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Vision Research 48 (2008) 30–41
Vision Research
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Priming of Pop-out provides reliable measures of target activation and distractor inhibition in selective attention ☆

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Received 27 July 2007; received in revised form 2 October 2007

Abstract

Recent research has demonstrated a striking role for intertrial priming in visual search. When searching for a discrepant target, repetition of the target feature speeds search, an effect known as Priming of Pop-out (PoP). In two experiments involving color singletons, we identified two independent components of PoP, target activation and distractor inhibition. Each component was reflected by two measures, a repetition benefit and a switching cost, that were highly correlated. Large individual differences on each component were observed and persisted when test and retest were separated by one week. The results suggest that PoP may be a reliable tool for assessing individual differences on target activation and distractor inhibition in selective attention.

Keywords: Priming of Pop-out; Repetition priming; Visual search; Target activation; Distractor inhibition

1. Introduction

Recent research has demonstrated a striking role for implicit visual memory factors in visual search performance (e.g., Chun & Jiang, 1998; Chun & Nakayama, 2000; Lamy, Bar-Anan, & Egeth, in press; Maljkovic & Nakayama, 1994; Maljkovic & Nakayama, 1996; Maljkovic & Nakayama, 2000; Müller, Heller & Ziegler,1995; Wolfe, Butcher, Lee, & Hyle, 2003). Maljkovic and Nakayama (1994) were the first to show 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 substantially improved when the target's discrepant feature happens to repeat from one trial to the next. They called this phenomenon "Priming of Pop-out" 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 distractor switched colors unpredictably from trial to trial. Repeated-color trials were faster than switched-color trials. This effect has been replicated with targets differing from the surrounding distractors by their color (e.g., Goolsby & Suzuki, 2001), their shape (e.g., Lamy, Carmel, Egeth, & Leber, 2006), their orientation (e.g., Hillstrom, 2000), their size (Huang, Holcombe, & Pashler, 2004), and the facial expression of emotion they displayed (Lamy, Amunts, & Bar Haim, in press).

Two possible mechanisms, that are not mutually exclusive, may underlie PoP. Performance may benefit from repetition of the target feature, that is, it may be easier to attend to a feature that has just been attended. Such facilitation may occur because following target selection on a given trial, activation of the target feature may persist to the next trial and thereby speed selection of the repeated-feature target. Alternatively, performance may benefit from repetition of the distractor feature, that is, it may be easier to ignore a feature that has just been ignored. Such facilitation may occur because inhibition of the distractor feature may persist to the next trial and thereby speed rejection of the repeated-feature distractors.

☆ Support was provided by the Israel Science Foundation (ISF) Grant No. 1382-04 to Dominique Lamy. We thank Ken Nakayama and an anonymous reviewer for useful comments.
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doi:10.1016/j.visres.2007.10.009

Because in a standard PoP experiment, the target and distractor features either remain the same or switch with one another from one trial to the next, activation and inhibition effects are typically confounded. Only two studies attempted to disentangle the two candidate components of PoP (Maljkovic & Nakayama, 1994, Experiment 8; Bichot & Schall, 2002). Other studies examined this question with tasks that deviated from the standard PoP paradigm, namely with conjunction search tasks (Geyer, Müller, & Krummenacher, 2006; Koshino, 2001) and singleton-search tasks in which changes in target and distractor features occurred across different dimensions rather than within the same dimension (Wolfe et al., 2003). These studies are considered in more detail in the general discussion.

Maljkovic and Nakayama (1994, Experiment 8) isolated target repetition effects by keeping the color of the target the same over various sequences of trials while changing the distractor color on each trial. Conversely, they isolated distractor-repetition effects by keeping the distractor color the same over various sequences of trials and changed the target color on each trial. They found both target- and distractor-repetition effects, reflected by decreases in reaction times (RTs) as the length of repeated target and distractor sequences, respectively, increased. In addition, RT reductions were larger for target repetitions than for distractor repetitions. Maljkovic and Nakayama concluded that both target activation and distractor inhibition mediate PoP, and that target activation is the more important mechanism.

The second study that examined the relative contributions of target and distractor repetition in PoP recorded the activity of single neurons in the frontal eye field (FEF) of monkeys performing a color pop-out search (Bichot & Schall, 2002). On each trial, the monkey was required to make an eye movement to a color singleton. As in most previous PoP experiments, target and distractor feature changes were confounded as the target and distractors colors switched unpredictably from trial to trial. However, because separate activity recordings could be obtained from neurons the receptive fields of which contained a target and from neurons the receptive fields of which contained a distractor, the effects of target- and distractor-color repetition could be dissociated. Bichot and Schall compared neuronal activation between early trials, defined as the first two color-repeated trials following a feature change and late trials, defined as the fourth or later color-repeated trials following a feature change. That is, they compared one-repetition trials to three-or-more repetition trials. Target activation, reflected by the mean number of spikes per second for neurons representing targets, was higher for late relative to early trials. Distractor activation, reflected by the mean number of spikes per second for neurons representing distractors, was lower for late relative to early trials. In addition, increase in target activation and decrease in distractor activation for late relative to early trials were of similar magnitude. Bichot and Schall (2002) concluded that target activation and distractor inhibition mechanisms contribute to the same extent to the PoP effect.

The findings from the two studies (Maljkovic & Nakayama, 1994, Experiment 8 and Bichot & Schall, 2002) converge to suggest that both target activation and distractor inhibition play a role in PoP, although they are at odds as to whether or not activation is more potent than inhibition. However, the conclusions from these studies may be limited in two respects. First, the effects attributed to the influence of the previous trials on the current trial may have been contaminated by top-down factors.[1] In Maljkovic and Nakayama's study (1994, Experiment 8), three different sequence lengths (2, 4, and 6) were used for both target- and distractor-color repetitions in order to avoid the prohibitively large number of trials required to examine the effects of long runs of target- and distractor-color repetitions using random color assignment on each trial. These sequences came up randomly and repeated target-color and repeated distractor-color sequences were intermixed. Following the last trial of a sequence, the colors from that trial alternated for the few subsequent trials. This design made sequences and non-sequences highly discriminable. Indeed, the beginning of each sequence was cued by alternations between the colors of the last trial, followed by a sudden change of both colors. Thus, following such a cue, subjects were likely to expect either target- or distractor-color repetition, and the effects attributed to intertrial repetition might therefore have resulted from top to down factors.

