ORIGINAL ARTICLE

Distinct, but top-down modulable color and positional priming mechanisms in visual pop-out search

Thomas Geyer · Hermann J. Müller

Abstract Three experiments examined reaction time (RT) performance in visual pop-out search. Search displays comprised of one color target and two distractors which were presented at 24 possible locations on a circular ellipse. Experiment 1 showed that re-presentation of the target at a previous target location led to expedited RTs, whereas presentation of the target at a distractor location led to slowed RTs (relative to target presentation at a previous empty location). RTs were also faster when the color of the target was the same across consecutive trials, relative to a change of the target's color. This color priming was independent of the positional priming. Experiment 2 revealed larger positional facilitation, relative to Experiment 1, when position repetitions occurred more likely than chance level; analogously, Experiment 3 revealed stronger color priming effects when target color repetitions were more likely. These position and color manipulations did not change the pattern of color (Experiment 2) and positional priming effects (Experiment 3). While these results support the independency of color and positional priming effects (e.g., Maljkovic and Nakayama in Percept Psychophys 58:977–991, 1996), they also show that these (largely 'automatic') effects are top-down modulable when target position and color are predictable (e.g., Müller et al. in Vis Cogn 11:577–602, 2004).

Introduction

Within the last decade, a number of studies have elaborated the beneficial role of visual memory (VM) for the guidance of visual search. Shore and Klein (2000) suggested to distinguish VM influences on visual search on three different time scales: first, VM guidance across sequences or blocks of trials, that is, perceptual learning (e.g., Chun & Jiang, 1998; Ogawa, Takeda, Kumada, 2007); second, VM influences across single experimental trials, that is, cross-trial priming (e.g., Wang, Kristjánsson, & Nakayama, 2005; Geyer, Müller, & Krummenacher, 2007); and third, VM influences within single experimental trials, that is, within-trial memory. With regard to the latter, two prominent VM mechanisms have been proposed to regulate the deployment of attention within a given trial: inhibition of return (e.g., Klein Munoz, Dorris, & Taylor, 2001; Müller & von Mühlenen, 2000) and visual marking (e.g., Braithwaite, Humphreys, Hulleman, & Watson, 2007; Müller, von Mühlenen, and Geyer, 2007).

Concerning cross-trial priming, in a pioneering study Maljkovic and Nakayama (1994) investigated featural priming in a pop-out search task. The search displays contained three diamond-shaped search items presented in regular triangular arrangement on the circumference of an imaginary ellipse (see Fig. 1 for an illustration of Maljkovic and Nakayama's set-up). Observers had to attend to the color singleton target: a red target amongst green distractors or vice versa, and respond to its orientation, that is: the
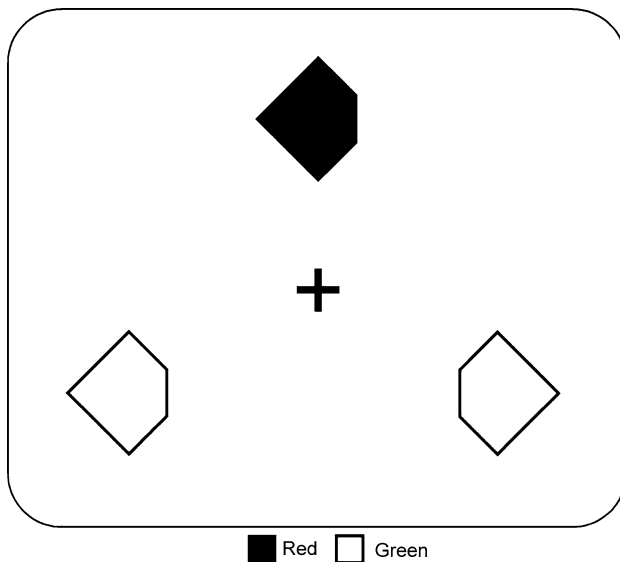
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■ Red □ Green

Fig. 1 Example of the search displays used by Maljkovic and Nakayama ([1994](#)). A given search display comprised of three display items (one target plus two distractors) which appeared in a roughly circular arrangement with equal inter-item separations. Observers had to attend to the color singleton target (*red* vs. *green*) and respond to its cut-off side (*left* vs. *right*). The color of the target determined the color of the distractors (as was the case for position), and the orientation of the target and of each of the two distractors (i.e., their cut-off sides) were varied independently. The color, orientation, and position of the target changed randomly from trial to trial

side on which the color singleton diamond was cut off (left or right). Across trials, the stimulus colors, orientations, and positions changed unpredictably, with stimulus values being assigned randomly to the target singleton. Maljkovic and Nakayama found that RTs were faster when the color of the singleton target on the current trial (N) was identical to the color of the target on a previous trial ($N - j$), relative to a change of the target's defining color. These color priming effects were evident across sequences of 5–8 preceding trials (Experiment 5), cumulative (i.e., the beneficial effect of repetition of the target color became larger as the number of repetitions increased; Experiment 7), and apparently not penetrable by top-down control (Experiment 4). In a follow- up paper, Maljkovic and Nakayama ([1996](#)) found further that the presentation of the N target at an $N - j$ target location led to expedited RTs, whereas the presentation of the N target at an $N - j$ distractor location led to slowed RTs (relative to the presentation of the N target at an $N - j$ empty, i.e., 'neutral' location). Maljkovic and Nakayama attributed these results to an implicit memory system ('priming'), whose function is to guide attention towards stimuli of recent behavioral relevance (the target) and away from stimuli recently avoided (the distractors)—importantly, without the need for 'supervisory' top-down control (Maljkovic & Nakayama, 2000).

