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Orientation search is mediated by distractor suppression: Evidence from priming of pop-out

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ARTICLE INFO

Article history:

Received 11 June 2012
Received in revised form 3 December 2012
Available online 1 February 2013

Keywords:

Inter-trial priming
Priming of pop-out
Visual search
Target activation
Distractor inhibition
Orientation singleton search

ABSTRACT

In search for a singleton target, performance is considerably improved when the target and distractors repeat than when they switch roles, an effect called priming of pop-out or PoP (Maljkovic & Nakayama, 1994). Although this phenomenon has been replicated across a variety of dimensions, orientation PoP has proved to be volatile. Recent research has shown that target activation and distractor inhibition mechanisms underlie PoP (Lamy, Antebi, et al., 2008). Relying on this finding, we show that unlike in color and shape search, only distractor inhibition processes contribute to PoP in orientation search, which resolves the apparent inconsistencies in the literature. The implications of this finding for mechanisms underlying PoP and orientation singleton search are discussed.

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1. Introduction

The role of memory processes in guiding visual attention has been increasingly acknowledged in recent years (e.g., Chun & Nakayama, 2000; Downing, 2000; Kristjánsson & Campana, 2010). In particular, an implicit short-term memory system has been invoked to account for mounting evidence showing that visual search performance is considerably improved when various aspects of the display repeat from recent trials. Repetition of the target-defining feature (Maljkovic & Nakayama, 1994), of the target location (Maljkovic & Nakayama, 1996), of the dimension in which the target is defined (Found & Müller, 1996), of the target's status as a singleton (Lamy, Bar-Anan, & Egeth, 2008), as well as repetition of the spatial lay-out in which the target appears (Chun & Jiang, 1998) have all been shown to speed search.

Maljkovic and Nakayama (1994) were the first to report such inter-trial priming effects. They showed that when there is uncertainty regarding the target feature, such as when the target is defined as the discrepant item in a homogeneous field of distractors, visual search performance is faster when the target's discrepant feature happens to repeat from one trial to the next. They called this phenomenon “priming of popout” or PoP. In their experiments, participants searched for an odd-colored diamond, either a red diamond among green diamonds or a green diamond among red diamonds. That is, the target and distractors switched

colors unpredictably from trial to trial. Repeated-color trials were faster than switched-color trials.

This effect has been generalized to targets differing from the surrounding distractors by their shape (e.g., Lamy et al., 2006), their orientation (e.g., Hillstrom, 2000), their size (Huang, Holcombe, & Pashler, 2004) or the facial expression of emotion they display (Lamy, Amunts, & Bar Haim, 2008), suggesting that similar implicit memory mechanisms are at play in different types of search.

However, when relatively subtle design changes are introduced in search for orientation singleton targets, priming of pop-out seems to break down. For instance, Found and Müller (1996) jointly investigated dimension and feature priming effects. In one experiment, distractor items were white vertical bars and target items could be a white bar tilted to the left or the right (orientation singleton), or either a red or a blue vertical bar (color singleton). As different types of targets were intermixed between trials, several repetition effects could be measured: dimension repetition and feature repetition (which could be either color repetition or orientation repetition). The results showed that search performance improved when the dimension in which the target was defined repeated, and when the target color repeated but not when its orientation repeated. These findings led Found and Müller to conclude that target-feature repetition effects play a marginal role in visual search and that “intertrial facilitation is indeed (largely) dimension specific rather than feature specific in nature”.

A similar failure to report PoP of orientation was recently reported by Lustig et al. (2012). They had their subjects search for a disk with a uniquely oriented texture and observed a target-repetition benefit when the target and distractors orientation

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randomly switched from trial to trial. Yet, they failed to replicate this effect when target repetition was uncorrelated with distractor repetition, that is, when the target and distractors never exchanged roles. Likewise, McBride, Leonard, and Gilchrist (2009, Exp. 3) reported that when possible target and distractor orientations were disjunctive, repeating distractor orientation speeded search, whereas repeating target orientation actually slowed search. Finally, Wolfe et al. (2003) found a significant orientation PoP effect when target and distractors could exchange roles but not when the distractor orientation was kept constant across trials.

Recently, Lamy, Antebi, et al. (2008) showed that two independent components contribute to intertrial priming in search for a singleton: target activation and distractor inhibition (see also Bichot & Schall, 2002; Kristjánsson & Driver, 2008; Maljkovic & Nakayama, 1994). They demonstrated that each of these is measured as the sum of a repetition benefit and a switching cost. They used a color search task similar to Maljkovic and Nakayama's (1994) and compared the different repetition conditions created by the use of four possible colors instead of only two. On each trial, two different colors were randomly drawn from the four possible colors and assigned to the target and distractors. This set-up resulted in three different kinds of sequences defined by target variation on successive trials (henceforth, trial $n - 1$ and trial n): On any given trial, the target color could be (a) the same as the previous target color (repeated target color), (b) the same as the previous distractor color (switched target color), or (c) different from the previous target and distractor colors (new target color). Similarly, there were three kinds of sequences defined by distractor variation on successive trials: On any given trial, the distractor color could be (a) repeated, (b) switched, or (c) new.