In the same vein, in Bichot and Schall's (2002) study, the colors of the target and distractors switched across trials with probabilities of 50% or 33%, or in blocks of 10 trials. Thus, target and distractor colors switched unpredictably in only one of the three different conditions of switch probabilities, and were more likely to repeat than to switch in the other two probability conditions. Because the data from the three different conditions were pooled, one cannot exclude the possibility that the changes in neuronal activity reflecting target activation and distractor inhibition may have resulted from the expectations promoted by the design.

In addition, target and distractor-color repetitions were manipulated separately rather than orthogonally in Maljkovic and Nakayama (1994), and their effects were assessed by measuring activity changes in different neurons in Bichot and Schall's (2002) study. Thus, a second limitation of these studies is that their design did not allow examining whether target activation and distractor inhibition are independent or interact with each other.

The objective of the present study was to disentangle the effects of target activation and distractor inhibition

[1] Maljkovic and Nakayama rejected the possibility that expectancy of the upcoming color plays any role in the difference between the blocked and the mixed condition (Experiments 2 and 4). However, while their results indeed suggest that PoP plays a more significant role than expectancy, they do not allow one to conclude that expectancy plays no role.

in PoP while avoiding the potential problems associated with previous studies. To this end, we used a color singleton search in which the target and distractors could take on one of four possible colors on any given trial. On each trial, two different colors were randomly drawn from the four possible colors and assigned to the target and distractors. Thus, there were three possible sequences with regard to target-color variation on successive trials: on any given trial, the target color could be (1) the same as the target color in the previous trial, (*repeated*-target condition), (2) the same as the distractors color on the previous trial (*switched*-target condition), or (3) a color that differed from both the target and distractors colors on the previous trial (*new*-target condition). Similarly, there were three possible sequences with regard to distractor-color variation on successive trials: the distractors color could be (1) the same as the distractors color in the previous trial, (*repeated*-distractors condition), (2) the same as the target color on the previous trial (*switched*-distractors condition), or (3) a color that differed from both the target and distractors colors on the previous trial (*new*-distractor condition). The combination of the different target- and distractor-color repetition conditions resulted in seven rather than nine conditions because "*switched* target–*repeated* distractor" and "*repeated* target–*switched* distractor" are impossible conditions. This design allowed us to investigate the contributions of target activation and distractor inhibition mechanisms in the PoP effect when target and distractor colors vary randomly from trial to trial, and to examine whether these mechanisms are independent from each other or interact.