While it is well accepted that priming effects can accumulate and last for several seconds (see, e.g., Huang, Holcombe, & Pashler, [2004](#)), there is an ongoing controversy whether repetition effects in visual search are simply due to passive and automatic processes that are not top-down penetrable, or whether a degree of top-down modulation is possible (pro top-down modulation: e.g., Hillstrom, [2000](#); Müller, Krummenacher & Heller, [2004](#); Müller, Reimann & Krummenacher, [2003](#); contra top-down modulation: e.g., Maljkovic and Nakayama [1994](#), [1996](#), [2000](#); McCarley & He, [2001](#)). Specifically, in Maljkovic and Nakayama's Experiment 4 (1994), the color of the target changed every second trial (i.e., red–red–green–green–red–red), enabling observers to fully predict the color of the target on the upcoming trial. Color priming was assessed by comparing RT performance between same- (e.g., red–red) and different-colored targets (e.g., green–red; = baseline performance) across two consecutive trials ($N - 1 \rightarrow N$). Two conditions were used in this experiment: first, an active condition in which observers had to respond to the orientation of the current target and subvocally name the color of the target on the next trial; and second, a passive condition in which observers only had to respond to the target's orientation. Maljkovic and Nakayama hypothesized that, if observers can take advantage of complete predictability of target color, facilitatory priming resulting from repetition of target color should be less in the active compared to the passive condition—because of observers' overall higher incentive to take advantage of the target's predictable color in the former condition. That is: active 'set' to target color should reduce the negative effect (RT slowing) of a change of target color, leading to less facilitatory priming in the active relative to the passive condition. But contrary to this expectation, the amount of facilitatory priming was near-equivalent in the two conditions, suggesting that top-down efforts do not influence the amount of priming. Consequently, Maljkovic and Nakayama ([1994](#)) assumed priming to be 'automatic' in nature.

In contrast, Hillstrom ([2000](#)) found a similar color facilitation effect as described by Maljkovic and Nakayama ([1994](#)) in a feature search task (Experiment 1). The experiment was run in trial sequences in which the target-defining color changed either randomly from one trial to the next (random sequence) or in regular (AABBAA…) alternations (alternating sequence). The main findings were that RTs were faster for alternating as compared to random trial sequences, and, of particular relevance, that the color repetition effect was larger for alternating relative to random sequences. Hillstrom interpreted both findings as effects of top-down "expectancy" (p. 803).

Thus, the existing data are equivocal with regard to whether or not priming can be influenced intentionally. The

present experiments were designed to reinvestigate this issue.

Two distinct priming systems in visual pop-out search

The study of Maljkovic and Nakayama (1996) is interesting in another respect: the separateness of color and positional priming. When examining the effects of repeated target color and target position, Maljkovic and Nakayama (1996) found that the pattern of positional priming (i.e., fastest RTs when the target was presented at a previous target location, intermediate RTs when it was presented at a neutral location, and slowest RTs when it was presented at a distractor location) was not affected by repetitions/changes of target color. This result led Maljkovic and Nakayama to suggest that positional and color priming are independent of each other.

Since then, the hypothesis of separate (color and positional) priming systems has received support from a variety of studies, ranging from neurophysiological (e.g., Fecteau & Munoz, 2003) to patient work (e.g., Kristjánsson, Vuilleumier, Malhotra, Husain, & Driver, 2005). For example, using functional magnetic resonance imaging (fMRI) under conditions similar to Maljkovic and Nakayama (1994); Kristjánsson, Vuilleumier, Schwartz, Macaluso, and Driver (2007) found that repetition (vs. change) of the target location led to the suppression of the blood oxygen level-dependent (BOLD) signal in the intraparietal sulci bilaterally, the anterior cingulate cortex, the frontal eye fields, and inferior regions of the right parietal cortex. These effects were evident independently of the current target position (left vs. right visual field) and target color repetitions (same vs. different). In contrast, repetition of target color (instead of target location) led to BOLD suppression in left inferior temporal cortex, independently of where the target appeared in the visual field (left vs. right visual field). These results provide evidence that positional and color priming involve separable brain mechanisms.

Similar conclusions have been reached in a study of neglect patients suffering from damage to the right inferior parietal lobe (Kristjánsson et al., 2005). Using an experimental paradigm adopted from Maljkovic and Nakayama (1994), Kristjánsson et al. found evidence of intact color and position priming even by stimuli presented in the patients' contralesional (left) visual field. As of most importance, when the search stimuli were presented for only 200 ms (Experiment 3), patients often failed to detect left-side targets, but nevertheless showed reliable color, but not positional, priming, even when they had missed the target on the previous trial. This dissociation again suggests that color priming is different from locational priming.

In sum, the available data suggest the existence of two distinct (color and position) priming systems in visual pop-out search. Therefore, a second aim of the present study was to provide additional (psychophysical) evidence regarding the operation of the two priming systems.

