Cross-Trial Priming of Element Positions in Visual Pop-Out Search Is Dependent on Stimulus Arrangement

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Two experiments examined cross-trial positional priming (V. Maljkovic & K. Nakayama, 1994, 1996, 2000) in visual pop-out search. Experiment 1 used regularly arranged target and distractor displays, as in previous studies. Reaction times were expedited when the target appeared at a previous target location (facilitation relative to neutral baseline) and slowed when the target appeared at a previous distractor location (inhibition). In contrast to facilitation, inhibition emerged only after extended practice. Experiment 2 revealed reduced facilitatory and no inhibitory priming when the elements' spatial arrangement was made irregular, indicating that positional—in particular, inhibitory—priming critically depends on the configuration of the display elements across sequences of trials. These results are discussed with respect to the role of the context for cross-trial priming in visual pop-out search.

Keywords: pop-out visual search, positional priming, context effects

Recently, there has been a great deal of interest in whether visual search performance is reliant on memory and in how the underlying mechanisms are to be characterized. Although some searches may rely on the explicit representation of the target definition in working memory (e.g., to bias processing toward target features and provide criteria for when the search is to be terminated), other short- and long-term memory mechanisms involved in the guidance of search appear to be more implicit in nature. Two such mechanisms, which operate across longer time spans, have recently been described: *cross-trial priming*, which modulates both singleton feature and conjunction search (e.g., Geyer, Müller, & Krummenacher, 2006; Kristjánsson, Wang, & Nakayama, 2002; Maljkovic & Nakayama 1994, 1996, 2000; Müller, Heller, & Ziegler, 1995), and *contextual cuing*, which has hitherto been shown to play a role only in conjunction search (e.g., Chun & Jiang, 1998, 1999).[1] Both of these mechanisms have been characterized as being implicit and rather primitive in nature.

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Cross-Trial Priming

In Maljkovic and Nakayama's (1994, 1996, 2000) experiments on priming in singleton feature (*pop-out*) search, observers responded to the orientation of a color singleton: either a red target among two green distractors or a green target among two red distractors. The three elements were presented on the circumference of an imaginary ellipse around central fixation, arranged in terms of a near-equilateral triangle. The color and position (as well as the response-critical orientation) of the target—and, consequently, of the distractors—changed unpredictably from trial to trial. Maljkovic and Nakayama (1996) found that observers responded faster when the color of the singleton target on the previous trial(s) was repeated compared with when it was changed. In addition, there was a positional-priming effect: Observers responded faster when the target on a given trial appeared at a previous target location relative to a neutral (previously empty) position, and they responded slower when the target appeared at a previous distractor location. These facilitatory and inhibitory effects could be traced back not only to the immediately preceding trial but also across a sequence of 5–8 trials (see Figure 1, which presents the positional-priming effects found by Maljkovic & Nakayama, 1996). Interestingly, these priming effects occurred even though observers were unable to report the search-critical (i.e., color, position) and response-critical (i.e., orientation) features of the targets on preceding trials (Maljkovic & Nakayama, 2000; see also Müller, Krummenacher, & Heller, 2004). Maljkovic and Nakayama (2000) concluded that the priming effects reflected

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[1] Other mechanisms are *inhibition of return* (e.g., Klein, 1988; Müller & von Mühlenen, 2000) and *visual marking* (e.g., Watson & Humphreys, 1997), which may be considered as within-trial memory effects.
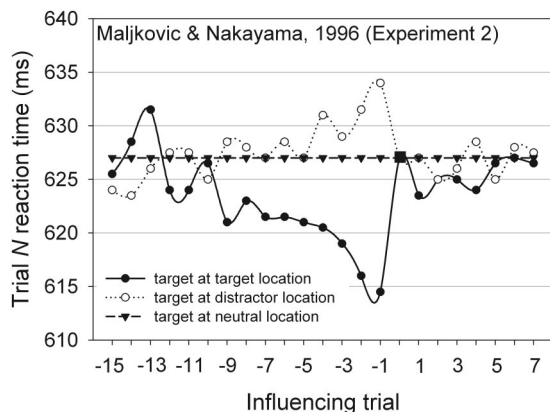
Figure 1. Reaction times (RTs) to targets on trial *N* presented at neutral, target, and distractor locations on previous (*N* − 15) and subsequent (*N* + 7) trials (for observer VM in Maljkovic & Nakayama's, 1996, Experiment 2). Presentation of a target at a previous target location expedited RTs relative to a previously neutral (i.e., empty) location (facilitation), whereas presentation of a target at a previous distractor location lengthened RTs (inhibition). Both facilitation and inhibition arising from previous trials were evident across sequences of 5–8 trials. Data are redrawn from "Priming of Pop-Out: II. The Role of Position," by V. Maljkovic and K. Nakayama, 1996, *Perception & Psychophysics, 58,* Figure 7, p. 983. Copyright 1996 by the Psychonomic Society. Adapted with permission.

an implicit—passive and automatic[2]—short-term memory for the guidance of visual search. Concerning positional priming, Maljkovic and Nakayama (1996) assumed that the status of stimulus locations as containing a target or a distractor is automatically— and, for each location, independently—retained in memory in terms of slow-decaying facilitatory and inhibitory (*valence*) tags, which then bias the allocation of attention on subsequent trials. That is, Maljkovic and Nakayama (1996) assumed this to be a universal mechanism in pop-out search, operating independently of any particular stimulus arrangements.