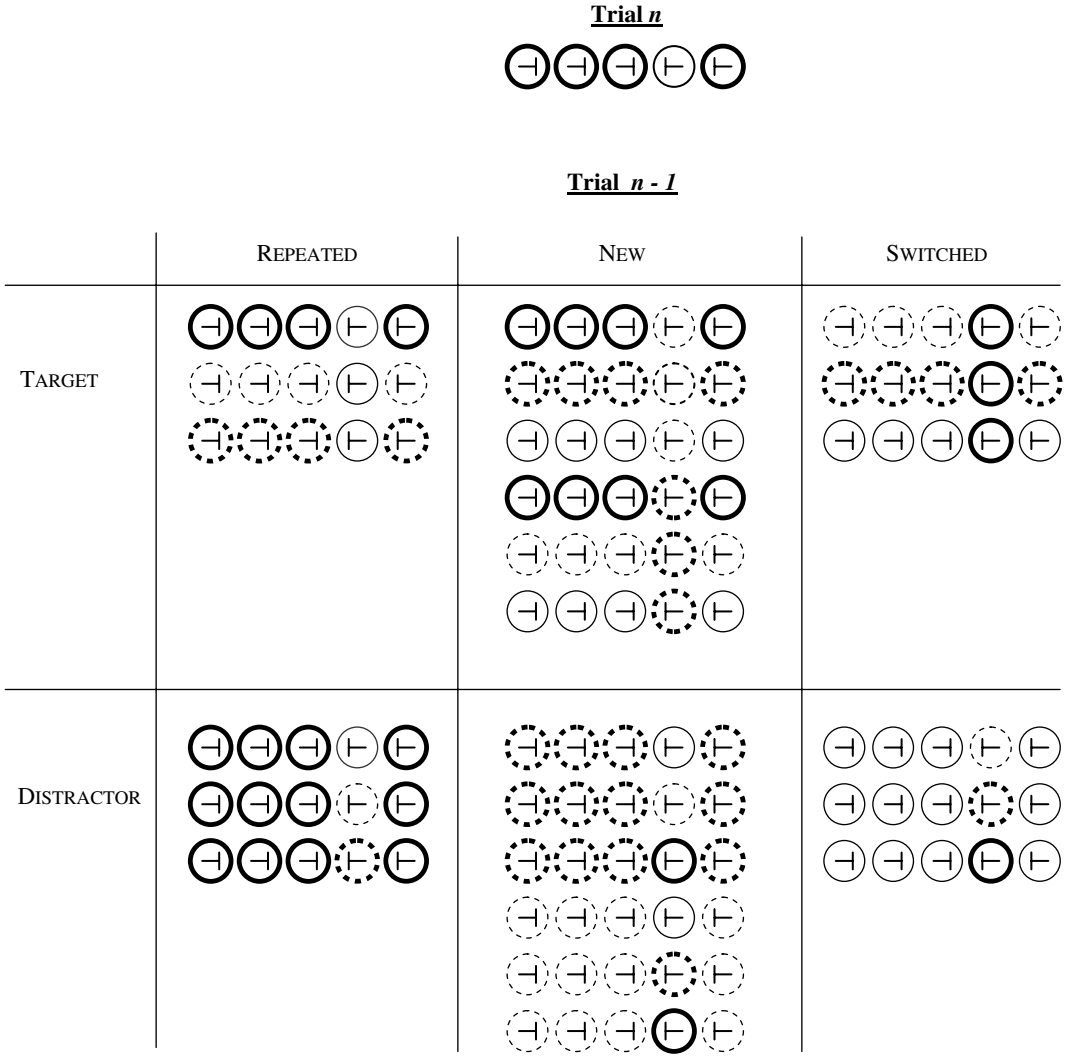

Fig. 1. Illustration of the trial sequence types in each condition. In this example, on trial *n* the target is the light-stroke (say, red) circle and the distractors are the heavy-stroke (say, green) circles, as depicted in the top row. The rows below represent displays on Trial $n-1$. The new colors (blue and yellow) are shown as heavy dotted lines and light broken lines. The difference in mean performance between the *repeated* and the *new* target-color conditions made up one index of target activation and the difference between the *switched* and the *new* distractor-color conditions made up the second index of target activation. The difference in mean performance between the *repeated* and the *new* distractor-color conditions made up one index of distractor inhibition and the difference between the *switched* and the *new* target-color condition made up the second index of distractor inhibition. For practical purposes, the displays are depicted as rows, but in the actual experiment, the circles were scattered in an imaginary matrix as shown in Fig. 2.

1.1. Overview of the analyses

In each experiment, we first examined whether the basic PoP effect was replicated by comparing performance on *repeated* target–*repeated* distractors trials vs. *switched* target–*switched* distractors trials. Then, to examine whether or not the effects of target-color variation on successive trials were independent from the effects of distractor-color variation on successive trials, we investigated (1) whether the effects of repeating the target color and the effects of repeating the distractor color interacted (*repeated* vs. *new* target color × *repeated* vs. *new* distractor color) and (2) whether the effects of the target color on the previous trial becoming the distractor color on the current trial and the effects of the distractor color on the previous trial becoming the target color on the current trial interacted (*switched* vs. *new* target color × *switched* vs. *new* distractor color). To preview, in neither of the experiments reported in the present study did these interactions or higher-order effects involving these interactions approach significance, all $ps > 0.25$. Thus, effects of target-color activation and of distractor-color inhibition were independent from each other and could be examined separately.

The effect of target-color activation could be quantified using two measures. Following target selection on trial $n-1$, activation of the target color should facilitate selection of a target of the same color on trial n (*repeated* vs. *new* target color) and slow rejection of distractors of the same color as the target on the previous trial (*switched* vs. *new* distractor color). Moreover, if these two measures indeed underlie the same target activation mechanism, they should be significantly correlated across observers. Similarly, following distractor rejection on trial $n-1$, inhibition of the distractor color should facilitate rejection of distractors of the same color on trial n (*repeated* vs. *new* distractor color) and slow selection of a target of the same color as the distractors on the previous trial (*switched* vs. *new* target color). Again, if these two measures underlie the same distractor inhibition mechanism, they should also be significantly correlated across observers. Fig. 1 illustrates the trial sequences from which each measure was derived. In all the correlation analyses presented here, the data points that exceeded the mean of their category by more than two standard deviations were removed from the correlation analysis. The outlier data points are surrounded by circles in the relevant scatter plots.

2. Experiment 1

2.1. Methods

2.1.1. Subjects

Subjects were 20 Tel-Aviv University undergraduate students who participated in the experiment for course credit. All reported having normal or corrected visual acuity and normal color vision.

2.1.2. Apparatus

Displays were generated by an Intel Pentium 4 computer attached to a 17 in. 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.

2.1.3. Stimuli

Examples of the stimulus displays are presented in Fig. 2. The fixation display was a gray $0.2° \times 0.2°$ plus sign (+), in the center of a black background. The stimulus display consisted of the fixation display with the addition of five colored outline circles, with each circle subtending 0.7° in diameter. Centered inside each circle was a T letter (0.37° in length and 0.25° in width) rotated by 90° and pointing either to the right or to the left. T letters were drawn with a 1-pixel stroke and the circles with a 2-pixel stroke. The display always contained either two left-pointing and three right-pointing Ts, or vice-versa. The circles appeared at random locations within an imaginary 3×3 matrix centered at fixation. No circle ever appeared in the central cell, where the fixation sign appeared. Each cell subtended 2° in side and each circle was centered inside its cell with a random jitter of −0.15°, 0° or 0.15°. Each display contained one circle with a unique color, the target, and four circles in a different color, the distractors. 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/m^2), blue (CIE coordinates 0.20/0.22, 18.67 cd/m^2), green (CIE coordinates 0.28/0.593, 18.44 cd/m^2), and yellow (CIE coordinates 0.42/0.49,

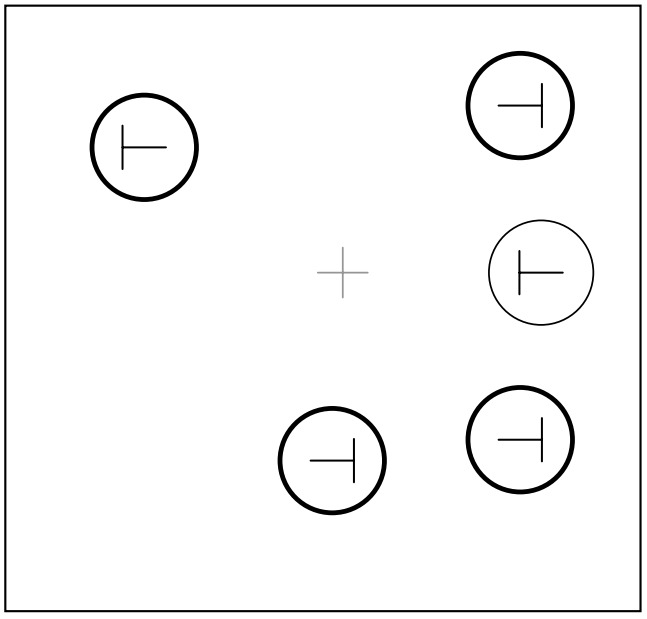

Fig. 2. Example of the visual search arrays in Experiment 1. Subjects had to respond to the orientation of the T inside the odd-colored circle. The colors of the target (thin stroke) and distractors (thick stroke) were randomly drawn from four possible colors. Stimuli are not drawn to scale.