To preview the results, all experiments (1 through 3) replicated positional priming: expedited RTs when the target appeared at a previous target location and slowed RTs when it appeared at a distractor location (relative to a neutral location). In addition, repetition of the target color (relative to a change of target color) led to RT gains, but the positional priming effects were independent of the color repetition effects. This result closely replicates previous findings (Maljkovic and Nakayama 1996), suggesting independency of color and position priming. Further, increasing the likelihood that a given target position (Experiment 2) or target color (Experiment 3) was repeated across sequences of trials led to more persistent priming effects (i.e., longer backward extension or slower decay rate) relative to the baseline Experiment 1. Importantly, the position manipulation in Experiment 2 did not affect the color priming effects, and the color manipulations in Experiment 3 did not affect the positional priming effects. Overall, these results support the assumption of independent, but top-down modulable color and position priming systems.

Experiments

The aim of the present set of three experiments was twofold: to examine, first, whether priming can be modulated intentionally; and second, whether positional and color priming are independent of each other. To investigate these issues, in all experiments, the color singleton target was either red or green and it appeared at one out of 24 possible locations. Experiment 1 served as the baseline condition, with repetitions of target location and target color occurring at chance level (i.e., $1/24 = 4.2\%$ for locational repetitions; $1/2 = 50\%$ for color repetitions). This was intended to provide a 'pure' measure of 'automatic' repetition effects in visual pop-out search (i.e., implicit top-down guidance—Wolfe, Butcher, Lee, & Hyle, 2003). In Experiments 2 and 3, there was a higher likelihood for the target to appear either at the same location (Experiment 2) or in same color (Experiment 3) as on the previous trial(s). It was hypothesized that, if observers can take advantage of the predictability of target position and/or color, then priming effects should be larger in Experiment 2 and/or Experiment 3, compared to Experiment 1, because top-down guidance should lead to expedited RTs when target attributes are repeated and/or slowed RTs when target attributes change. Related to this, top-down effects may become manifest not only following a single repetition (i.e., from trial $N - 1$ to trial N), but also after a series of repetitions (e.g., Geyer, Müller, & Krummenacher, 2006). According to the latter

hypothesis, top-down effects were expected to modulate the temporal extension of priming (i.e., slower decay of priming across longer sequences of same-position and/or same-color trials).

Furthermore, if two separate color and position priming systems exist, the positional manipulation in Experiment 2 should have an effect on positional priming, but not color priming; conversely, the color manipulation in Experiment 3 should influence color, but not positional, priming.

Method

Participants

Eight different observers participated in each experiment, giving a total of 24 observers (17 females; mean age: 22.3 years; all reported normal or corrected-to-normal visual acuity and intact color vision). All observers were naïve as to the purpose of the study, and gave informed consent prior to their participation. They were paid at a rate of Euro 8.00 per session.

Apparatus

The experiment was conducted in a dimly lit laboratory, to minimize reflections on the CRT monitor. Stimulus presentation and RT measurement were controlled by a 75 MHz Pentium I PC. Stimuli were presented on a 17-in. color monitor (at a frame rate of 60 Hz), with a resolution of 640 × 480 pixels. Observers viewed the monitor at a distance of approximately 60 cm, maintained by the use of a chin rest. They responded by pressing the right and, respectively, left buttons of a serial Microsoft mouse, with track ball removed to improve timing accuracy (Segalowitz & Graves, 1990). The experimental control software was purpose-written in C++.

Stimuli

The stimuli, which were modeled after Maljkovic and Nakayama (1994), (1996); (see also Fig. 1), were red and green diamonds, all with a cut-off section to the left or right side (with side determined randomly for each stimulus). There were always one target plus two distractors in the display. The target was unique in color; when the target was red, the distractors were green, and vice versa. The colors were near-equiluminant: red, 7.7 cd/m²; green, 8.0 cd/m². The screen background was black (luminance of 0.5 cd/m²). The size of the diamonds was $1.2° \times 1.2°$ of visual angle, with a cut-off section of 0.3° either to the left or the right side. The search elements were arranged on a near-circular 'ellipse', with horizontal and vertical axes of 17.5° and 14.0°, respectively. The center of the ellipse was marked by a white fixation point, $0.5° \times 0.5°$ in size and 13.7 cd/m² in luminance.

In the baseline Experiment 1, the probabilities for the target's position and color to be repeated on one of the trials $(N + j)$ following a given trial N were unbiased (chance level): 0.04 (1/24) and 0.50 (1/2), respectively. In Experiments 2 and 3, the position and, respectively, color of the target could be same across longer, biased sequences of (up to five) trials. These sequences were generated according to the procedure introduced by Kristjánsson, Wang, and Nakayama (2002): In Experiment 2, the probability that the target position was repeated on any one of the subsequent trials was equal to $1-R$ $(0.2-0.002R)$, where R represents the number of repetitions. Thus, if the target was positioned, say, at the top of the ellipse on trial $N - 1$ and at the bottom on trial N, the probability for the target to be represented at the bottom of the ellipse on trial $N + 1$ was 0.80 (and 0.61, 0.42, 0.23, and 0.05 for trials $N + 2$, $N + 3$, $N + 4$, and $N + 5$, respectively). In Experiment 3, the probability that target color was repeated was equal to $1 - R$ $(0.1-0.0025R)$. For example, if the target was red on trial $N - 1$ and green on trial N, the probability that it was again green on trial $N + 1$ was 0.90 (and 0.81, 0.72, 0.64, and 0.56 for trials $N + 2$, $N + 3$, $N + 4$, and $N + 5$, respectively). For both repetitions of target position and of target color, the probabilities were set to 0 when R reached 6. Thus, while sequence length was variable for both target attributes (though it was likely that a given attribute would be repeated on the next trial), repetitions were limited to 5 trials maximally.