Contextual Cuing

Another form of positional memory for the guidance of visual search has recently been described by Chun and Jiang (1998, 1999; see also Chun & Nakayama, 2000; Jiang, Olson, & Chun, 2000): relational information coding. Chun and Jiang (1998, 1999) surmised that search is guided not only by the differential features of the target and distractor stimuli in the display but also by the *context* in which they are embedded. To examine this, Chun and Jiang (1998) made observers perform a standard conjunction search, and they compared the search reaction times (RTs) between *consistent* and *inconsistent* trials: On consistent trials, observers were presented with search displays that were identical to previously encountered displays in terms of target and distractor arrangements; in contrast, on inconsistent trials, newly composed target and distractor arrangements were presented. Chun and Jiang (1998) found RTs to be expedited for consistent relative to inconsistent trials—an effect they referred to as *contextual cuing.* Importantly, this effect, which emerges with extended practice, is critically dependent on the target location being fixed (rather than variable) relative to the spatial arrangement of the distractors on

consistent trials. That is, only under such conditions does the distractor arrangement provide a contextual cue to the target location, which suggests that contextual cuing is based on a *relationally coded* target-location memory. Furthermore, this memory is largely implicit in nature—observers are typically unable to discriminate consistent from inconsistent stimulus arrangements. However, what is unclear is whether the contextual memory guides search simply by facilitating the selection of the target location without concomitant inhibition of the distractor locations or whether it involves both facilitation and inhibition (analogous to cross-trial priming). There is indirect evidence that the former is true: Changing the target location on trials with a consistent distractor arrangement fails to produce an RT advantage relative to inconsistent trials (Chun & Jiang, 1998, Experiment 3). Such an advantage would be expected assuming that the repetition of a consistent context on a given trial would permit the distractors to be suppressed efficiently: Efficient distractor suppression would single out the target whether it was located at a consistent-unchanged or a consistent-changed position.

Rationale and Overview of the Present Experiments

The evidence for relational location coding and the guidance of search on the basis of stimulus context may qualify the positional-priming effects described by Maljkovic and Nakayama (1996). In particular, positional priming in pop-out search may be determined not simply by the status of an individual stimulus location as containing a target or a distractor but also by the (consistency of the) spatial arrangement of the target and distractors. This cannot be ruled out on the basis of Maljkovic and Nakayama's (1996) experiments, in which the stimuli—one target and two distractors—were always presented in a fixed spatial arrangement: a near-equilateral triangle that rotated, across trials, around the circumference of an imaginary ellipse. That is, in terms of Chun and Jiang (1998), Maljkovic and Nakayama examined positional priming only for consistent trials, with predictable stimulus arrangements. Thus, it remains a possibility that positional cross-trial priming is acquired through "consistent" practice with a particular stimulus arrangement rather than being a primitive mechanism that applies immediately and universally to any type of arrangement.

The present experiments were designed to examine this possibility: Experiment 1 used the same procedure as Maljkovic and Nakayama (1996), with the target and the two distractors always presented in a simple, near-equilateral triangle configuration. The data revealed a strong effect of practice on cross-trial priming—in particular, inhibitory priming: The effect extended further back in time with practice, suggesting that observers learned to exploit the regularity of the stimulus arrangement to optimize task performance. In Experiment 2, the arrangement of the display elements (i.e., the separations of the distractors from the target and amongst themselves) was variable across trials, so it was no longer possible to apply a regular (near-equilateral triangular) frame to place facilitatory and inhibitory tags at the target and distractor locations. When there were frequent repetitions of irregular stimulus arrange-

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[2] Whether or not cross-trial priming is top-down modulable is the subject of an on-going debate (e.g., Hillstrom, 2000; Maljkovic & Nakayama, 1994; Müller, Reimann, & Krummenacher, 2003; Theeuwes, 1991).

ments, there was still significant facilitation for target locations but no reliable inhibition for distractor locations. When the stimulus arrangements were made completely random (with hardly any repetitions), there was neither facilitatory nor inhibitory priming.

Thus, inhibitory positional priming fully emerges only after extended practice. With regularly arranged displays, it is likely that observers use a top-down spatial reference frame, anchored on the target location, to assign inhibitory tags to distractor locations. This strategy fails, or is no longer operable, when the stimulus arrangement is made irregular and variable across trials (see the present Experiment 2). However, even with irregular arrangements, there remains facilitatory priming when the arrangements are frequently repeated. This suggests that facilitatory priming is, at least in part, attributable to contextual cuing.

Experiment 1

Experiment 1 was designed to replicate the facilitatory and inhibitory positional-priming effects described by Maljkovic and Nakayama (1996) and to examine how these effects are modulated by practice on the task. The search displays (see Figure 2) consisted of one unique-color target plus two distractors. The target was either red with green distractors, or vice versa. All stimuli were diamond shaped, with a corner section missing on either the left or the right. Observers had to detect the color target and respond *left* or *right* according to the side of the missing corner section (*compound task*). On a given trial *N*, the target could appear either at a previously (e.g., on trial *N* − 1) empty location (*neutral* baseline), a location occupied by a target, or a location occupied by a distractor. On the basis of prior work (e.g., Maljkovic & Nakayama, 1996), expedited RTs relative to the neutral baseline were expected for targets appearing at the location of a previous target, and lengthened RTs were expected for targets appearing at the location of a previous distractor.

Method

Participants. Ten observers (6 female, 4 male; age range = 19–27 years; all reporting normal or corrected-to-normal vision) took part in Experiment 1. They were paid at a rate of €8 (U.S.$10) per session.

Apparatus. The experiment was conducted in a dimly lighted laboratory, to minimize reflections on the monitor. Stimulus presentation and RT measurement were controlled by a standard PC running under DOS (with the control software purpose-written in C++). Stimuli were presented on a 17-in. (43.18-cm) color monitor at a frame rate of 60 Hz (256 colors; resolution = 640 × 480 pixels). Observers viewed the monitor from the distance of 60 cm, maintained by a chin rest. They responded by pressing the right or left buttons of a serial Microsoft mouse, with the track ball removed to improve timing accuracy (Segalowitz & Graves, 1990).

