime for fluid uptake. During weekdays the
332 animals received diluted fruit juice in the experimental set-up upon correctly performed trials. We ensured
333 that the animals drank sufficient fluid in the set-up and supplemented extra fluid after the recording session if
334 the monkeys did not drink enough. In the weekend the animals received at least 700 ml of water in the home-
335 cage supplied in a drinking bottle. The animals were regularly checked by veterinary staff and animal
336 caretakers and their weight and general appearance were recorded in an electronic logbook daily during
337 fluid-control periods.

338 **Surgical procedures and training.** We implanted both monkeys with a titanium head-post (Crist
339 instruments) under aseptic conditions and general anesthesia as reported previously (101–103). The monkeys
340 were first trained to fixate a 0.5 diameter fixation dot and hold their eyes within a small fixation window (1.2
341 diameter). They then underwent a second operation to implant arrays of 4x4, 4x5 and 5x5 micro-electrodes
342 (Blackrock Microsystems) in V4. The inter-electrode spacing of the arrays was 400 μm . The animals were
343 later extensively trained to perform the visual search task at adequate performance levels (22 training
344 sessions with the final task for M1, 56 sessions for M2). During the early phase of the training the animals
345 were required to make an eye movement from the fixation point to a single target, and in later phases the
346 distractors were introduced at low contrast which over sessions gradually increased to the same contrast as
347 the target.

348 **Electrophysiology.** Recordings from the chronically implanted electrode arrays were made with TDT
349 (Tucker Davis Technology) recording equipment using a high-impedance head-stage (RA16AC) and a
350 preamplifier (either RA16SD or PZ2). The signal was referenced to a subdural electrode and digitized at 24.4
351 kHz. It was band-pass filtered (2nd order Butterworth filter, 500 Hz – 5 kHz) to isolate high-frequency
352 (spiking) activity. This signal was rectified (negative becomes positive) and low-pass filtered (corner
353 frequency = 200 Hz) to produce multi-unit activity (MUA), which is the envelope of the high-frequency
354 activity (104). MUA reflects the spiking of neurons within 100-150 μm of the electrode and MUA
355 population responses are very similar to those obtained by pooling across single units (103–107). We used a
356 video-camera based eye-tracker (Thomas Recording) to measure the eye position at a sampling frequency of

357 250 Hz. V4 receptive fields were mapped by presenting white squares (1° , luminance 115 cd/m^2) on a dark
358 background (2 cd/m^2) at different positions of a grid (1° spacing). We defined the RF borders as the locations
359 where activity fell below 50% of the maximum (108).

360 We removed trials with artifacts first by calculating the time-average for each trial and removing trials with
361 extreme average MUA responses. We used an iterative z-scoring procedure (values higher than 3 were
362 removed). If z-scores higher than 20 remained in the cleaned collection of trials, the process was repeated,
363 leading to the removal of less than 2% of all the trials. We also removed trials that included any samples
364 (without averaging) that had a z-score higher than 10. To normalize MUA, we subtracted the spontaneous
365 activity level in a 100 ms time window prior to the onset of the stimulus and divided by the peak response
366 after LOWESS smoothing (26 ms window). We only included recording sites with a signal-to-noise (SNR)
367 higher than 2.5. SNR was computed for individual recording sessions by dividing the peak of the smoothed
368 response by the standard deviation of the spontaneous activity level across trials. We excluded recording
369 sites with fewer than 3 recording sessions that met the SNR criterion. For the other recording sites, we
370 averaged the activity per recording site across sessions so that every recording site contributed only once to
371 the statistics.