Design and procedure

Experiments 1 through 3 consisted of 1,152 trials each. At the beginning of each trial, a fixation cross was presented in the center of the monitor. After 1,000 ms, the search array was displayed (with the fixation cross remaining on) until the observer responded to the orientation (i.e., the side of the cut-off section) of the target by pressing the left or the right mouse button, respectively, using the index finger of the corresponding hand. The response was followed by a blank screen for 1,000 ms, after which the next display was presented. Error feedback (an error occurred when the right section of the target was cut off and the observer pressed the left button, and vice versa) was not provided. Observers viewed the monitor from a distance of about 60 cm, with head position maintained by the use of a chin rest.

Each experiment consisted of one session (of about 1 h), with a session consisting of 12 blocks of five (unrecorded) warming-up trials plus 91 experimental trials. Blocks were separated by short breaks. At the beginning of the first session, observers performed two blocks of 96 practice trials each (data not recorded).

Results

Data were analyzed using *R* (Ihaka & Gentlemen, 1996). Trials on which a response error was made (Experiment 1: 4.2%; Experiment 2: 3.2%; Experiment 3: 5.3%; see also Fig. 2) were eliminated prior to RT analysis. When examining for the effects of repetition, the current trial may have been influenced by the preceding trial or it may have influenced the subsequent trial. Therefore, responses on trials that preceded or followed an erroneous response were not analyzed. Furthermore, for each observer and experimental condition, RTs 2.5 standard deviations above or

below the mean were discarded as outliers (overall, 2.6% of the trials).

First-order repetition effects

Figure 2 presents the group mean correct RTs and repetition effects (left section of each diagram), along with the error rates (right section), as a function of experiment and separately for repetitions of target position (left panels) and color (right panels). RTs to the target on trial *N* were examined dependent on the position and color of the current target relative to the position and, respectively,
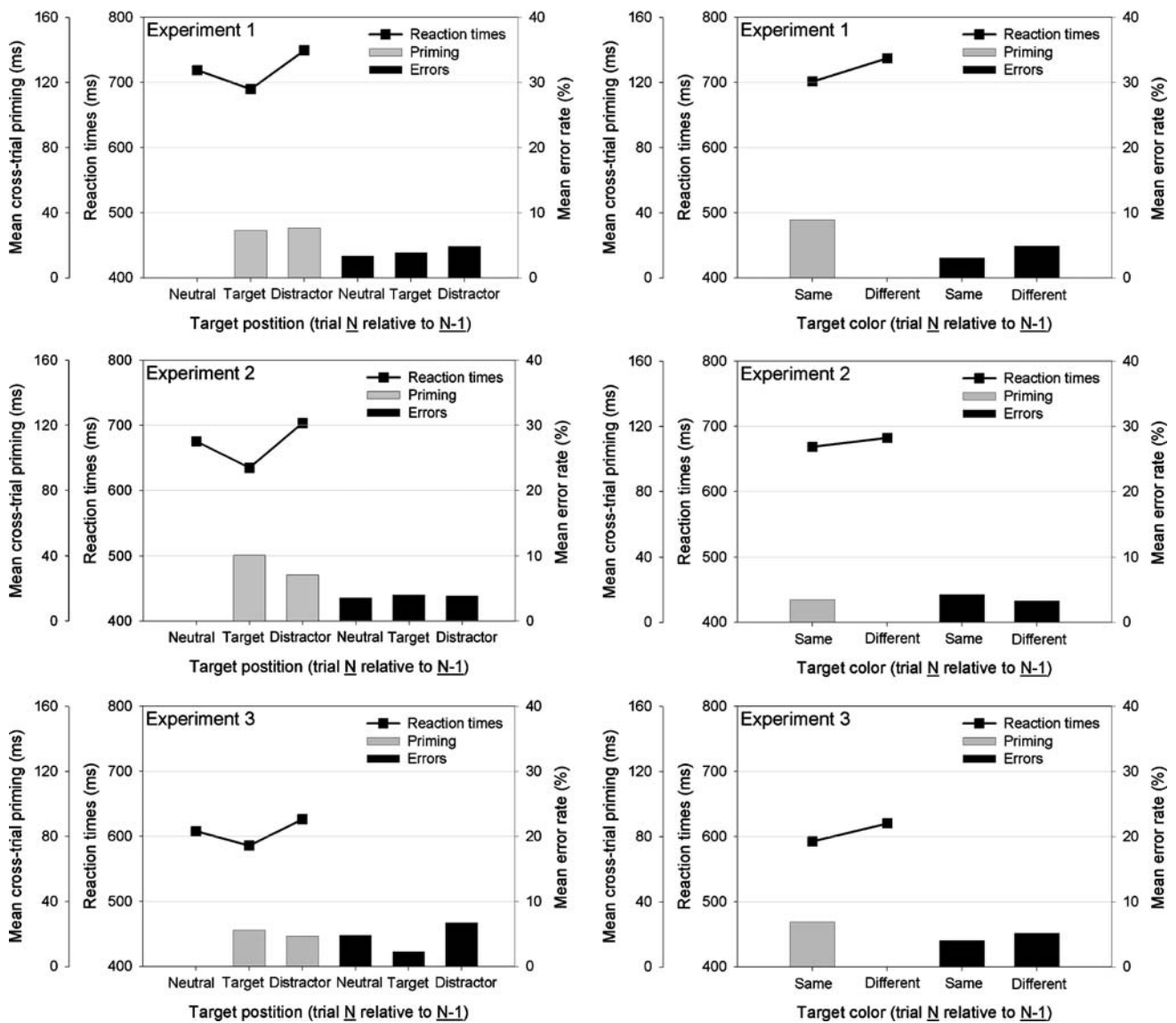
Fig. 2 Mean correct RTs (compare lines with inner left *y*-axis) and mean cross-trial priming (compare *grey bars* with outer left *y*-axis) and error rates (compare *black bars* with right *y*-axis) in Experiment 1 (*top panel*), Experiment 2 (*middle panel*), and Experiment 3 (*bottom panel*), separately for repetitions of target position (*left*) and color (*right*). Positional priming resulting from trial *N* − 1 was assessed by