Stimuli. The stimuli were red and green diamonds, each with a cutoff section to the left or right, with side determined randomly for each stimulus (henceforth, the side of the cutoff section is referred to as the diamond's *orientation*). The display always contained one target and two distractors. 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 (0.5 cd/m²). The size of the diamonds was 1.2° × 1.2° of visual angle, with a cutoff section of 0.3° either on 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. An elliptical frame was also used by Maljkovic and Nakayama (1996), to compensate for the normally faster responses to targets on the horizontal compared with the vertical meridian of the display (e.g., Kröse & Julesz, 1989). The center of the ellipse was marked by a white fixation point, 0.5° × 0.5° in size and 13.7 cd/m² in luminance.

The singleton color target could appear at any of 24 possible locations around the circumference of the ellipse. The distractors were then positioned such that the distances between adjacent stimuli on the circumference (target–distractor and distractor–distractor distances) were equal; that is, the target and distractors formed a regular (near-equilateral) triangle.

Design and procedure. With respect to the position of the target on the previous trial *N* − 1, the target on the current trial *N* could appear at one of three types of locations: a previously neutral (neither target nor distractor [i.e., an empty]) location (*target on neutral location*), a target location (*target on target location*), or a distractor location (*target on distractor location*). Because there
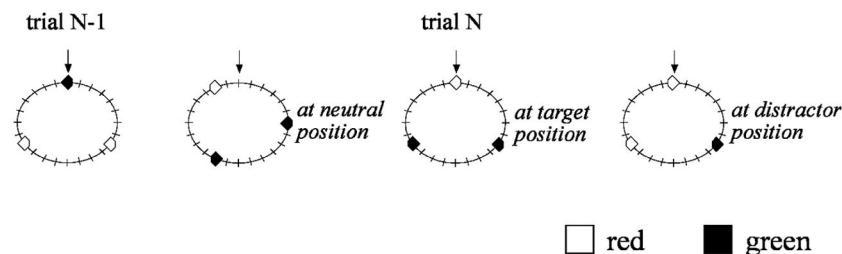

Figure 2. Examples of the four distractor conditions in Experiment 1, with the singleton color target appearing among two distractors. Illustrated is where the target on a given trial *N* could appear with respect to the previous trial *N* − 1. From trial to trial, the location, color, and orientation (i.e., side of cut-off segment) of the target (and distractors) varied randomly. Observers had to respond to the orientation of the singleton color target. (The near-circular ellipses, around which the target and distractors were arranged, were not shown in the experimental displays; they are included here only for purposes of illustration.)
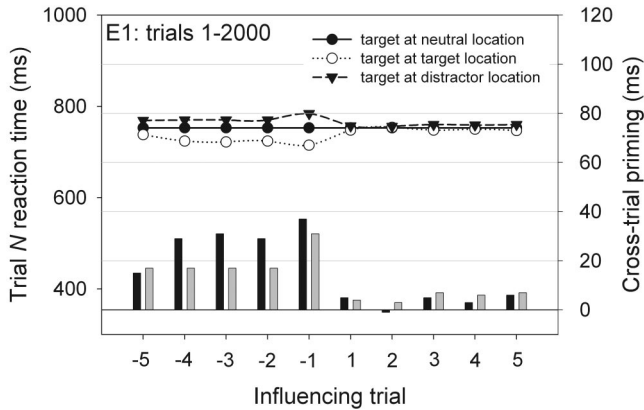
Figure 3. Experiment (E) 1: Mean correct reaction times (RTs) to targets on trial N presented at neutral, target, and distractor locations on previous trials $N - j$ or subsequent trials $N + j$ (compare lines with left y-axis). Also given are the RT differences (priming) for presenting the target at a target relative to a neutral location (black bars; compare with right y-axis) and for presenting the target at a distractor relative to neutral location (gray bars). RTs and priming were unaffected by whether target N appeared at a future $(N + j)$ neutral, target, or distractor location.

were 24 possible target and distractor locations on the ellipse, it was highly probable that a target on trial N was presented at a location that was empty on trial $N - 1$ (and less probable that it was presented at the location of a distractor or a target on trial $N - 1$). Thus, to provide at least 80 observations for target-on-target-location conditions and at least 160 observations for target-on-distractor-location conditions, we set the total number of trials to 2,000. The location, color, and orientation of the target were varied randomly from trial to trial.

At the beginning of each trial, the fixation marker was presented in the center of the monitor. After 1,000 ms, the search array was displayed (with the fixation marker remaining on) until the observer responded to the orientation (i.e., the side of the cutoff section) of the target by pressing the left or the right mouse button 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.

The experiment was divided into two sessions (each of about 50 min), which were conducted on 2 separate days. Each session consisted of eight blocks with 5 unrecorded warm-up trials and 120 experimental trials, with blocks separated by short breaks. At the beginning of the first session, observers performed one block of 100 practice trials (data for which were not recorded).

Results

For each target location condition, RTs outside the range of plus or minus 2.5 standard deviations from the mean were discarded as outliers (2.1% of all trials). Error-response trials were also excluded from the analysis (3.3% of all trials).[3] Furthermore, repetition effects were analyzed only for two consecutive trials on which the responses were correct; that is, responses on trials that preceded or followed an erroneous response were not analyzed.

Positional-priming effects. The positional priming effects on RTs are shown in Figure 3, which presents the mean RTs to the

target on trial N as a function of the trial N target position relative to target and distractor locations on the preceding trial $N - j$ and the subsequent trial $N + j$. The three data points for each influencing trial (trials $N - j$ through $N + j$) represent the mean RTs on trial N when the target appeared at a (previously or subsequently) neutral, target, or distractor location. To determine the influence of, say, trial $N - j$ on trial N, we included in the analysis only trials for which all intervening trials ($N - 1$ through $N - j + 1$) had targets appearing at neutral locations with respect to trial $N - j$ (this resulted in the elimination of very few trials).