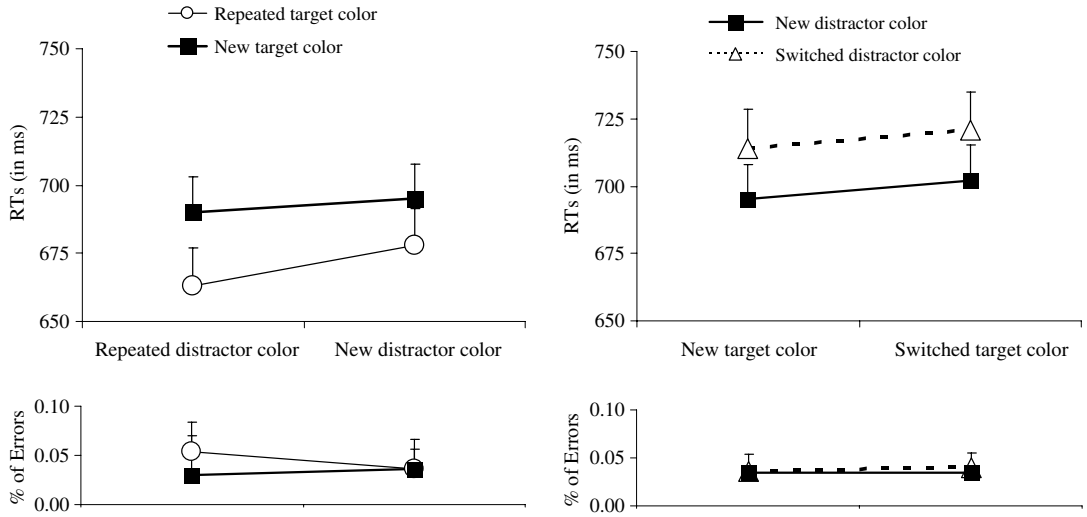

Fig. 3. Experiment 1. *Left panels*: performance on *repeated* and on *new* distractor-color trials by conditions of target-color repetition (*repeated* vs. *new*). *Right panels*: performance on *switched* and on *new* target-color trials by conditions of distractor-color switch (*switched* vs. *new*). *Upper panels*: mean reaction times (RTs) in milliseconds. *Lower panels*: percent errors.

18.32 cd/m^2). Each of the resulting 12 target–distractor color combinations was equally probable.

2.1.4. Procedure

The subjects had to determine whether the T inside the color singleton target pointed to the right (by pressing the "z" key on the computer keyboard with their right-hand) or to the left (by pressing the "3" keypad key with their left-hand)[2] as quickly as possible, while maintaining high accuracy. Error trials were followed by a 500-ms feedback beep.

Each trial began with the 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. Each trial began with the presentation of the fixation display. Eye movements were not monitored, but subjects were explicitly requested to maintain fixation throughout each trial.

2.1.5. Design

There were three possible variations of the target color from one trial to the next (*repeated*, *new*, and *switched* target color) and three possible variations of the distractors color from one trial to the next (*repeated*, *new*, and *switched* distractor color). 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-color repetition (*repeated* target color vs. *new* target color) and distractor-color repetition (*repeated* distractor color vs. *new* distractor color) as factors. The second ANOVA included target-color switch (*new* target color vs. *switched* target color) and distractor-color switch (*new* distractor color vs. *switched* distractor color) as factors.

The experiment began with a block of 40 practice trials, followed by 360 experimental trials divided into six blocks. Subjects were allowed a short rest after each block.

2.2. Results and discussion

In all RT analyses, error trials (4.2% of all trials) were removed from analysis, and RTs for each subject were sorted into cells by conditions of target and distractor color 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. Mean RT and accuracy scores are depicted in Fig. 3.

2.2.1. Replication of the basic PoP effect

Reaction Times. Comparison of the RTs on *repeated* target-color–*repeated* distractor-color trials relative to *switched* target-color–*switched* distractor-color trials confirmed that the basic PoP effect (Maljkovic & Nakayama, 1994) was replicated in the present experiment, $t(19) = 6.35$, $p < 0.0001$.

Accuracy. The pattern of results on the accuracy measure was similar to that observed with the RT measure, namely, subjects tended to make less errors on *repeated* target-color–*repeated* distractor-color trials than on *switched* target-color–*switched* distractor-color trials, $t(19) = 1.83$, $p < 0.09$. Thus, speed-accuracy trade-off was not a concern.

[2] T-rotation-to-key assignment was counterbalanced between subjects. Half the subjects were told to press with their right hands when the T's head pointed to the right and the other half were told to press with their right hand when the T's tail pointed to the right (and vice-versa for left-hand presses).

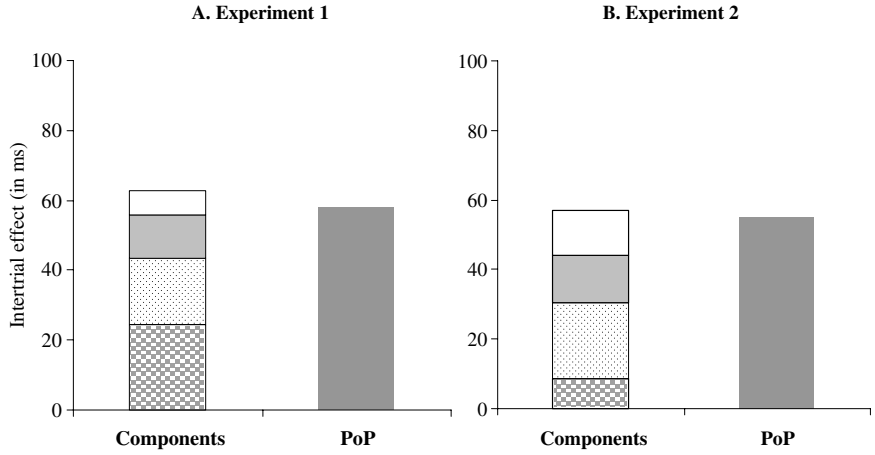

Fig. 4. Experiments 1 and 2 (panels A and B, respectively). Comparison of the sum of the four component effects (target-color repetition, target-color switch, distractor-color repetition and distractor-color switch) and the basic PoP effect (*repeated* target color/*repeated* distractor color vs. *switched* target color/*switched* distractor color). Dotted 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.