comparing RTs in the target-at-target-location (facilitation) and target-at-distractor-location condition (inhibition) to RTs in the target-at-neutral-location condition, respectively. Color priming was assessed by comparing RTs on trial *N* dependent on whether the target color was different versus the same relative to trial *N* − 1

color of the target on trial $N - 1$. RTs were analyzed by a mixed-design ANOVA with the factors experiment (1, 2, 3; between-subject variable), target position (target at neutral location, target location, distractor location; within-subject variable), and target color (same, different; within-subject variable). All three main effects were significant: experiment [$F(2, 14) = 9.75$, $P < 0.01$, MSE = 15,759.95], target position [$F(2, 14) = 17.94$, $P < 0.01$, MSE = 2,119.64], and target color [$F(1, 7) = 52.16$, $P < 0.01$, MSE = 452.17]. No interaction effects were significant (this includes the target position × color interaction). Tukey LSD post-hoc tests revealed that RTs were overall faster in Experiment 3 compared to Experiments 1 and 2 (606 vs. 719 and 670 ms), and there was also a tendency for RTs to be faster in Experiment 2 than in Experiment 1 (670 vs. 719 ms; $0.10 > P > 0.05$). Furthermore, RTs were fastest when the target appeared at a target location, intermediate when it appeared at a neutral location, and slowest when it appeared at a distractor location (636 vs. 667 vs. 692 ms; main effect of target position). Finally, RTs were faster when two consecutive targets were the same, rather than different, in color (653 vs. 679 ms; main effect of target color).

Higher-order repetition effects

Figure 3 presents the priming effects arising from the repetition of target position and, respectively, color across sequences of up to five trials ('higher-order repetition effects'). To determine the influence of the target location on, say, trial $N - 5$ on the RT on trial N, only trials for which all intervening trials ($N - 4$, $N - 3$, $N - 2$, $N - 1$) had targets appearing at either a neutral or the repeated target, but not a distractor, location (relative to trial $N - 5$) were included. Regarding color priming, to determine the influence of the target color on trial $N - 5$ on the RT on trial N, all intervening trials ($N - 4$ through $N - 1$) on which the target appeared in same or a different color (relative to trial $N - 5$) were included in the analysis. 'Higher-order' RTs were entered into linear regressions to estimate the RT gains associated with each repetition of target position or color (i.e., the slopes of the RT × target repetition function). For Experiment 2 (predictable target location) linear regressions revealed the effects of repetition of target location constant across trials (although there was a tendency for RTs being slowed by 5 ms for each repetition of target location this effect was non-significant: Beta = 0.54, $P > 0.30$]. In contrast, for Experiment 1 (baseline) and Experiment 3 (predictable target color), each repetition of target location *slowed* RTs by 5 and, respectively, 2 ms [Experiment 1: Beta = 0.92, $P < 0.05$; Experiment 3: Beta = 0.96, $P < 0.01$]. As suggested by Fig. 3 (left-middle panel), the non-finding of

temporally extended priming when target location was predicable may be due to observers expecting a change, rather than repetition, of the target's location at the end of a trial sequence (i.e., when the probability for positional repetitions was only low—i.e., 0.05 for trial $N + 5$). This hypothesis was confirmed by additional linear regression analyses, but only for trials $N - 1$ through $N - 4$. While for Experiment 2 (predictable target location), each repetition of target location speeded up RTs by 2 ms [Beta = −0.80, $P < 0.05$], for Experiment 1 (baseline) and Experiment 3 (predictable target color), each repetition of target location slowed RTs by 7 and, respectively, 1 ms [Experiment 1: Beta = 0.99, $P < 0.01$; Experiment 3: Beta = 0.92, $P < 0.05$].