Facilitatory and inhibitory effects attributable to preceding ($N - j$) and subsequent ($N + j$) trials were examined by post hoc Tukey honestly significant difference tests (on the basis of a separate Target Position × Influencing Trial ANOVA) comparing RTs to targets at target locations (facilitation) and distractor locations (inhibition) relative to targets at neutral locations for each influencing trial. Influences of subsequent trials ($N + j$) on performance on trial N were examined only for control purposes: Later trials in the sequence could not have logically influenced the response on an earlier trial and may, therefore, be taken to provide a random-effect baseline.

Figure 3 shows that the RT facilitation for targets at target relative to neutral locations was significant for the trials $N - 1$ through $N - 4$. More precisely, the RT facilitations deriving from the presentation of the N target at an $N - j$ target, relative to a neutral, location were 37 ms (influencing trial $N - 1$), 29 ms ($N - 2$), 31 ms ($N - 3$), and 29 ms ($N - 4$). In contrast—and despite the trends apparent in Figure 3—there was no significant RT inhibition for targets at distractor, relative to neutral, locations except for influencing trial $N - 1$ (31 ms). Thus, although the facilitatory effect was reliable across a sequence of trials, the inhibitory effect did not show robust persistence beyond trial $N - 1$.

Comparison of positional-priming effects between practiced and unpracticed performance. To examine whether the effects of target position were influenced by practice on the task, we reanalyzed the RTs on trials 1–1,000 (*unpracticed* performance) and trials 1,001–2,000 (*practiced* performance) by post hoc tests (on the basis of two separate Target Location × Influencing Trial ANOVAs) comparing RTs to targets at target and distractor locations relative to targets at neutral locations for each influencing trial. The results are presented in Figure 4. For unpracticed performance, the facilitatory effect was reliable for influencing trials $N - 1$ though $N - 4$ (average effect size: 24 ms), whereas the inhibitory effect was reliable only for influencing trial $N - 1$ (33 ms). In contrast, for practiced performance, both the facilitatory effect and the inhibitory effect were significant across influencing trials $N - 1$ trough $N - 5$ (average effect sizes: 28 ms and 20 ms, respectively). That is, facilitation and inhibition extended significantly further back in time with practiced, relative to unpracticed,

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[3] Overall, observers' error rates were relatively balanced across the target locations conditions: 3.1%, 3.4%, and 2.8% for targets at target, distractor, and neutral locations, respectively. An ANOVA of the error rates failed to reveal a significant effect of target position.
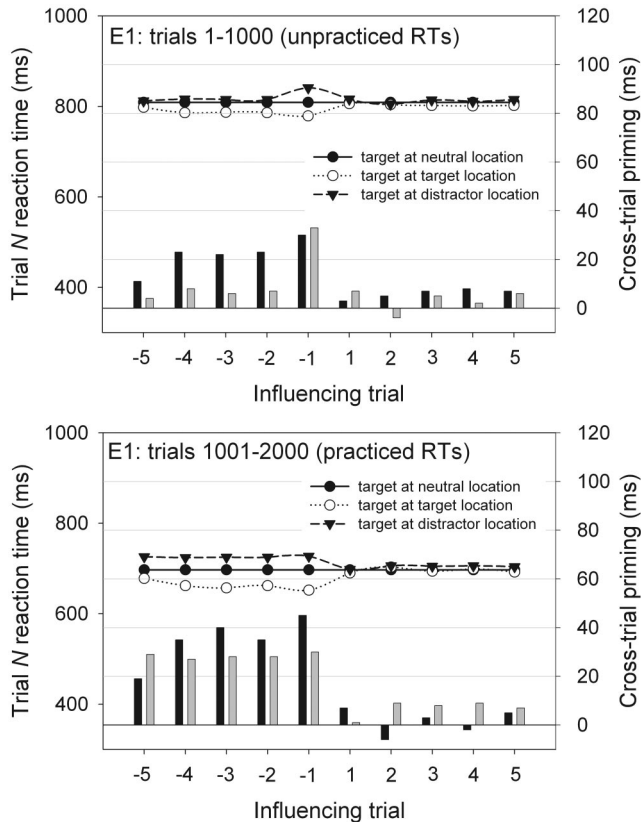
Figure 4. Experiment (E) 1: Mean correct reaction times (RTs) to targets on trial *N* presented at neutral, target, and distractor locations on previous trial *N* − *j* or subsequent trial *N* + *j* (compare lines with left *y*-axes), dependent on the amount of practice on the task. Also given are the respective RT differences between targets presented at a target relative to a neutral location (black bars; compare with right *y*-axis) and targets presented at a distractor relative to a neutral location (gray bars). Although practice led to overall expedited RTs, priming performance was overall larger and longer lasting in practiced than in unpracticed trials.

performance. In summary, practice led to enhanced priming in terms of both magnitude and backward extension.[4]

Discussion

Consistent with Maljkovic and Nakayama (1996), repetition of the target location was found to influence performance across sequences of trials: RTs were overall shortest when the current target appeared at the location of a previous target. In contrast, RTs were longest when the target appeared at the location of a previous distractor.

However, considering performance across the whole experiment, the inhibitory effect did not show robust persistence beyond influencing trial *N* − 1. This is at variance with Maljkovic and Nakayama's (1996) study, in which the effect of presenting a target at the location of a distractor was evident for the last 5–8 trials. However, evidence for longer lasting inhibitory priming (i.e., influencing trials *N* − 1 through *N* − 5) was found when only the last 1,000 trials of Experiment 1 were analyzed. This suggests that positional priming—in particular, robust inhibitory priming—

emerges only after extended practice. Although this is consistent with Maljkovic and Nakayama (1996), whose observers were highly practiced, it raises the question about the cause(s) of the more robust priming effects that are developed over the course of practice.