2.2.2. Target activation and distractor inhibition

Reaction times. An ANOVA with target repetition (*repeated* vs. *new* target color) and distractor repetition (*repeated* vs. *new* distractor color) showed no interaction between the two factors, $F < 1$. Likewise, an ANOVA with target switch (*new* vs. *switched* target color) and distractor switch (*new* vs. *switched* distractor color) showed no interaction between the two factors, $F(1,19) = 1.09$, $p > 0.3$. Thus, effects of target-color activation and of distractor-color inhibition were independent from each other and could be examined separately.

Planned comparisons showed that the two measures of target activation yielded significant effects. *Repeated* target-color trials were faster than *new* target-color trials, $t(19) = 6.19$, $p < 0.0001$ and *new* distractor-color trials were faster than *switched* distractor-color trials, $t(19) = 5.52$, $p < 0.0001$. The two measures of distractor inhibition also yielded significant effects. *Repeated* distractor-color trials were faster than *new* distractor-color trials, $t(19) = 2.36$, $p < 0.03$ and *switched* target-color trials were slower than *new* target-color trials, $t(19) = 2.24$, $p < 0.04$. As illustrated in Figs. 3 and 4A, effects of target activation and distractor

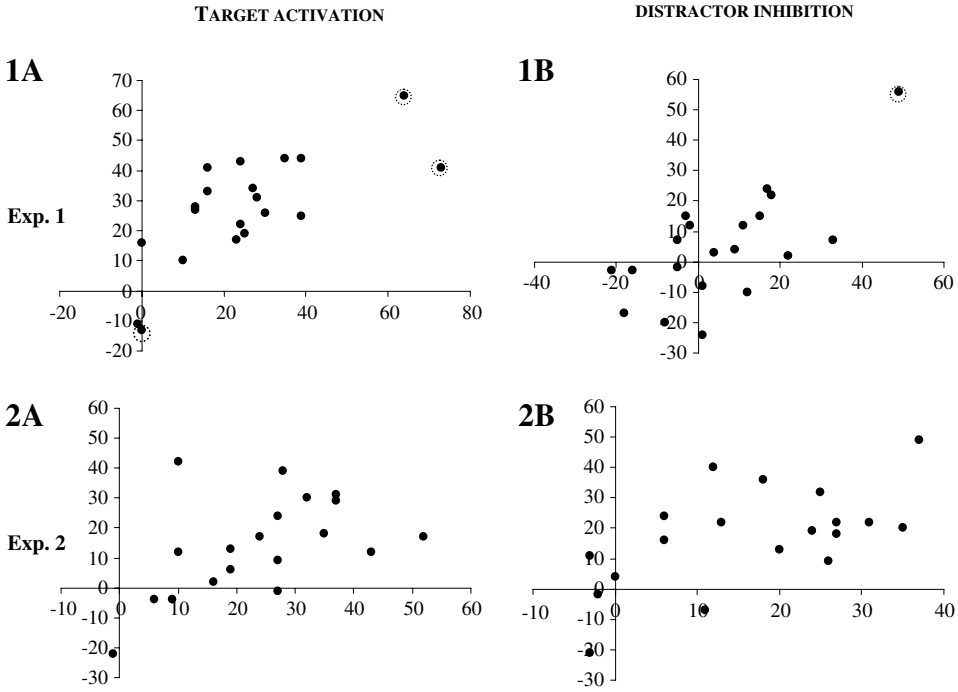

Fig. 5. Experiments 1 and 2 (upper and lower panels, respectively). Scatter plots depicting the correlations between the two measures of target activation (RT cost of *switched* vs. *new* distractor color on the *X* axis and RT facilitation of *repeated* vs. *new* target color on the *Y* axis) on left (A) panels, and between the two measures of distractor inhibition (RT facilitation of *repeated* vs. *new* distractor color on the *X* axis and RT cost of *switched* vs. *new* target color on the *Y* axis) on right (B) panels. Facilitation and cost are in milliseconds. Circled data points represent outliers.

inhibition were additive. The sum of the four effects (target-color repetition, target-color switch, distractor-color repetition, and distractor-color switch) was similar in magnitude to the basic PoP effect (*repeated* target color–*repeated* distractor color vs. *switched* target color–*switched* distractor color), 58 ms vs. 63 ms, respectively, $t < 1$ (see Fig. 4A). The sum of the two effects reflecting target activation was larger than the sum of the two effects reflecting distractor inhibition, $t(19) = 2.40$, $p < 0.03$.

Accuracy. Although there were numerical trends for speed-accuracy trade-off (see Fig. 3), none of the effects approached significance, all ps > 0.15.

RT correlations. The two measures of target activation were significantly correlated, $r(15) = 0.63$, $p < 0.007$ ($r(18) = 0.73$, $p < 0.0003$ when outliers were not excluded), and so were the two measures of distractor inhibition, $r(17) = 0.73$, $p < 0.0004$ (and $r(18) = 0.79$, $p < 0.0001$ when outliers were not excluded). These correlations are illustrated in scatter plots shown in Fig. 5 (panels 1A and 1B). For comparison, there were no significant correlations between measures of activation and measures of inhibition. A composite measure of activation was created by averaging the Z-scores of the two measures of activation and a composite measure of inhibition was created by averaging the Z-scores of the two measures of inhibition. Data points with a Z-score exceeding 2 were removed from the correlation analysis. The correlation between the composite activation and inhibition scores was non-significant, $r(17) = 0.009$, $p > 0.9$ ($r(18) = 0.01$, $p > 0.9$, when no outlier was excluded).