This RT pattern was confirmed by a mixed-design ANOVA with the factors experiment (1, 2, 3; between-subject variable), target position (at neutral, at target position; within-subject variable) and influencing trial ($N - 1$ through $N - 5$; within-subject variable), which revealed the theoretically important three-way interaction significant: [$F(8, 56) = 3.24$, $P < 0.01$, MSE = 84.03]. As confirmed by Tukey LSD post-hoc tests this interaction reflects the fact that, in Experiment 2, the facilitatory RT effect arising from the re-representation of the target at a previous target location was significant from trial $N - 1$ through $N - 5$ (average effect: 39 ms); in contrast, in Experiments 1 and 3, it was reliable only for trials $N - 1$ through $N - 3$ (Experiment 1: 21 ms; Experiment 3: 19 ms; data collapsed for trials $N - 1$ through $N - 3$).

A similar pattern was obtained with regard to repetitions of target color. For Experiment 3 (predictable target color) each repetition of target color speeded up RTs by 8 ms [Beta = −0.94, $P < 0.01$]; by contrast, in Experiment 1 (baseline) and Experiment 2 (predictable target position), each repetition of target color led to a slowing of RTs by 5 and, respectively, 1 ms [Experiment 1: Beta = 0.89, $P < 0.05$; Experiment 2: Beta = 0.78, $P < 0.05$]. And this was confirmed by a mixed-design ANOVA with the factors experiment (1, 2, 3), target color (same, different; within-subject variable), and influencing trial, which revealed the three-way interaction to be significant [$F(8, 56) = 2.75$, $P < 0.05$, MSE = 205.21]. This interaction was due to the fact that, in Experiment 3, the facilitatory effect resulting from target color repetition extended back across all trials intervening between the current trial N and the influencing trial $N - 5$ (average effect size: 45 ms); in contrast, in Experiments 1 and 2, the facilitatory effect was significant only for influencing trials $N - 1$ and $N - 2$ (Experiment 1: 28 ms; Experiment 2: 16 ms; data collapsed for trials $N - 1$ and $N - 2$). In sum, increasing the probability within which a given target location (Experiment 2) or color (Experiment 3) was repeated led to temporally extended facilitatory priming,
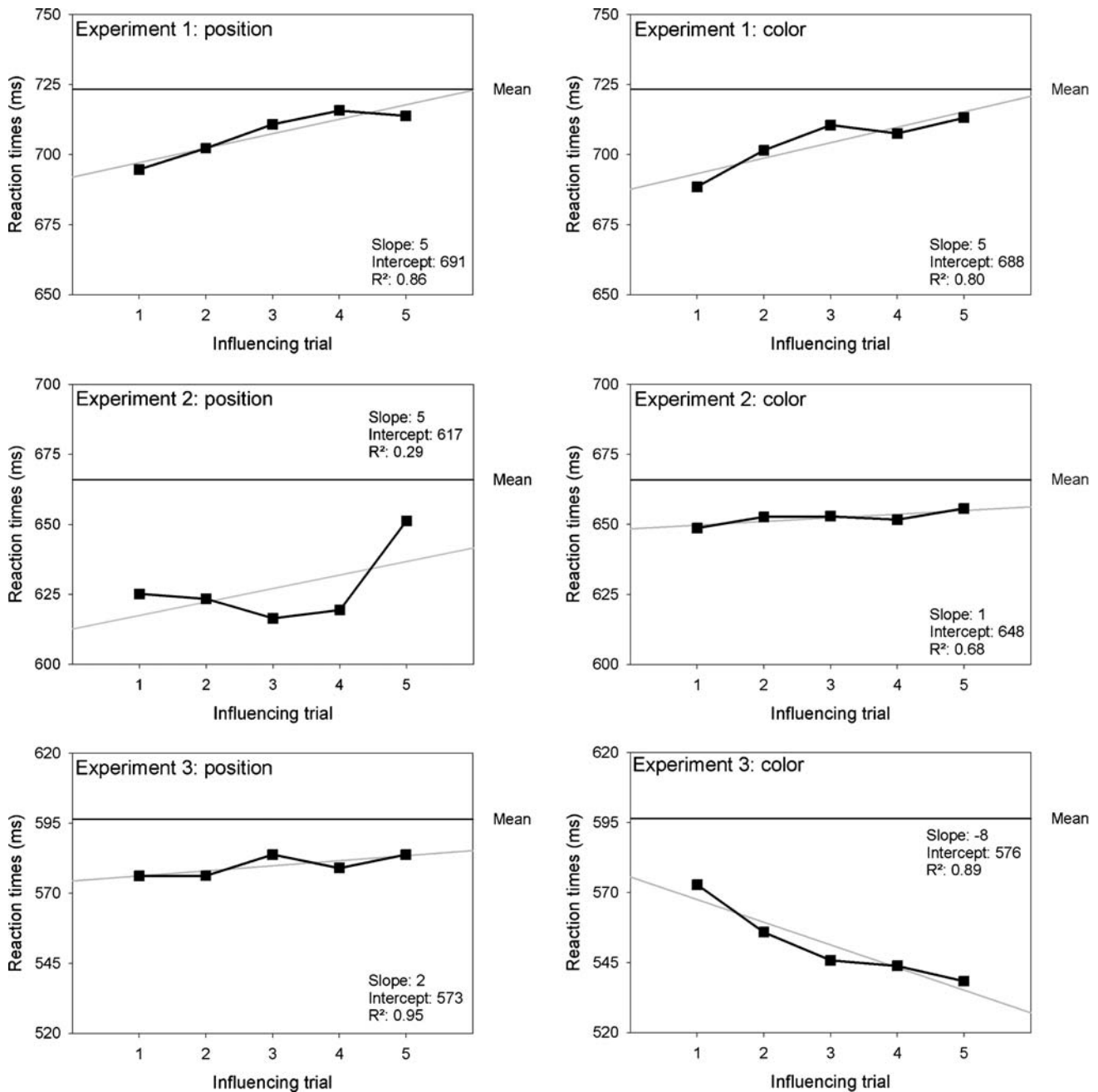
Fig. 3 Mean 'higher-order' RTs to targets on trial N presented at an $N - j$ target location (*left*) or in $N - j$ target color (*right*), separately for Experiment 1 (*top panel*), Experiment 2 (*middle panel*), and Experiment 3 (*bottom panel*). For example, for influencing trial number 3, the location, or color, of the current target N are same as the location, or color, of target $N - 3$ (with targets on intervening trials $N - 2$ and $N - 1$ presented at the $N - 3$ target or a neutral location, or presented in the same or a different color relative to the $N - 3$ target). The *black lines* represent the trial N mean RTs, the *grey lines* the best linear fit to the data. All panels also list the RT slopes and intercepts, and the amount of variance explained by the linear regression (R^2)