The effect of target-color activation was quantified using two measures. Selecting the target color on trial $n - 1$ facilitated selection of a target of the same color (repeated vs. new target color or *target-activation benefit*) and slowed rejection of distractors of that color (switched vs. new distractor color or *target-activation cost*) on trial n . Likewise, rejection of the distractor color on trial n facilitated rejection of distractors of the same color (repeated vs. new distractor-color trials or *distractor-inhibition benefit*) and slowed selection of a target of that color (switched vs. new target-color trials or *distractor-inhibition cost*).

Within this framework, the aspect of the design that is common to studies that failed to report PoP in orientation singleton search is that only target-activation measures were probed. Found and Müller had only the target's feature vary from trial to trial, while the distractors' feature remained constant across the experiment (see also McBride, Leonard, & Gilchrist, 2009; Exp. 1; Wolfe et al., 2003). Lustig et al. (2012) measured only target-feature repetition effects which were unaffected by distractor-feature repetition or changes (see also McBride, Leonard, & Gilchrist, 2009, Exp. 3). Based on this observation, we suggest that unlike in color search, PoP in orientation search may rely solely on distractor-inhibition processes.

The objective of the present study was to test this hypothesis. It was similar to Lamy et al.'s (2008) study described above, but the target was defined as an orientation singleton rather than as a color singleton.

1.1. Method

1.1.1. Subjects

Subjects were eighteen Tel-Aviv University undergraduate students who participated in the experiment for course credit. All reported having normal or corrected-to-normal visual acuity and normal color vision.

1.1.2. Apparatus

Displays were generated by an Intel Pentium 4 computer attached to a 17" TFT monitor, using 640×480 resolution graphics mode. Responses were collected via the computer keyboard. A chin-rest was used to set viewing distance at 60 cm from the monitor.

1.1.3. Stimuli

Examples of the stimulus displays are presented in Fig. 1 (left panel). The fixation display was a gray $0.2^\circ \times 0.2^\circ$ plus sign (+), in the center of a black background. The stimulus display consisted of the fixation display with the addition of eight colored line segments, drawn with a 2-pixel stroke and subtending 0.8° of visual angle in length. The lines appeared in the eight peripheral cells of an imaginary 3×3 matrix centered at fixation. Each cell subtended 2° in side and each line was centered inside its cell with a random jitter of 0.15° , 0 or 0.15° .

One line (the target) had a unique orientation, and the seven remaining lines (the distractors) were uniformly oriented in an orientation that differed from that of the target. There were four possible line orientations: 0° , 90° , 45° , or 315° . In each display, four lines were pinkish gray (CIE coordinates 0.29/0.27, 35.60 cd/m²), and four were greenish gray (CIE coordinates 0.28/0.32, 42.10 cd/m²). The two colors were matched for equiluminance using a Minolta ColorCAL colorimeter.

1.1.4. Procedure

The subjects had to report whether the uniquely oriented line was red or green¹ by pressing designated keys with each hand as quickly as possible, while maintaining high accuracy. Target color-to-key assignment was counterbalanced between subjects. Error trials were followed by a 500-ms feedback beep.

Each trial began with a fixation display. After 500 ms, the stimulus display followed, and remained visible for 2000 ms or until response. The screen went blank for 500 ms before the next trial began. Eye movements were not monitored, but subjects were explicitly requested to maintain fixation throughout each trial.

1.1.5. Design

On each trial the target and distractor orientations were randomly drawn from the four possible orientations. Each of the resulting 12 target-distractor orientation combinations was equally probable. Thus, there were three possible variations of the target orientation from one trial to the next (*repeated*, *new* and *switched* target orientation) and three possible variations of the distractors orientation from one trial to the next (*repeated*, *new* and *switched* distractor orientation). Because the design included missing cells corresponding to impossible conditions (*switched* target color – *repeated* distractor color and *repeated* target color – *switched* distractor color conditions), it was not possible to analyze all the conditions within the same 3×3 Analysis of Variance (ANOVA). Thus, the different conditions were analyzed in two different ANOVAs. The first ANOVA included target-orientation repetition (*repeated* target orientation vs. *new* target orientation and distractor-orientation repetition (*repeated* distractor orientation vs. *new* distractor orientation) as factors. The second ANOVA included target orientation switch (*new* target orientation vs. *switched* target orientation) and distractor-orientation switch

¹ In a pilot study we used highly discriminable red and green colors. At debriefing, subjects reported that their strategy was to randomly pick one color, search for a discrepant orientation in that color and to press the key corresponding to the alternative color if they found no odd-orientation line in that color. This strategy could not fail because there was a target on each trial. Thus, we chose colors that were similar enough not to yield a clear segmentation of the display into two groups of lines. Debriefing questions confirmed that with the new colors, subjects did not search through color-defined groups of lines.