372 **Behavioral task and stimuli.** Stimuli were presented on a 21" CRT monitor (Dell Trinitron) with a refresh
373 rate of 85 Hz and a resolution of 1024×768 pixels, viewed at a distance of 87 cm. All stimuli were created
374 using the COGENT graphics toolbox (developed by John Romaya at the LON at the Wellcome Department
375 of Imaging Neuroscience) running in MATLAB (Mathworks Inc.) with custom experimental control
376 software (109). The monkeys were trained to perform a visual search task. A trial started when the monkey
377 acquired fixation on a 0.3° red (26.2 cd/m^2) fixation dot in the center of the screen. After 200 ms of fixation
378 within a 1.2° diameter window, 6 stimuli appeared, arranged in a circle around the fixation point, at 5.3°
379 eccentricity. Simultaneously, the fixation dot became green (98.6 cd/m^2) cueing the monkey to make a
380 saccade. The stimuli were visible for 2,000 ms, during which the monkey was required to respond. If the
381 monkey failed to respond in time, the trial was classified as aborted. Each stimulus could be either a square
382 or a circle and was either red (76.0 cd/m^2) or green (114.1 cd/m^2), presented on a gray background (54.2
383 cd/m^2). Stimuli had a size of 1.8° diameter. On each trial, one stimulus had a different shape (the target
384 stimulus), one stimulus had a different color (the salient distractor stimulus), and the 4 remaining stimuli
385 (non-salient distractors) had the same color as the target stimulus and the same shape as the salient distractor.
386 The task of the monkey was to make an eye movement to the target stimulus, while ignoring the salient and
387 non-salient distractors. Choices were detected as the eye-position entering a 4° diameter circular window
388 around one of the stimuli. Upon a correct response, the monkey received a juice reward. This reward was
389 randomly selected to be either small or large (~ 4 times the small amount). The trials were ordered in a
390 pseudorandom fashion. We recorded 34,543 trials across 28 sessions in monkey 1 and 13,815 trials across 16
391 sessions in monkey 2.

392 **Computation of target and salient distractor modulation.** Average MUA responses for target, non-salient
393 distractor, and salient distractor stimuli were calculated for individual monkeys and the pooled data. To
394 compute target and salient distractor modulation we subtracted the response to non-salient distractors from
395 the response to targets and salient distractors, respectively, for each recording site in a 150-200 ms time
396 window after stimulus onset. As statistical test we used paired t-tests over recording sites. The time-courses
397 of target and salient distractor modulation were furthermore evaluated by recalculating the modulation in 10
398 ms non-overlapping bins and statistically tested with a series of t-tests, using Bonferroni correction for
399 multiple comparisons.

400 **Latency of target selection and distractor suppression.** To estimate the latency of the enhancement of the
401 representation of the target and the suppression of the representation of the salient distractor we used a fitting
402 procedure that has been described before (70). Briefly, a cumulative gaussian function was fit to the
403 difference between either the target and the non-salient distractor response (i.e., target modulation) or the
404 non-salient distractor and the salient distractor response (i.e., salient distractor modulation). The latency is
405 estimated as the time point at which the fit reaches 33% of its maximum (SI Appendix, Fig. S4). The fits
406 were calculated based on the population responses, i.e., after averaging across recording sites. We used a
407 bootstrapping procedure (100 times) with replacement to estimate the mean and standard deviation of these
408 latency estimates and compared latencies of target and salient distractor modulations with paired t-tests.

409 **Saccadic reaction times.** We investigated the susceptibility to attentional capture by the salient distractor as
410 a function of saccadic reaction time (SRT). We removed SRTs that were faster than 75 ms because we
411 deemed such responses to be too fast to be visually guided based on previous reports . This resulted in the
412 removal of 6 target (M1: 2, M2: 4) and 9 salient distractor responses (M1: 7, M2: 2). For the remaining
413 responses we calculated the 25th percentile SRT per animal and classified all faster responses as ‘fast SRTs’.
414 The values of these fast SRTs for target and salient distractor choices were compared with Wilcoxon rank
415 sum tests. We also used the full range of SRTs to calculate a proportion of salient distractor choices ($p_{SD} =$
416 N_{SD}/N_{ALL}) within a 20 ms sliding window moving through the range of SRTs with 10 ms increments.

417 **Data, Materials, and Software availability.** All Data & Analysis Code reported in this paper are available
418 on GIN (<https://doi.org/10.1101/2022.06.23.497353>).