but only for the target attribute (position or color) that was subject to this manipulation.

Concerning the higher-order color priming effects, one potentially confounding factor may be that, in Experiment 3 (predictable target color), color priming extended further back in time because the number of intervening trials with same-color targets was larger than in Experiments 1 (baseline) and 2 (predictable target position). Restated, color priming effects may have been reduced in the latter experiments because statistically any influences of same- and different-colored trials between the critical trials $N - j$ and N might have averaged out due to identical probabilities of same

(0.50) and different target colors (0.50) for each intervening trial.[1] In contrast, the decay of color priming may have been less marked in Experiment 3 because the probability of same-color trials was higher than that of different-color trials (about 70 vs. 30%; values collapsed across trials $N + 1$ through $N + 5$). Therefore, it cannot be ruled out that the differences in color priming between Experiment 3 versus Experiments 1 and 2 are attributable to these differential target color probabilities, rather than to top-down guidance. To examine this alternative explanation directly, 'higher-order' RTs in the three experiments were re-analyzed for the special case in which the target color was identical across a sequence of six trials (i.e., trial N RTs were examined only when the trial N target color was same as that on trials $N - 1$, $N - 2$, $N - 3$, $N - 4$, and $N - 5$). This 'cumulative' analysis permits the 'net' top-down effect to be assessed (without confounding by differential target color probabilities on intervening trials), because in each experiment (1, 2, 3) only pure sequences of same-colored target trials (not intermixed with different-colored target trials) will be analyzed.

As in the above 'higher-order' analysis, linear regressions were calculated to estimate the RT gains associated with each target color repetition in cumulative sequences of same-color trials for each experiment. These analyses revealed each repetition of target color to expedite RTs by 3, 5, and 14 ms in Experiments 1 (baseline), 2 (predictable target position), and 3 (predictable target color), respectively [Experiment 1: $F(1, 3) = 7.86$, $P < 0.01$, rescaled-to-1 MSE = 0.52; Experiment 2: $F(1, 3) = 2.35$, $0.10 > P > 0.05$, rescaled-to-1 MSE = 1,03; Experiment 3: $F(1, 3) = 33.57$, $P < 0.01$, rescaled-to-1 MSE = 0.52]. However, this decrease in RTs was larger in Experiment 3 relative to Experiments 1 and 2: a mixed-design ANOVA, with the

factors experiment, target color, and influencing trial, revealed the three-way interaction significant [$F(8, 56) = 11.50$, $P < 0.01$, MSE = 39.59]. This result rules out that color priming is simply larger (in terms of backward extension) because if more targets have the same, rather than a different color, on the intervening trials (relative to the critical trials). Instead, it demonstrates that top-down expectancies influence the speed with which color priming decays across sequences of same-colored target trials.

Discussion

There was facilitatory priming for targets presented at a previous target location, and inhibitory priming for targets at a previous distractor location (Experiments 1–3). In addition, RTs were expedited when the target was defined by the same, rather than a different, color compared to the previous trial, with the positional repetition effects being independent of the color repetition effects (Experiments 1–3). Furthermore, predictability of target location in Experiment 2 led to enhanced positional, but not enhanced color, priming, relative to the baseline Experiment 1. Similarly, predictability of target color in Experiment 3 influenced the cross-trial extension of the priming effect: color priming was enhanced across sequences of same-color trials, compared to Experiment 1. However, in line with Experiment 2, predictability of one target attribute (color) did not change the amount of priming associated with the repetition of another target attribute (position). This pattern of results provides further evidence for the independence of positional and color priming effects, consistent with previous findings (e.g., Kristjánsson et al., 2006).