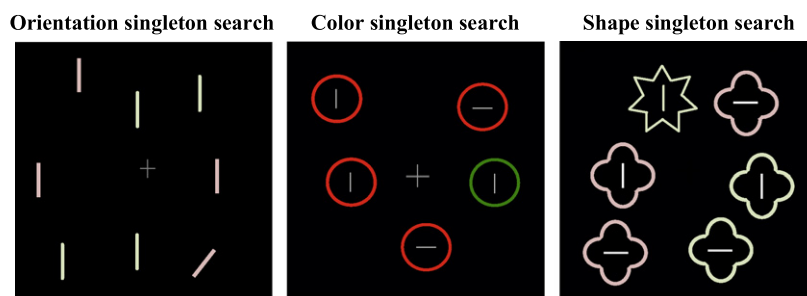


Fig. 1. Example of the visual search arrays. Left panel (Experiments 1 and 2): Orientation singleton search: subjects had to respond to the color of the odd-oriented line. Central panel (Experiment 2): Color singleton search: subjects had to respond to the orientation of the odd-colored line. Right panel (Experiment 3): Shape singleton search: subjects had to respond to the color of the odd-shaped object (color-response condition) or to the orientation of the line inside this object (orientation-response condition). Dotted and broken lines represent pinkish gray and greenish gray lines. Stimuli are not drawn to scale. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(new distractor orientation vs. switched distractor orientation) as factors.

The experiment began with a block of 40 practice trials, followed by 720 experimental trials divided into 12 blocks. Subjects were allowed a short rest after each block.

1.2. Results and discussion

In all RT analyses, error trials (7.6%) were removed from analysis, and RTs for each subject were sorted into cells by conditions of target and distractor orientation inter-trial variation. Reaction times exceeding the mean of a given cell by more than 2.5 standard deviations were trimmed. Less than 1% of all observations were removed following this procedure. In this and the next experiments, reaction time analyses were performed on the means of the log transformed RTs. The basic PoP effect and its components are depicted in Fig. 2.

1.2.1. Replication of the basic PoP effect

Reaction times. A planned comparison between trials with repeated target and distractor orientations and trials with switched target and distractor orientations showed that the basic PoP effect previously reported with pop-out targets differing from their background in orientation (e.g., Hillstrom, 2000) was replicated in the

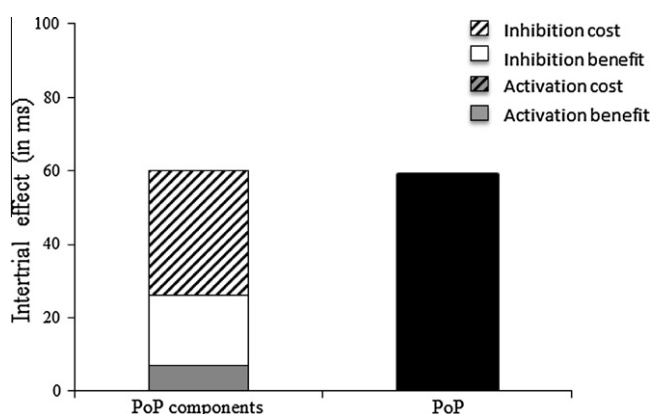


Fig. 2. Results of Experiment 1. Comparison of the basic PoP effect (repeated target color/repeated distractor color vs. switched target color/switched distractor color) and the sum of the four component effects (target repetition effect = target activation benefit; distractor switch effect = target activation cost; distractor repetition effect = distractor inhibition benefit; target switch effect = distractor inhibition cost). Striped areas represent the two effects reflecting target activation and plain areas represent the two effects reflecting distractor inhibition. The effects represent RT differences in milliseconds. Note that the target activation cost was null.

present experiment, $M = 905$ ms and $SD = 70$ vs. $M = 964$ ms and $SD = 92$ for repeated vs. switched trials, respectively, $t(1,17) = -4.41$, $p < 0.0004$.

Accuracy. The effect was non-significant, $t < 1$.