One possibility is that during practice, observers became sensitive to regularities, or consistencies, in the visual display. Specifically, long-term learning may have improved observers' ability to use the regular stimulus arrangement and its rotation across trials, to guide their search. Recall that the target and the two distractors were always arranged as a regular, near-equilateral triangle. During postexperimental debriefing, observers reported that, phenomenally, this triangular arrangement appeared to rotate around the ellipse from trial to trial, with one reference point within the triangle being "marked": the target location. Thus, observers could have used this apparent triangle arrangement to pinpoint the target (in terms of an anchor point) and, as an automatic consequence, facilitate the target and inhibit the distractor locations more efficiently. Such apparent movement of configurally organized display elements can become stronger phenomenally as a function of practice (e.g., Müller & von Mühlenen, 1996), potentially explaining the practice effects in Experiment 1.

Another possibility is that the enhanced facilitatory and inhibitory priming effects at the end of Experiment 1 are attributable, at least in part, to the presentation of identical displays across search trials—that is, contextual cuing (e.g., Chun & Jiang, 1998).[5] Recall that the three display elements appeared at 3 out of 24 possible locations, giving a total of 8 spatially different arrangements (with regular interitem spacing) that were randomly repeated across trials (i.e., 3 × 8 arrangements when the relative position of the target to the distractors is taken into account). This leaves the possibility that the repetition of a only a limited number of element arrangements (8) did affect priming—over and above any strategic effects deriving from observers exploiting the regular stimulus arrangement. Note that Chun and his colleagues (e.g., Chun & Jiang, 1998; Chun & Nakayama, 2000) always used display matrices of irregularly arranged targets and distractors to investigate contextual cuing—that is, the effect is not necessarily dependent on regular stimulus layout. Instead, what is critical for contextual cuing is simply that "contextual information is invariant over time and covaries with a variable important for visual behavior" (Chun & Nakayama, 2000, p. 76).

Experiment 2

Experiment 2 was designed to decide between these alternatives: Do observers, with increasing practice, learn to use the regular triangular arrangement of the three display elements to

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[4] The increase in the strength of priming was unlikely to simply reflect the fact that the data became more reliable (i.e., less noisy) with increased practice, making it easier to demonstrate statistical differences. If anything, the mean RT standard deviations were smaller for unpracticed compared with practiced trials: A *t* test (one-tailed) comparing standard deviations for unpracticed versus practiced trials (39.0 ms vs. 43.7 ms) was nonsignificant, $t(9) = 1.83$, $p = .17$ (data combined for trials $N - 1$ through $N - 5$).

[5] Hitherto, contextual cuing has not been (consistently) demonstrated with simple pop-out searches. However, whether it operates in such situations is an empirical issue.

enhance performance by spatially referencing the target and distractor locations and allocating facilitatory and inhibitory tags accordingly (*revised positional-priming account*)? Or do they learn to optimize search guidance by exploiting contextual cues to the target location (*contextual-cuing account*)?

One way to disentangle these alternatives is to vary the distances between the search items across trials. Consider, for example, displays with three search elements in which the separations between the items can vary but with the restriction that the number of possible (irregular) target and distractor configurations is limited to 8. Comparing search performance in this irregular (8-configuration) 3-item condition with a regular (8-configuration) condition in which the interitem spacing is constant across trials would permit the pure effects of (regular) stimulus arrangement on positional priming to be estimated. This is because, in the irregular 3-item condition, the number of differently arranged search displays equals the number of different search displays in the regular 3-item condition, which should give rise to comparable contextual cuing effects.

In contrast, if the separations between the search items can vary without any restriction, and given that the target and two distractors can appear at 24 possible locations, the number of differently arranged search displays would be much greater than 8 (i.e., $24 \times 21 \times 18 = 9,072$, if neighboring items are separated by at least one empty location[6]). Under these conditions, no effects of regular stimulus arrangement or contextual cuing would be expected. Thus, comparing this irregular 3-item, 9,072-configuration condition with the irregular, 8-configuration condition would permit the pure impact of contextual cuing on positional cross-trial priming to be estimated.

On the basis of this rationale, Experiment 2 was designed to examine the effects of constant stimulus arrangement as well as repeated context (i.e., repetition of identically arranged search displays) on positional cross-trial priming. In Experiment 2A, the target and the two distractors appeared in regular arrangements (as in Experiment 1). In contrast, in Experiments 2B and 2C, the separations between the target and distractors—and, thereby, the regularity of their arrangements—were varied across successive trials, eliminating any strategy based on the simple, regular arrangement of the display elements. In Experiment 2B, there were only a limited number of irregularly arranged search displays (8). In Experiment 2C, in contrast, no restrictions were made as to the number of differently arranged displays. We hypothesized that if priming is affected by both regularity of stimulus arrangement and context repetition, then cross-trial priming of positions should be largest in Experiment 2A, intermediate in Experiment 2B, and smallest in Experiment 2C.

Method

The design and procedure in Experiment 2 were the same as in Experiment 1, with the following exceptions.

Participants. Thirty unpracticed observers (21 female, 9 male; age range = 21–38 years; all reporting normal or corrected-to-normal vision) took part in Experiment 2, with 10 observers assigned to each condition (Experiments 2A, 2B, and 2C, respectively). They performed the respective condition in two separate sessions, each of which lasted about 40 min.

Design and procedure. On all trials, a singleton color target appeared amongst two distractors. As in Experiment 1, the color, orientation, and position of the singleton target changed randomly across trials. In Experiment 2A, the distances between the target and the two distractors were fixed (*regular search displays*). With 24 possible item locations, this resulted in 8 different target and distractor configurations that were randomly repeated across trials. In Experiments 2B and 2C, the distances between the search elements were variable—that is, the locations of two distractors were determined independently of the location of the target and without the distractors maintaining a fixed (simple, regular, predictable) spatial relation with reference to the target. The target was equally likely to appear at any of the 24 locations ($p = 1/24$) on the ellipse, and there was a probability of 1/21 and 1/18 for the first and second distractor, respectively, to appear at any of the remaining positions on the ellipse. That is, there were a total of $24 \times 21 \times 18 = 9,072$ potential target and distractor configurations (see Footnote 6). In Experiment 2B, only a limited number of 8 such irregular target and distractor configurations were selected (individually for each observer) and randomly repeated across the trials. In contrast, in Experiment 2C, the display presented on a given trial was randomly drawn out of the possible 9,072 configurations.