A second major conclusion to be derived from the present results is that 'automatic' priming is top-down modulable (e.g., Hillstrom, 2000). This conclusion is supported by (at least) three findings. First, RTs were overall faster in Experiment 3, in which target color was predictable, compared to Experiment 1, in which it was non-predictable. Note that there was also a tendency for RTs to be faster in Experiment 2 (compared to Experiment 1), in which target location was more predictable. Parts of the RT advantage in Experiment 3 may well be due to 'automatic' priming, as evidenced by the finding that the effects of color repetition across two consecutive trials (with a different-color trial preceding the sequence of two same-color trials) were statistically of same magnitude in Experiment 3 (predictable color repetitions) and Experiment 1 (baseline), which suggests that first-order color repetition effects are relatively uninfluenced by top-down factors. However, other parts of the RT advantage in Experiment 3 are attributable to top-down enhanced priming across longer trial sequences, as evidenced by the speeding-up of responses by each repetition of the target color. Second (and related to the first point), higher-order color

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[1] This alternative explanation may, in principle, also hold for the pattern of positional priming effects found in Experiments 1–3: positional priming effects may have been reduced in Experiments 1 (baseline) and 3 (predictable target color) relative to Experiment 2 (predictable target position) because, in the latter, the probability of an intervening trial (between the critical trials $N - j$ and N) containing a same-position target was higher than the probability of a different-position target [Experiments 1 and 3: p(same-position) = 0.04, p(different position) = 0.96; Experiment 2: p(same-position) = 0.40, p(different position) = 0.60; values for Experiment 2 collapsed across trials $N - 1$ through $N - 5$]. Unfortunately, an analogous analysis to that of color priming effects (with pure sequences of same-color trials) could not be conducted for the position priming effects, because the number of pure position repetition sequences was too low in Experiments 1 and 3 to permit statistical examination. However, previous findings suggest that the relative proportions of same- and different-position trials do not affect the temporal extension of positional priming (Maljkovic and Nakayama 1996). Specifically, Maljkovic and Nakayama (1996; Experiment 2) showed that positional priming extended back 5–8 trials – importantly, independently of whether there were 6 or 12 possible target locations. That is, doubling the probability with which a given target position is repeated did not change the temporal extension of positional priming.

repetition effects were temporally extended in Experiment 3 (predictable target color), and higher-order positional repetition effects in Experiment 2 (predictable target position), both relative to the baseline Experiment 1. Third, and importantly, higher-order color repetition effects were also larger in Experiment 3, relative to Experiments 1 and 2, when only identical (i.e., cumulative) sequences of same-color target trials were taken into account.

As reviewed in the Introduction, some prior studies did find evidence of top-down modulation of 'automatic' priming (e.g., Hillstrom, 2000), whereas others did not (e.g., Maljkovic and Nakayama 1994). This raises the question as to the cause(s) of these divergent findings and the conclusions drawn from them. One possible explanation stems from Maljkovic and Nakayama (1994) themselves. In particular, when taking a closer look at their Experiment 4, priming effects in the active condition (in which observers had to subvocally name the color of the target on the next trial, while discriminating the orientation of the target on the current trial) were indeed comparable to the effects in the passive condition (in which observers had only to discriminate target orientation). More precisely, the priming effects resulting from the repetition of target color were of the order of 30 ms in both conditions. However, when comparing the priming effects between alternating and random sequences (Maljkovic and Nakayama 1994; Experiment 4 vs. Experiment 3), observer KN who had participated in both conditions (there were only three observers in each condition) showed a larger color priming effect for random compared to alternating sequences (50 vs. 30 ms). This suggests two things: First, predictable target color changes in the active and, importantly, passive condition may as such reduce the detrimental effects (i.e., RT slowing) resulting from target color changes. Second (and related to the first point), 'automatic' priming seems to be modulable only to some limited degree, as indicated by the comparable priming effects in the active and passive conditions (for a similar conclusion see, e.g., Müller et al., 2003, 2004). In other words, naming of the upcoming target color seems to produce no additional RT advantage or, in terms of Maljkovic and Nakayama, not to further reduce the detrimental effect associated with a change of the target's defining color. Thus, the results of Maljkovic and Nakayama (1994) do not necessarily argue against the notion that priming is top-down modulable, in particular, when RT performance is examined for predictable (alternating) and random sequences (cf. Hillstrom, 2000) rather than predictable (active, passive) sequences alone.

Summary

The present experiments show that priming of color and position are independent phenomena that are top-down modulable. When target attributes were repeated, search RTs were faster relative to the non-repetition of target attributes. Further, facilitatory priming was larger when repetitions of target attributes were predictable across sequences of trials. Color and respective positional repetition effects in visual pop-out search are likely to modulate target feature coding (enhancement) prior to and at the level of the overall saliency computation stage (Töllner, Gramann, Müller, Kiss, & Eimer, 2008; Kristjánsson et al., 2007).[2]

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[2] Of course, this does not rule out other accounts of inter-trial priming effects in terms of the retrieval of task-relevant episodic memories attributing repetition benefits at stages following focal attentional selection (i.e., stimulus-response translation; e.g., Logan, 1990, 2002; Neill, 1997; Waszak, Hommel, & Allport, 2003).

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