1.2.2. Target activation and distractor inhibition

Next, we examined the relative contributions of target activation and distractor inhibition in the observed PoP effect. RTs were analyzed in two separate ANOVAs, one with target repetition (repeated vs. new) and distractor repetition (repeated vs. new) as factors and the other with target switch (switched vs. new) and distractor switch (switched vs. new) as factors. As the interaction between the two factors was non-significant in both analyses ($F_s < 1$), the main effects in the former analyses measured the target-activation benefit and distractor-inhibition benefit and the main effects in the latter analysis measured the target-activation cost and distractor inhibition cost.

Reaction times. Neither of the two measures of target activation yielded a significant effect, $F_s < 1$ both for the repeated- vs. new-target-color trials and for the switched vs. new-distractor-color trials. The two measures of distractor inhibition yielded significant effects. Participants responded more quickly to repeated-distractor-color trials than to new-distractor-color trials, $F(1,17) = 10.25$, $p < .006$, and slower to switched-target-color trials than to new target-color trials, $F(1,17) = 14.39$, $p < .002$.

Accuracy. The accuracy data mirrored the RT data. There was no target activation effect, both $p_s > 0.2$. The switched-target vs. new target measure of distractor inhibition was significant, $F(1,17) = 8.81$, $p < 0.009$ but the repeated- vs. new-distractor orientation measure did not reach significance, $F(1,17) = 1.70$, $p > 0.2$.

The findings from Experiment 1 support our hypothesis that PoP of orientation relies exclusively on distractor inhibition processes, with no role for target activation processes. This finding resolves the apparent inconsistencies in the literature in which inter-trial repetition effects of orientation appeared to be volatile (e.g., Hillstrom, 2000; Kristjansson, 2006 vs. Found & Müller, 1996; Lustig et al., 2012).

2. Experiment 2

Lamy et al. (2008) reported large individual differences in the magnitude of the activation and inhibition components of PoP in color search. One may therefore argue that in Experiment 1, our sample may have happened to include a large number of subjects with low activation scores. In order to more firmly establish the conclusion that that PoP of orientation relies exclusively on distractor inhibition processes, in Experiment 2 we sought to demonstrate that the same subjects who show both significant target

activation effects and significant distractor inhibition effects when searching for a color target (as reported in Lamy et al., 2008) show only distractor inhibition effects when searching for an orientation target.

2.1. Subjects

Subjects were twenty-four Tel-Aviv University undergraduate students who participated in the experiment for course credit. All reported having normal or corrected-to-normal visual acuity and normal color vision.

2.2. Apparatus, stimuli, procedure and design

The apparatus, stimuli, procedure and design were similar to those of Experiment 1 except for the following differences. There were two sessions: an orientation-search session and a color-search session (similar to Lamy et al.'s (2008)). The orientation-search session was similar to that of Experiment 1.

An example of the displays used in the color-search session is presented in Fig. 1 (central panel). Each stimulus display contained 5 colored outline circles (0.7° of visual angle in diameter, 2-pixel stroke). Centered inside each circle was a line segment (0.37° in length, 1-pixel stroke) either horizontal or vertical. The display always contained either two horizontal and three vertical line segments, or vice versa. The circles appeared at random locations within the 3×3 matrix. Each display contained one circle with a unique color, the target, and four circles in a different color, the distractors. Subjects had to respond to the orientation of the line segment enclosed in the target. On each trial the target and distractor colors were randomly drawn from four possible colors, matched for equiluminance using a Minolta ColorCAL colorimeter: red (CIE coordinates 0.63/0.34, 18.75 cd/m²), blue (CIE coordinates 0.20/0.22, 18.67 cd/m²), green (CIE coordinates 0.28/0.593, 18.44 cd/m²) and yellow (CIE coordinates 0.42/0.49, 18.32 cd/m²).

Each session began with a block of 40 practice trials. Each of the two sessions consisted of 360 experimental trials divided into 6 blocks. Subjects were allowed a short rest after each block. They were allowed to leave the room after the first session and were invited to return half an hour later in order to run on the second session. Session order was counterbalanced across subjects.

2.3. Results

In all RT analyses, error trials (5.9%) were removed from analysis, and so were RTs outliers following the same procedure as in Experiment 1. Less than 1.4% of all observations were removed following this procedure. The data from 3 subjects were discarded because their mean error rates exceeded the subjects' mean by more than 2.5 standard deviations. The effect of session order was non-significant and did not interact with any other effect in neither this experiment nor in the next one, all $ps > 0.15$. The data were therefore collapsed across session order. The basic PoP effects and their components are depicted in Fig. 3.