The independent variables were experiment (2A, 2B, 2C) and target position (target at neutral location, target at target location, target at distractor location). The total number of trials in each experiment was 2,000, with at least 80 and 160 trials in the target-at-target-location and target-at-distractor-location conditions, respectively. Each experiment consisted of eight blocks, each consisting of 5 (unrecorded) warming-up trials and 120 experimental trials, with blocks separated by short breaks. At the beginning of each experiment (2A, 2B, 2C), observers performed one block of 100 practice trials (data from which were not recorded).

Results

In Experiment 2, the same outlier-filtering procedure was used as in Experiment 1, which led to the elimination of 2.5% of all responses from further analysis. Error rates in Experiment 2 ranged between 1.9% and 4.0%, with an average of 3.1%.[7]

Positional-priming effects. To examine facilitatory and inhibitory effect arising across the trials $N - 1$ through $N - 5$, we conducted an ANOVA with the factors experiment (2A, 2B, 2C [between-subjects]), target position (target at neutral location, target at target location, target at distractor location [within-subject]), and influencing trial (trials $N - 1$ through $N - 5$, [within-

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[6] Note, though, that neighboring elements were separated by at least one empty location. This constraint was introduced because Maljkovic and Nakayama (1996) had shown gradients of facilitation and inhibition around previous target and distractor locations, respectively. Thus, permitting the target and a distractor to appear at adjacent positions without any constraint may have diminished any facilitatory and inhibitory priming effects resulting from (irregular) stimulus arrangement.

[7] A mixed-design ANOVA of the error rates, with the between-subjects factor experiment (2A, 2B, 2C) and the within-subject factor target position (target at neutral location, target at target location, target at distractor location) failed to reveal any significant effects.

subject]). This ANOVA revealed a significant main effect of target position, $F(2, 18) = 161.76$, $p < .01$, $MSE = 454$. Overall, RTs were shortest for targets appearing at previous target locations, intermediate for targets at previously neutral locations, and longest for targets at previous distractor locations (732 vs. 749 vs. 764 ms, respectively). Furthermore, the Experiment × Target Position interaction was significant, $F(4, 36) = 9.66$, $p < .01$, $MSE = 792$. This interaction is illustrated in Figure 5, which presents the RTs to the target on trial N presented at previously neutral, target, and distractor locations, separately for Experiments 2A, 2B, and 2C. As can be seen, the effect of target position was more marked in Experiment 2A than in Experiments 2B and 2C.

Specifically, in Experiment 2A, the facilitatory was significant across influencing trials $N - 1$ through $N - 5$ (average effect size: 26 ms), whereas the inhibitory effect was significant across trials $N - 1$ and $N - 2$ (average effect size: 37 ms). In Experiment 2B, only the facilitatory effect was significant across trials $N - 1$ through $N - 5$ (average effect size: 22 ms). In contrast, in Experiment 2C, there was neither a facilitatory nor an inhibitory effect for any influencing trials in the range $N - 1$ through $N - 5$.

Comparison of positional-priming effects between practiced and unpracticed performance. To examine for practice effects in Experiment 2, we reanalyzed trials 1–1,000 (*unpracticed performance*) and trials 1,001–2,000 (*practiced performance*) by post hoc tests (on the basis of a separate Experiment × Practice × Target Position × Influencing Trial ANOVA) comparing RTs to targets at previous target locations with RTs to targets at previous neutral locations (facilitation) and RTs to targets at previous distractor locations (inhibition) for each influencing trial $N - 1$ through $N - 5$. In the first 1,000 trials of Experiment 2A, the facilitatory effect was reliable across trials $N - 1$ through $N - 5$ (average effect size: 26 ms); however, the inhibitory effect did not extend beyond trial $N - 1$ (23 ms). In contrast, in the last 1,000 trials of Experiment 2A, both the facilitatory and inhibitory effects were significant across trials $N - 1$ through $N - 5$ (both average effect sizes: 27 ms). In Experiment 2B, the facilitatory effect was reliable across trials $N - 1$ through $N - 4$ for unpracticed performance and across trials $N - 1$ through $N - 5$ for practiced performance (average effect sizes: 23 ms and 17 ms, respectively). However, there was no evidence of inhibitory priming for either the first or the last 1,000 trials of Experiment 2B. In Experiment 2C, neither the facilitatory nor the inhibitory effect was reliable in either the first or the last 1,000 trials. This pattern of results confirms that practice influences the magnitude and backward extension of priming when target and distractors appear with regular arrangement.

Discussion

With regular target and distractor arrangement (Experiment 2A), robust facilitatory and inhibitory effects were obtained when the target appeared at previous target and distractor locations, respectively. This closely replicates the results of Experiment 1.