The results of Experiment 1 yielded three main findings. First, they showed that both target activation and distractor inhibition underlie PoP of color. These effects were not contaminated by expectations concerning the colors of the target and distractors on the upcoming trial because these varied randomly from trial to trial. Second, these effects were additive, suggesting that their contributions to the PoP effect are independent. Target activation played a larger role than distractor inhibition, consistent with Maljkovic and Nakayama (1994). Finally, the two measures of target activation were correlated with each other and so were the two measures of distractor inhibition. By contrast, measures of target activation and measures of distractor inhibition were uncorrelated. Taken together, these findings strengthen the construct validity of the target activation and distractor inhibition measures in this study.

3. Experiment 2

The notable individual differences in the magnitude of target activation and in the magnitude of distractor inhibition effects found in Experiment 1 raise the question of whether different individuals might be categorized as "good activators" vs. "poor activators", and as "good inhibitors" vs. "poor inhibitors" in the context of target selection and distractor inhibition in visual search. The main objective of Experiment 2 was to investigate whether individual target activation and distractor inhibition scores would show some stability in a test-retest procedure. Thus, Experiment 2 consisted of two sessions run a week apart.

3.1. Method

3.1.1. Subjects

Subjects were 20 Tel-Aviv University undergraduate students who participated in the experiment for course credit. All reported having normal or corrected visual acuity and normal color vision.

3.1.2. Apparatus, stimuli, and procedure

The apparatus, stimuli, and procedure were the same as in Experiment 1, except that two sessions instead of only one were run, a week apart. The two sessions were similar in all respects except for trial order that was randomly determined on each session.

3.2. Results and discussion

In all RT analyses, error trials (2.7%) were removed from analysis, and RTs for each subject were sorted into cells by conditions of target, distractor color inter-trial variation and session, and outliers were removed following the procedure used in Experiment 1. The data from one subject were removed from the analysis because this subject made more than 25% of errors. Mean RT and accuracy scores are depicted in Fig. 6.

3.2.1. Replication of the basic PoP effect

Reaction times. An ANOVA with condition (*repeated* vs. *switched* target and distractors) and session (first vs. second) as factors showed that the basic PoP effect was replicated, $t(1,18) = 13.79$, $p < 0.002$. In addition, performance was faster in the second relative to the first session, showing practice effects, $F(1,18) = 4.75$, $p < 0.05$. The two effects did not interact, $F < 1$.

Accuracy. There were no significant effects, all Fs < 1.

3.2.2. Target activation and distractor inhibition

Reaction times. Two ANOVAs, one with target repetition (*repeated* vs. *new* target color), distractor repetition (*repeated* vs. *new* distractor color) and session as factors, and the other with target switch (*new* vs. *switched* target color), distractor switch (*new* vs. *switched* distractor color) and session as factors were conducted. The interaction between target- and distractor-color repetition was non significant, and so was the interaction between target- and distractor-color switch, ps < 0.2. The 3-way interactions with session were also non-significant, $F(1,18) = 1.30$, $p > 0.2$, and $F < 1$, respectively. Thus, effects of target-color activation and of distractor-color inhibition were independent from each other and could be examined separately, across sessions.

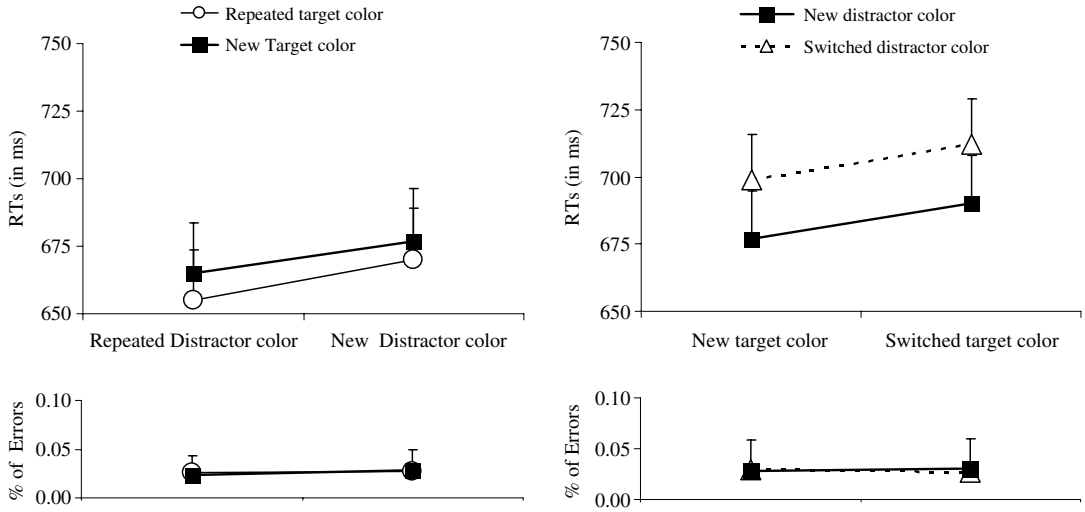

Fig. 6. Experiment 2. *Left panels*: performance on *repeated* and on *new* distractor-color trials by conditions of target-color repetition (*repeated* vs. *new*). *Right panels*: performance on *switched* and on *new* target-color trials by conditions of distractor-color switch (*switched* vs. *new*). *Upper panels*: mean reaction times (RTs) in milliseconds. *Lower panels*: percent errors.