2.3.1. Replication of the basic PoP effect

Reaction times. An ANOVA with search dimension (color vs. orientation) and repetition (repeated target and distractor features vs. switched target and distractor features) revealed significant main effects of search dimension, $F(1,20) = 146.32$, $p < 0.0001$ and of repetition, $F(1,20) = 46.18$, $p < 0.0001$, with faster RTs for color than for orientation search, $M = 736$ ms and $SD = 105$ vs. $M = 954$ ms and $SD = 131$, respectively, and for repeated than for switched target and distractors features, $M = 800$ ms and $SD = 151$ vs. $M = 889$ ms and $SD = 159$, respectively. The interaction between the two factors was significant, $F(1,20) = 9.65$, $p < 0.006$, with a larger repetition effect in the color relative to the orientation dimension, 104 ms vs. 76 ms, respectively.

Accuracy. The effect of search dimension approached significance, $F(1,20) = 3.76$, $p < 0.07$, with higher accuracy for color than for orientation search, $M = 95.4\%$ and $SD = 4.0\%$ vs. $M = 92.8\%$ and $SD = 6.8\%$, respectively. There was no other significant effect, all $F_s < 1$.

2.3.2. Target activation and distractor inhibition

Next, we conducted two separate ANOVAs with search dimension, target repetition and distractor repetition as factors and with search dimension, target switch and distractor switch as factors. Neither the interaction between target repetition and distractor repetition nor between target switch and distractor switch was significant, $F_s < 1$, and nor were the 3-way interactions with search dimension, $ps > 0.2$.

Reaction times. The interactions between search dimension and target activation benefit and cost were significant, $F(1,20) = 6.11$, $p < 0.03$ and $F(1,20) = 23.42$, $p < 0.0001$, respectively. The target

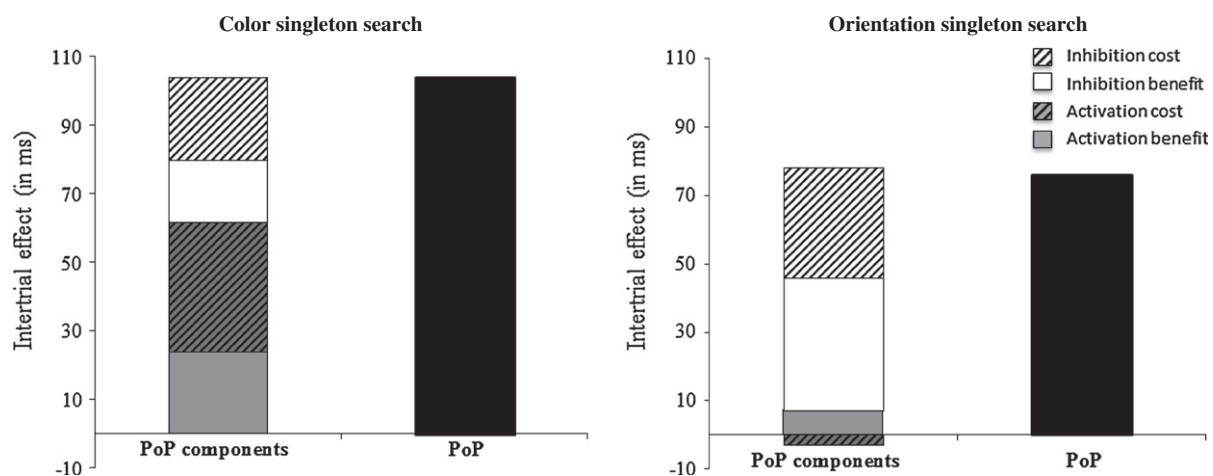


Fig. 3. Results of Experiment 2. Comparison of the basic PoP effect vs. the sum of the four component effects in the color search condition (left panel) and in the orientation search condition (right panel). Striped areas represent the two effects reflecting target activation and plain areas represent the two effects reflecting distractor inhibition. The effects represent RT differences in milliseconds. The negative target activation cost in the orientation search condition indicates that RTs were faster when the distractor took on the orientation of the target on the previous trial than when its orientation was new.

activation benefit and cost were significant in the color search, $F(1,20) = 18.93$, $p < 0.0003$ and $F(1,20) = 50.14$, $p < 0.0001$, respectively, and were non-significant in the orientation search, both $F_s < 1$.

The interaction between search dimension and distractor inhibition benefit was significant, $F(1,20) = 8.22$, $p < 0.01$, revealing that the benefit was significant for both the color, $F(1,20) = 6.28$, $p < 0.03$, and the orientation search, $F(1,20) = 36.46$, $p < 0.0001$ but was larger for the latter than for the former search dimension. The interaction between search dimension and distractor inhibition cost was non-significant, $F < 1$ and the effect was significant in both the color search, $F(1,20) = 13.35$, $p < 0.002$ and in orientation search, $F(1,20) = 9.10$, $p < 0.007$, respectively.