In contrast to Experiment 2A, Experiments 2B and 2C used irregular target and distractor arrangements, on the basis of the following rationale: If, with regular arrangements (as in Experiment 2A), observers learn to exploit the regularity to guide search by placing facilitatory and inhibitory tags on target and distractor locations, respectively, then the random variation of the interele-
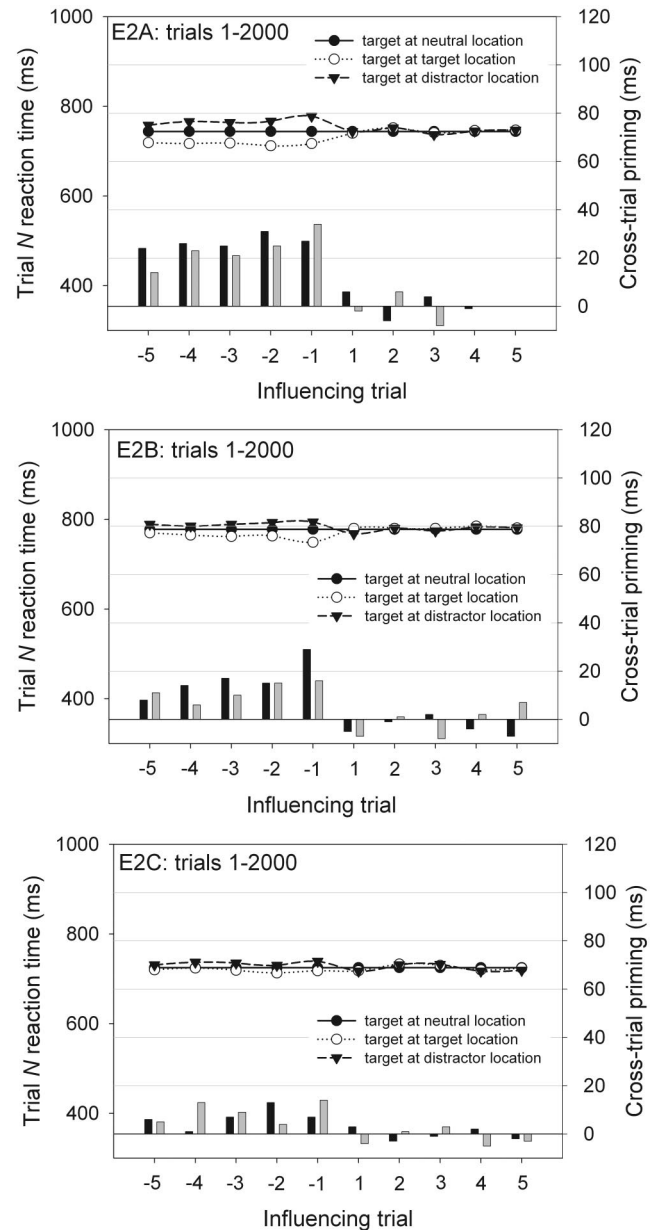

Figure 5. Experiment (E) 2: Mean correct reaction times (RTs) to targets on trial N presented at neutral, target, and distractor locations on previous trial $N - j$ or subsequent trial $N + j$ (compare lines with left y-axes), separately for Experiment 2A (regular stimulus arrangement: overall 8 different target–distractor configurations), Experiment 2B (irregular stimulus arrangement: overall 8 different target–distractor configurations), and Experiment 2C (irregular stimulus arrangement: overall 9,072 different target–distractor configurations). Also given are the respective RT differences between targets presented at a target relative to a neutral location (black bars; compare with right y-axis) and targets presented at a distractor relative to a neutral location (gray bars). Although in Experiment 2A, both the facilitatory and inhibitory effects were reliable, in Experiment 2B, only the facilitatory effect turned out to be significant. In Experiment 2C, no effects reached the level of significance.

ment spacing in Experiments 2B and 2C would be expected to diminish, if not entirely abolish, the effects of the target position. Alternatively (or in addition), with regular display arrangements, observers may learn to detect the target more efficiently by ex-

ploiting contextual cues (Chun & Jiang, 1998). To disentangle these possibilities, in Experiment 2B there were only 8 irregular target and distractor configurations, which were repeated randomly across trials—the same as the number of regular arrangements in as Experiment 2A. Thus, the comparison of Experiment 2B against Experiment 2A was designed to provide a pure measure of the effects of regular stimulus arrangement on positional priming, controlling for any effects of repeated contextual information. The results of Experiment 2B revealed robust facilitation for previous (trials $N - 1$ through $N - 5$) target locations (average effect sizes in Experiments 2B and 2A, respectively: 17 ms vs. 26 ms); however, there was no reliable inhibition for previous distractor locations (average effect sizes in Experiments 2B and 2A, respectively: 12 ms vs. 24 ms). This pattern suggests that inhibitory priming of distractor locations is largely dependent, and facilitatory priming of target locations is to some extent dependent, on regular display arrangement.

In contrast to Experiment 2B, in Experiment 2C, there was no limitation to the number of irregular target and distractor configurations. Thus, the comparison of Experiment 2B versus Experiment 2C was designed to provide a pure measure of the effects of repeated contextual information on positional priming, controlling for any effects of (irregular) stimulus arrangement. The results of Experiment 2C revealed hardly any evidence of facilitation for previous target locations (average effect sizes in Experiments 2C and 2B, respectively: 7 ms vs. 19 ms) and of inhibition for previous distractor locations (9 ms vs. 12 ms). This pattern argues that facilitatory priming of previous target locations is largely dependent on contextual cuing.

In summary, the results indicate that search performance in Experiment 2 was influenced by both positional priming (as indicated by the differential priming effects between Experiments 2A and 2B) and contextual cuing (as indicated by the differential priming effects between Experiments 2B and 2C). Thus, at least two memory mechanisms had an effect on performance in Experiment 2, both exploiting contextual information that is invariant over time: contextual cuing, which does not depend on item regularities and produces only facilitation for the target location, and cross-trial positional priming, which is sensitive to regular target and distractor arrangement and produces both facilitation for the target location and inhibition for distractor locations.[8]

General Discussion

Inhibition of distractor locations was observed only when the distractors were regularly positioned relative to the target location (Experiments 1 and 2A), not when their positioning was irregular (Experiments 2B and 2C). In contrast, repetition of the target location yielded facilitation relatively independently of its positioning (Experiment 2B). Furthermore, in the relevant conditions (see above), facilitation was found to be quite robust and enduring (from trial $N - 5$ through trial $N - 1$ onto trial N [Experiments 1, 2A, and 2B]), whereas inhibition was more short lived (mainly from trial $N - 1$ onto trial N [Experiments 1 and 2A]). Finally, there was no evidence of inhibition and facilitation when the distances between the target and distractor locations varied randomly across trials (Experiment 2C).