Planned comparisons showed that both measures of target activation yielded significant effects. Reaction times were faster on *repeated* target-color trials than on *new* target-color trials, $t(18) = 3.83$, $p < 0.002$ and *switched* distractor-color trials were slower than *new* distractor-color trials, $t(18) = 7.57$, $p < 0.0001$. Both measures of distractor inhibition yielded significant effects. The advantage of repeating the distractor color was significant $t(18) = 5.92$, $p < 0.0001$ and so was the cost of the target on the current trial taking on the color of the distractors on the previous trial, $t(18) = 4.52$, $p < 0.0003$. Again, as illustrated in Figs. 6 and 4B, effects of target activation and distractor inhibition were additive. The sum of the four effects (target-color repetition, target-color switch, distractor-color repetition and distractor-color switch) was similar in magnitude to the basic PoP effect (*repeated* target color–*repeated* distractor color vs. *switched* target color–*switched* distractor color), 57 ms vs. 55 ms, respectively. There was no significant difference between the sum of the two effects reflecting target activation and the sum of the two effects reflecting distractor inhibition, $t < 1$.

Accuracy. There were no significant effects, all Fs < 1.

RT correlations. The significant correlations between two measures of the same components observed in Experiment 1 were replicated in the present experiment. None of the subjects obtained a score that deviated from the mean by more than two standard deviations, thus there were no outliers in these analyses. The two measures of target activation were highly correlated, $r(17) = 0.50$, $p < 0.02$, and so were the two measures of distractor inhibition, $r(17) = 0.60$, $p < 0.007$. These correlations are illustrated in scatter plots shown in Fig. 5 (panels 2A and 2B). For comparison, there were no significant correlations between measures of activation and measures of inhibition. Again, a composite measure of activation was created by averaging the Z-scores of the two measures of activation and a composite measure of inhibition was created by averaging the Z-scores of the two measures of inhibition, across sessions. The correlation between the composite activation and inhibition scores was non-significant, $r(17) = 0.11$, $p > 0.5$ (with no outliers).

Of primary interest here was the question of whether the activation and inhibition components measured in the first session would be correlated with the activation and inhibition components measured in the second session, that is, a week later. Composite measures of activation and of inhibition were created by averaging the Z-scores of the two measures of activation and of the two measures of inhibition, respectively, separately for each session. Data points with a Z-score exceeding 2 were removed from the correlation analysis. The correlation between the composite activation scores on session 1 and on session 2 was $r(18) = 0.45$, $p < 0.06$ (with no outliers) and the correlation between the composite inhibition scores on session 1 and on session 2 was $r(16) = 0.58$, $p < 0.02$ ($r(17) = 0.55$, $p < 0.02$ when outliers were not excluded). These correlations are illustrated in scatter plots shown in Fig. 7.

The results from the present experiment show that individual differences in the two components of PoP persisted from one session to the next when these were separated by one week. This finding strongly indicates that PoP yields reliable measures of target activation and distractor inhibition. In addition, consistent with the findings of Experiment 1, measures of both target activation and distractor inhibition were highly significant, although the larger magnitude of the former process relative to the latter found in Experiment 1 was not replicated in the present study. This finding confirms that although individual differences samples might modulate the relative magnitude of the activation and inhibition components, both components play an important role in the PoP task used in here.

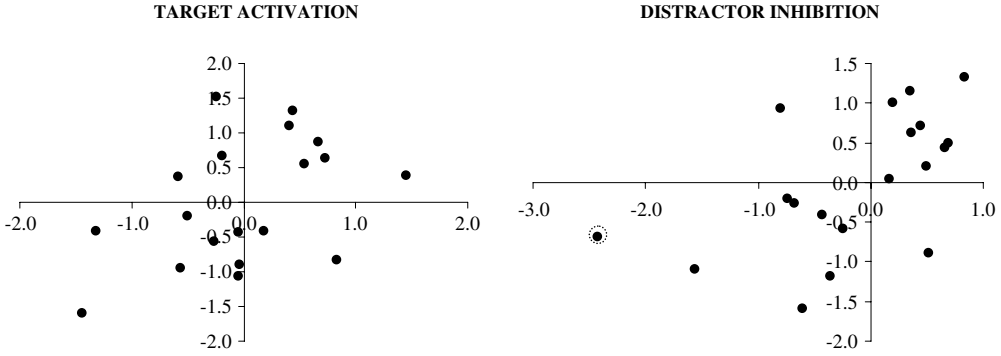

Fig. 7. Experiment 2. *Left panel*: scatter plot depicting the correlations between the composite target activation *Z*-score in the first session (*X* axis) and in the second session (*Y* axis). *Right panel*: scatter plot depicting the correlations between the composite distractor inhibition *Z*-score in the first session (*X* axis) and in the second session (*Y* axis). The first and second sessions were separated by one week.

4. General discussion

The present study yielded three main novel findings. First, in line with the findings from previous PoP studies, both target activation and distractor inhibition processes were found to mediate Priming of Pop-out, but under conditions in which top-down processes cannot provide an alternative account. Second, the contributions of these processes were independent, as there was no interaction between target activation and distractor inhibition effects, and the correlations between these effects were non-significant. Finally, individual differences on target activation and distractor inhibition measures persisted when retest was administered one week after the initial test.

4.1. Two components of PoP

Our findings show that two different processes underlie the PoP effect. Target activation was expressed in two measures: facilitation when the target feature repeated from one trial to the next and a cost when the distractor feature on a given trial was the same as the target feature on the previous trial. Likewise, distractor inhibition was expressed in two measures: facilitation when the distractor feature repeated from one trial to the next and a cost when the target feature on a given trial was the same as the distractor feature on the previous trial. In both experiments, the correlations between the two measures of target activation and between the two measures of distractor inhibition were high, while measures of target activation and distractor inhibition were uncorrelated. These findings strongly indicate that the facilitation and cost measures of target activation and distractor inhibition derived from the present variant of the PoP paradigm reflected the same underlying processes, and that activation and inhibition processes are independent from each other.