Accuracy. The interaction between search dimension and target activation cost was significant, $F(1,20) = 5.16$, $p < 0.04$. Follow-up comparisons revealed that while the target activation cost did not reach significance in color search, $F(1,20) = 2.24$, $p > 0.1$, it was significant but in the opposite direction in orientation search, $F(1,20) = 5.08$, $p < 0.04$: subjects made more errors when the target orientation was new relative to the previous trial than when it had been the distractors' orientation. No other effect was significant, all $p_s < 0.2$.

The finding that orientation PoP is fully accounted for by distractor inhibition processes with no role for target activation processes was thus replicated in the present experiment. In addition, we confirmed that the mechanisms underlying PoP of color and PoP of orientation differ: for the same participants, both target activation and distractor inhibition processes contributed to color PoP.

3. Experiment 3

While the findings from the previous experiments provide a coherent account of previous discrepancies between color and orientation PoP (e.g., Found & Müller, 1996), they are nonetheless open to alternative accounts.

First, the color and orientation search tasks used in the previous experiment differed in several aspects other than the search dimension: (1) color search was substantially faster than orientation search and (2) whereas in orientation search the relevant response dimension was color, in color search, the relevant response dimension was orientation. Thus, rather than search dimension, task difficulty and response dimension might modulate the contribution of target activation processes to PoP.

Second, as activation and inhibition processes underlying inter-trial priming have been dissociated only for the color dimension (Bichot & Schall, 2002; Lamy et al., 2008; Maljkovic & Nakayama, 1994), it might be the case that color, rather than orientation, is the exception. It would therefore be useful to determine whether both activation and inhibition processes indeed underlie PoP in other dimensions.

The objective of Experiment 3 was to test these alternative accounts. Subjects searched for a shape singleton and responded to the color of the target shape in one session (color-response session) and to the orientation of a line enclosed in the target shape in another session (orientation-response session).

Pilot data confirmed that with this set-up, shape singleton search performance was at least as slow as the orientation searches used in Experiments 1 and 2, irrespective of whether the response dimension was color or orientation. Thus, if search difficulty accounts for the differences observed between color and orientation search, then we expect only distractor inhibition effects to emerge in the present experiment, for both response dimension conditions.

If response dimension rather than search dimension is the critical factor, we expect to observe both target activation and distrac-

tor inhibition effects in the orientation-response session and only distractor-inhibition effects in the color-response session.

3.1. Method

3.1.1. Subjects

Subjects were twenty-four Tel-Aviv University undergraduate students who participated in the experiment for course credit. All reported having normal or corrected-to-normal visual acuity and normal color vision.

3.1.2. Apparatus, stimuli, procedure and design

The apparatus, stimuli, procedure and design were similar to those of Experiment 2 except for the following differences. Subjects searched for a shape singleton target. An example of the display is presented in Fig. 1 (right panel). Each display contained one object with a unique shape, the target, and five objects with a different shape, the distractors. On each trial the target and distractor shapes were randomly drawn from four possible shapes: a circle (1.39° in diameter), a diamond (a rotated square 1.13° in side), a 7-branch star (1.15° for the inner diameter and 1.4° for the outer diameter) and a flower (1.15° for the inner diameter and 1.4° for the outer diameter). Three shapes were drawn in pinkish gray and three in greenish gray (the same colors as those used for the lines in Experiments 1 and 2), with a 2-pixel stroke. Centered inside each shape was a gray line segment similar to that used in the color session of Experiment 2. Each display contained exactly three vertical and three horizontal line segments. There were two sessions: a color-response session, in which subjects responded to the color of the target object and an orientation-response session, in which subjects responded to the orientation of the line segment enclosed in the target.

3.2. Results

In all RT analyses, error trials (4.8%) were removed from analysis, and so were RT outliers following the same procedure as in Experiment 1. Less than 1.2% of all observations were removed following this procedure. The data from 3 subjects were discarded because their mean error rates exceeded the subjects' mean by more than 2.5 standard deviations. The basic PoP effects and their components are depicted in Fig. 4.

3.2.1. Replication of the basic PoP effect

Reaction times. An ANOVA with response dimension (color vs. orientation) and repetition (repeated target and distractor shapes vs. switched target and distractor shapes) revealed significant a main effect of repetition, $F(1,20) = 70.52$, $p < 0.0001$, with faster RTs for repeated than for switched target and distractors shapes, $M = 919$ ms and $SD = 168$ vs. $M = 1057$ and $SD = 165$, respectively. There was no main effect of response dimension, $F(1,20) = 1.22$, $p > 0.2$, $M = 1005$ ms and $SD = 185$ vs. $M = 971$ ms and $SD = 175$ for the orientation vs. color response dimension, respectively. The interaction between the two factors approached significance, $F(1,20) = 3.45$, $p < 0.08$: repetition effects tended to be larger when the response dimension was color, than when it was orientation, 159 ms vs. 115 ms, respectively. **Accuracy.** The effect of repetition was significant, $F(1,20) = 10.40$, $p < 0.005$, with higher accuracy on repeated than on switched-shape trials, $M = 96.8\%$ and $SD = 3.2\%$ vs. $M = 93.6\%$ and $SD = 5.8\%$, respectively. There was no other significant effect, all $F_s < 1$.