Implications for the Nature of Positional Priming in Visual Search

Experiment 2 revealed the manifestation of positional—in particular, inhibitory—priming to be dependent on the regularity of the target and distractors' spatial arrangement across sequences of trials. This result qualifies Maljkovic and Nakayama's (1996) characterization of cross-trial priming as rather "primitive"—that is, passive, automatic—in nature. Although Maljkovic and Nakayama (1996) may be right in considering priming to be "a simple storage of valence" (p. 989), in all of their experiments, the spatial arrangement of the stimuli (one target and two distractors) was regular and, therefore, well predictable—as was the case in the present Experiments 1 and 2A. The present results would therefore argue that not only the salience of the target relative to the distractor features but also the simplicity and predictability of stimulus locations should be taken into consideration in any account of positional cross-trial priming. Furthermore, it is important to note that although the pattern of facilitatory and inhibitory priming reported by Maljkovic and Nakayama (1996) was replicated in the present experiments, it applies only to a very special case: one target and two distractors arranged in a regular triangular configuration, with the full pattern of backward effects becoming manifest only after extended practice. To some extent, these practice effects are likely to be due to observers learning to exploit contextual cues (e.g., Chun & Jiang, 1998).

However, contextual cuing gave rise only to reliable facilitation, not inhibition, and even concerning the former, the presentation of regularly arranged search displays produced additional facilitation over and above the effect attributable to the presentation of "consistent" displays alone. This suggests that some other mechanism must be taken into consideration in a revised positional-priming account. One possibility, which is consistent with observers' subjective reports, is that inhibition of distractor locations and, to some extent, facilitation of target locations is dependent on observers applying a regular spatial "frame" in which the target location (facilitatory tag) provides an anchor point for placing inhibitory tags on the distractor locations. This organizing frame is a relatively high-level representation acquired through perceptual learning. Thus, in a sense, inhibitory and, to some extent, facilitatory positional priming involve a component of top-down processing, which is not necessarily "intentional" (but, rather, *implicit*) in nature.

Position- Versus Feature-Based Priming in Visual Search

The proposal that stimulus arrangement plays an important role in priming is in line with a number of recent studies that have demonstrated short- and long-term effects of the search context on RTs (e.g., Karni & Sagi, 1993; Kristjánsson et al., 2002; McCarley & He, 2001; D. L. Wang, Kristjánsson, & Nakayama, 2005; Q.

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[8] We conducted a further test (*t* test) to compare the facilitatory priming effects between Experiments 2A and 2B (27 ms and 19 ms, respectively; data combined across trials $N - 1$ trough $N - 5$ and for practiced and unpracticed performance). This test, $t(18) = 1.98$, $p < .05$ (one-tailed), revealed facilitatory priming to be stronger with regularly arranged target and distractors displays (Experiment 2A) compared to irregular but "consistent" stimulus arrangements (Experiment 2B).

Wang, Cavanagh, & Green, 1994). For example, Kristjánsson et al. (2002) emphasized the role of *mid-level grouping*—that is, perceptual organization in visual search (besides the roles of bottom-up and top-down processes)—in contrast with prominent models of visual search that have tended to underrate such organizational processes (Duncan & Humphreys, 1989; Treisman & Gelade, 1980; Treisman & Sato, 1990; Wolfe, 1994; Wolfe, Cave, & Franzel, 1989). Kristjánsson et al. showed that priming in singleton (conjunction) search could lead to a dramatic reduction in RTs on both target-present and target-absent trials. Because facilitation was found not only for the repetition of the target but also for that of the distractors features, Kristjánsson et al. suggested that priming resulted from expedited grouping of repeated distractors, which, in turn, could facilitate the discernment of target presence against the homogeneously grouped distractors.

Note that Kristjánsson et al. (2002) found robust inhibitory priming effects even with irregularly arranged search displays—that is, under conditions in which (a) the distances between the search items were variable and (b) the target and distractors could appear at different positions across search trials. This appears to be at variance with the present Experiment 2, which revealed the inhibitory priming effects to be dependent on stimulus regularity. One possible reason for this discrepancy is that grouping of similar display elements can occur even if the elements are not arranged regularly (e.g., Duncan & Humphreys, 1989). Another possible explanation derives from the differential search tasks used in the present study and by Kristjánsson et al. to investigate priming: pop-out versus conjunction search. Kristjánsson et al. demonstrated priming in visual search for targets defined by a conjunction of color and orientation: The target, if present, was always red and unique in orientation, and it was presented amongst red and (relative to the target) differently oriented distractors together with green and (relative to the target) identically oriented distractors. From trial to trial, the orientation of the target could switch between horizontal and vertical, with vertical-red/horizontal-green or horizontal-red/vertical-green distractors. Kristjánsson et al. found inhibitory priming on search target-absent trials when the orientation of the target changed from trial $N - 1$ to trial N relative to when it was repeated. Further, an inhibitory priming effect was found also on search target-absent trials when the orientation of the distractors changed relative to when it was the same. In a follow-up study, Geyer, Müller, and Krummenacher (2006) demonstrated that the inhibitory priming effect on search target-present as well as search target-absent trials resulted mainly from the change of the distractors', rather than the targets', orientation. Moreover, Geyer et al. showed that this inhibitory effect resulted from the change of only a subset of distractors: those that shared the target's color, which was constant across trials.

The latter finding strongly suggests that observers (top-down) limited their search to particular subsets of (target-colored) distractors. Consequently, it is possible that priming under these conditions was more strongly, if not entirely, bound to change/repetition of the featural (color) information rather than positional information of the display items. The assumption of feature-based, rather than position-based, priming in conjunctive visual search would explain why Kristjánsson et al. (2002) found priming even with irregularly arranged search displays.

Conclusion

In summary, the results of present study argue that positional cross-trial priming in visual pop-out search is dependent on "consistent" arrangement of the target relative to the distractors in the search display and that these consistencies need to be learned during practice on the task. Although facilitatory priming may be largely due to contextual cuing, inhibitory priming is dependent on observers applying a perceptually organizing (geometrically regular) reference frame to the search display.

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