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429 **Figure Legends**

430 **Figure 1. Task description and behavioral results. A)** Real-life example of visual search with a salient
431 distractor. When looking for your keys on a crowded desk, you may be looking for small key-shaped objects.
432 Your attention may however be captured by salient objects like the bright green parrot, which might interfere
433 with the process of finding your keys. **B)** We recorded from area V4 while monkeys performed a visual
434 search task in which they selected the odd-shape-out (here a square among circles) with an eye movement.
435 One of the six visual items was in the V4 receptive field. The target was the stimulus that differed from the
436 others by shape. Non-salient distractor stimuli had the same color as the target, while a single salient
437 distractor stimulus popped out because it had a different color. **C)** Example series of three trials. In the
438 second trial the target and distractor shapes swapped with respect to the first trial (this occurred 50% of the
439 time). In the third trial, the target and distractor colors swapped (this also occurred 50% of the time). In
440 addition, the reward magnitude was randomly varied (50% high, 50% low). **D)** Accuracy (green bars) and
441 the proportion of trials on which the monkeys made an error by choosing a non-salient distractor (ND, grey
442 bars) or the salient distractor (SD, red bars). Non-salient distractors are 4 times more prevalent than targets
443 and salient distractors (prevalence indicated with dashed horizontal lines). The insets show the proportion of
444 choices of distractor stimuli corrected for prevalence. Even after this correction, the animals chose the salient
445 distractor less often than the non-salient distractors (* indicates $p < 0.001$ for a one-tailed t-test $SD < ND$).
446 Error bars indicate the standard deviation over recording sessions. **E)** The effects of color and shape swaps
447 on accuracy (top panel) and reaction time (bottom panel) for both monkeys. Yellow lines indicate trials in
448 which the target and salient distractor colors swapped relative to the previous trial; blue lines are trials in
449 which those colors stayed the same. The horizontal axis indicates whether the target shape changed relative
450 to the previous trial. Error bars (often smaller than the data points) indicate S.E.M., asterisks denote $p <$
451 0.001 for main effects as indicated by two-way ANOVAs (no interaction effects were significant at $p <$
452 0.05). **F)** Dependence of erroneous choices on the relative locations of the target (T) or salient distractor
453 (SD) stimuli. The proportion of SD or ND choices on error trials is plotted as function of the distance
454 between the chosen stimulus in the search array (a distance of one indicates the two stimuli were next to each
455 other, a distance of two means there was one stimulus in between, etc.), the identity of the chosen stimulus
456 (grey: ND; red: SD), and the reaction time (30% fastest and slowest response indicated with square and
457 diamond symbols respectively). The dashed lines indicate chance level.

458

459 **Figure 2. Saccadic reaction times and choices. A)** Distributions of shortest saccadic reaction times (SRTs,
460 fastest 25th percentile) for target (T, green) and salient distractor choices (SD, red) in the two monkeys. The
461 distributions were normalized such that both the red and green bars sum up to 100% (see SI Appendix, Fig.
462 S2 for the full SRT distributions, normalized within choice type (as here) and also by the total number of
463 saccades). The dark colors indicate overlap between the red and green distributions. The probability of
464 choosing the salient distractor was increased at short SRTs (black arrows). **B)** Proportion of salient distractor
465 choices (p_{SD}) calculated in a sliding 20 ms window, moving at 10 ms increments. Solid vertical lines are the
466 median, 25th, and 75th percentiles of the full SRT distributions. In both monkeys, the proportion of salient
467 distractor choices is significantly higher for the 12.5% fastest responses (first octile, left of the dashed
468 vertical line) than in the second through fourth octiles (chi-squared test, M1: $X^2(1) = 8.55$, $p < 0.01$; M2:
469 $X^2(1) = 21.41$, $p < 0.001$).

470

471

472 **Figure 3. V4 activity during visual search reveals the time-course of pop-out and pop-in.** **A)** Neuronal
473 responses in area V4 responses on correct trials. Average V4 activity elicited by the target (T, green trace),
474 non-salient distractors (ND, gray trace) and the salient distractor (SD, red trace) averaged across animals (left
475 panel) and for individual monkeys (M1: middle panel; M2: right panel). Shaded area corresponds to S.E.M.
476 across recording sites. Black arrows indicate the average reaction time (for M1 this was later than 250 ms
477 and is not depicted). The light grey areas indicate the time window used for statistical testing of the response
478 modulation, with * indicating $p < 0.001$ with a paired t-test (green: T-ND; red: SD-ND). **B)** Time-course of
479 neuronal target and salient distractor modulation. Top row, difference in activity elicited by the target and
480 non-salient distractor (T-ND; non-overlapping 10 ms time bins) pooled across monkeys (left) and individual
481 animals (middle and right panels). Green bars indicate significant epochs at $p < 0.05$ (t-test with Bonferroni
482 correction for multiple comparisons). Bottom row, difference in activity elicited by the salient distractor and
483 non-salient distractor (SD-ND) with the red bars indicating $p < 0.05$ (t-test, Bonferroni correction). In both
484 animals, there is an initial epoch of salient distractor enhancement, followed by suppression, later than 150
485 ms. Colored arrows indicate the latency of target enhancement (green) and salient distractor suppression
486 (red).

487

488 **Figure 4. Pop-out and pop-in.** During the early phase of the V4 response (middle) to a visual search
489 stimulus (left), both the shape and color singletons pop-out. In a later phase of the response (right), top-down
490 influences invert the pop-out of the salient color distractor into pop-in.