3.2.2. Target activation and distractor inhibition

Next, we conducted two separate ANOVAs with response dimension, target repetition and distractor repetition as factors and with response dimension, target switch and distractor switch

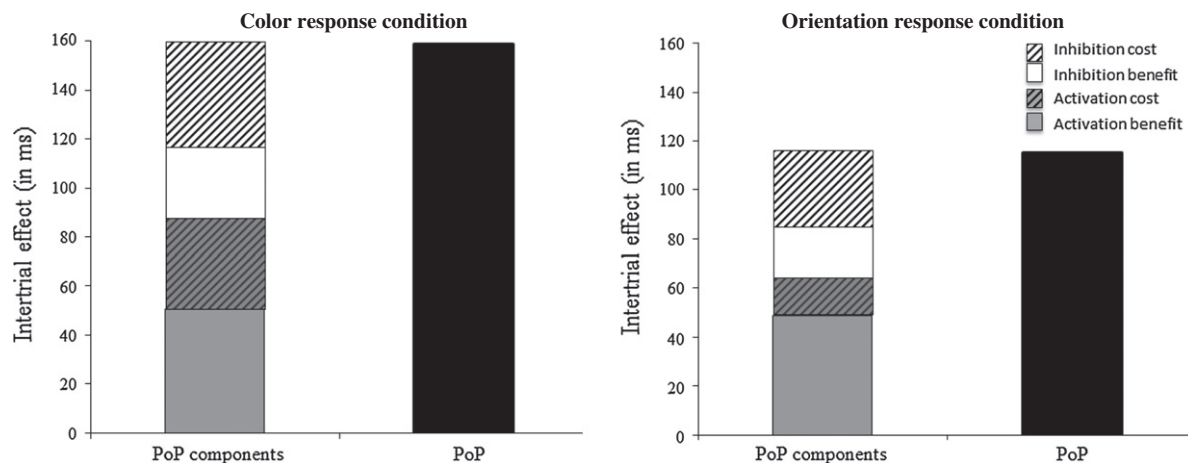


Fig. 4. Results of Experiment 3. Comparison of the basic PoP effect vs. the sum of the four component effects in the color response condition (left panel) and in the orientation response condition (right panel). Striped areas represent the two effects reflecting target activation and plain areas represent the two effects reflecting distractor inhibition. The effects represent RT differences in milliseconds.

as factors. Neither the interaction between target repetition and distractor repetition nor between target switch and distractor switch was significant, $F_s < 1$, and nor were the 3-way interactions with response dimension, all $p_s > 0.25$.

Reaction times. The target activation benefit and cost were significant, $F(1,20) = 47.66$, $p < 0.0001$ and $F(1,20) = 8.86$, $p < 0.008$, respectively. The target activation benefit did not interact with response dimension, $F < 1$. The interaction between target activation cost and response dimension approached significance, $F(1,20) = 3.55$, $p < 0.08$ and revealed that the cost tended to be higher when subjects had to respond to the target color than to the orientation of the line enclosed in the target. Note that this marginal interaction is in the opposite direction of that expected if response dimension rather than search dimension had been the critical factor for target activation effects: in Experiment 2, a significant target activation cost effect was found when the response dimension was line orientation (color search condition) but not when it was target color (orientation search condition).

The distractor inhibition benefit and cost were significant, $F(1,20) = 16.45$, $p < 0.0006$ and $F(1,20) = 25.90$, $p < 0.0001$. Neither of these effects interacted with response dimension, both $F_s < 1$.

Accuracy. The main effects of target activation benefit and of distractor inhibition cost were significant, $F(1,20) = 8.86$, $p < 0.08$ and $F(1,20) = 5.44$, $p < 0.04$, respectively. No other effect was significant, all $p_s < 0.2$.

The findings from the present experiment allow us to reject the alternative accounts we raised for the findings from Experiments 1 and 2. Neither differences in task difficulty nor the different response dimensions used in our color vs. orientation search tasks can account for the finding that while both target activation and distractor inhibition mechanisms contribute to PoP in color singleton search, only the latter mechanisms contribute to PoP in orientation singleton search. In addition, the orientation dimension seems to be the exception rather than the rule, as we showed that both mechanisms contribute to PoP in shape singleton search.

4. General discussion

We demonstrated that in search for an orientation singleton, only distractor inhibition processes underlie priming of pop-out (PoP), whereas in search for a color or for a shape singleton, target activation processes also play an important role. We showed that neither differences in task difficulty nor differences in the dimension relevant for response can provide alternative accounts for

the finding that the mechanisms that underlie PoP of orientation differ qualitatively from the mechanisms that underlie PoP of color or shape.

These findings have four main implications.

First, they resolve the apparent inconsistencies in the literature concerning orientation PoP: no inter-trial priming effects are observed when the measure employed reflects only target activation processes (e.g., Found & Müller, 1996; Lustig et al., 2012), whereas these effects emerge when the measure employed reflects also distractor inhibition processes (Hillstrom, 2000; Kristjansson, 2006).

Second, they corroborate the idea that PoP results from the operation of two distinct mechanisms, target activation and distractor inhibition, each of which is reflected by two components: a repetition benefit and a switch cost. Indeed, we replicated our previous findings on the color dimension (Lamy et al., 2008) and extended them to orientation and shape: in all the experiments reported here, the PoP effect, calculated as the difference in performance between trials in which both the target and distractors repeat vs. exchange roles, was almost identical in magnitude to the sum of the four components: target activation benefit, target activation cost, distractor inhibition benefit and distractor inhibition cost. In addition, for the orientation dimension, both the components attributed to distractor inhibition were absent, which strongly supports the claim that these components indeed reflect the same underlying mechanism.

Third, these findings suggest that there is no unitary answer to the question of whether target inhibition or distractor inhibition plays a larger role in PoP (Bichot & Schall, 2002; Maljkovic & Nakayama, 1994). For color and for shape, target activation effects tended to be larger than distractor inhibition effects (see Lamy et al., 2008, for a similar finding), whereas for orientation search, only distractor inhibition effects were observed.

Finally, as inter-trial priming effects of PoP occur as a consequence of the search process, our results suggest that the mechanisms underlying search for an orientation singleton differ from the mechanisms underlying search for a color or a shape singleton. Specifically, they suggest that selection of an orientation singleton is essentially mediated by iso-feature suppression of the background elements (e.g., Knierim & van Essen, 1992; Li, 2000; Sagi, 1990).

Consistent results have been reported with regard to perceptual learning. For instance, Karni and Sagi (1991) required their subjects to detect a target made up of three lines that differed only in orientation from a background of horizontal lines and to make a

forced-choice response as to whether the lines making up the target formed a horizontal or a vertical object. They showed that long-term learning of this task was specific to the orientation of the background elements but not to the target orientation (see however Ahissar & Hochstein, 1996, for conflicting results).

Likewise, Nothdurft (1993) investigated the role of the local contrast between the target and background elements in preattentive vision, using a variety of tasks for the color, orientation and motion dimensions. He found that whereas the detection of orientation- and motion-singleton targets depended only on local feature contrast, detection of color targets also depended on the known target property itself. Interestingly, studies conducted by Müller and colleagues point to a similar parallel between search for orientation targets and search for motion targets. They measured inter-trial feature priming for color vs. orientation targets (Found & Müller, 1996) and for color vs. motion targets (personal communication by Hermann Müller regarding unreported findings in a study by Weidner, Pollmann, Müller, & von Cramon, 2002). In both studies, a constant-distractor design was used, that is, a design in which only the target-activation component of feature priming could be measured and the inhibition component could play no role. Color repetition speeded search, but neither orientation nor motion repetition did. Taken together, these findings suggest that in orientation- and motion-singleton search, only distractor suppression mediates detection. It would be useful to further test this conclusion by measuring target activation and distractor inhibition components of PoP in a motion singleton search.

We currently have no satisfactory explanation for why in search for singletons defined in one class of dimensions (orientation and motion direction), the implicit memory effects observed in inter-trial priming and long-term perceptual learning seem to rely only on distractor-related traces, whereas for singletons defined in another class of dimensions (color and shape), memory of the target feature also plays a role.² Further research is clearly needed in order to classify additional dimensions into these categories and to characterize the mechanisms that underlie the differences observed between them. However, our findings may provide useful constraints and novel predictions for models of preattentive vision. In particular, they suggest that conclusions drawn from studies investigating orientation pop-out search may not apply to other dimensions.

Acknowledgment

Support was provided by the Binational Science Foundation (BSF) Grant No. 2009425 to Dominique Lamy and Andrew Leber.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.visres.2013.01.008>.

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² One may speculate that processes related to distractor inhibition might rely on iso-feature suppression mechanisms occurring in the primary visual cortex, the role of which has been suggested to reside mainly in determining the most salient item in the visual field (e.g., Li, 2002) in addition to coding the specific features of each filled location in the visual field, whereas target activation processes may arise in higher cortical regions such as V4. Indeed, whereas coding of orientation and local motion is mainly supported by V1 cells, color and shape information is recoded in important ways in higher cortical areas.