While in Experiment 1, target activation played a larger role than distractor inhibition (in line with Maljkovic & Nakayama, 1994), we found the two processes to contribute equally to PoP in Experiment 2 (in line with Bichot & Schall, 2002). Such differences between two experiments that involved the same task are most likely to result from individual differences between the participants sampled in each study. Indeed, in both studies we showed that the magnitude of target activation and distractor inhibition varied considerably across individuals. It is therefore conceivable that Experiment 1 included poorer "inhibitors" or better "activators" than did Experiment 2.

By contrast with the significant effects found for each component in the present study, however, Geyer et al. (2006) found large distractor inhibition effects with little or not target activation effects. The fact that this finding was replicated in two experiments involving ten different participants each reduces (but does not eliminate) the probability that individual differences alone account for this discrepancy. In Geyer et al.'s study, participants had to detect the presence of a red target that had a unique orientation within the red items subset in a display that also involved green items. For instance, on a given trial, the display might include a red horizontal target among green horizontal and red vertical distractors, and on the next trial, a red vertical target among red tilted and green vertical distractors. Thus, Geyer et al.'s study differed from the present one in several respects. First, it involved a detection task whereas our experiments involved a discrimination task. Second, participants searched for a conjunctively defined target whereas in the present study they search for a target that differed from the surrounding distractors on only one dimension. Third, repetition effects were measured for the orientation dimension, whereas we measured them for the color dimension. Further research is needed to elucidate which factors, beyond individual differences, determine the relative weights of target activation and distractor inhibition in inter-trial repetition priming.

4.2. Independent effects of target repetition and distractor repetition

The prevailing theoretical account for PoP stipulates that intertrial repetition effects occur early in processing, and reflect facilitation of the deployment of attention to the objects possessing the repeated attribute (e.g., Chun

& Nakayama, 2000; Maljkovic & Nakayama, 1994; Wolfe et al., 2003). Support for this selection-based account of PoP comes from findings showing that precuing the location of the upcoming target abolishes the PoP effect, and from single-cell recording studies in monkeys (e.g., Bichot & Schall, 2002) and brain imaging studies in humans (e.g., Kristjansson et al., 2006) showing that intertrial priming affects the activity of sensory and attentional brain areas.

However, Huang et al. (2004) recently challenged this view. In their study, subjects searched for an odd-sized target and reported its orientation. The color of the items was irrelevant to the task. When target size was repeated from the previous trial, repetition of target color speeded the response. When target size was different from that in the previous trial, repetition of target color slowed responses. Repetition of target size also interacted with repetition of the response feature (orientation). Huang et al. (2004) interpreted these findings in terms of an "episodic memory theory of PoP" according to which intertrial priming effects occur at a post-perceptual stage, when the observer double-checks whether a candidate target is indeed the target, before selecting the appropriate response. They proposed that when selecting a target, memories of similar previous episodes are automatically retrieved (Logan, 1988). When all the features of the target cohere in their implications (all favoring a "same" judgment or all favoring a "different" judgment) the double-checking process is fast and responses are speeded, while inconsistency across dimensions produces the opposite effect. It should be noted, however, that modulation of the size-repetition effect by repetition of features in an irrelevant dimensions in Huang et al.'s study was very weak. In addition, responses on the two "coherent" conditions (e.g., same size–same color and different size–different color) differed markedly, with the former condition being much faster than the latter, a finding that is not readily explained by the episodic retrieval account. Taken together, these findings suggest that retrieval from episodic memory might play only a minor role in PoP.

Consistent with this conclusion, the findings from the present study do not support Huang et al.'s (2004) episodic retrieval account of PoP. Repetition of the distractors feature affected performance in both experiments. Consequently, when retrieving memories of previous trial events, the matching process must have included both the target and distractor features. According to Huang et al.'s (2004) account, an interaction between target-feature repetition and distractor-feature repetition should have been observed. Specifically, *new* target-*repeated* distractor trials (in which target and distractors features did not cohere in their implications) were expected to be slower than *new* target-*new* distractor trials (in which both the target and distractors features favored a "different" judgment). However, this pattern of results was found in neither of the present experiments.

The notion that following selection of the target, the representation of the target feature remains activated and the representation of the distractor inhibited provides a parsimonious account for the present findings. However, these are also compatible with an episodic retrieval account suggested by Hillstrom (2000) that differs from Huang et al.'s in that it situates the effects of PoP *at* rather than *after* the stage of selection. According to this account, memory for a trial includes a representation of the features that were prioritized higher than others. When a new display is presented, standard prioritization algorithms and prioritization rules retrieved from previous episodes compete to determine selection weights on the current trial. If traces of both target prioritization and distractor suppression are laid down during selection, this account predicts the independent target activation and distractor inhibition effects reported here.

4.3. Individual differences in target activation and distractor inhibition

In the present study, we found the measures of target activation and of distractor inhibition derived from the various conditions of target- and distractor-feature repetition embedded in our modified PoP task to be reliable. Indeed, individual differences on these measures were maintained when test and retest were separated by one week (Experiment 2). In order to determine whether PoP might be a useful tool for assessing target activation and distractor inhibition processes in selective attention, it will be important to further establish the construct validity of the measures derived from the PoP paradigm. A first step towards this goal might be to examine whether the individual differences observed on each component of PoP in a task involving search for a discontinuity on a given dimension are maintained when the same individuals are retested on a task involving a discontinuity on a different dimension.

Measures of inhibitory processes have attracted considerable interest because deficient inhibitory processes have been associated with various mental illnesses (see Nigg, 2000 for a review). The negative-priming paradigm is one of the most widely used tools to assess inhibition processes in selective attention (e.g., Fox, 1995; May, Kane, & Hasher, 1995) and their disruption in various pathologies (e.g., MacQueen, Galway, Goldberg, & Tipper, 2003 in schizophrenia; Enright & Beech, 1993 in obsessive-compulsive disorder; Fox, 1994 in high trait anxiety). In a typical negative-priming experiment, subjects are presented with pairs of trials consisting of a prime and a probe. In both trials, two stimuli are displayed: one is the target to which participants must respond and the other is the distractor that must be ignored. The negative-priming effect is the performance impairment that is observed when the distractor on the previous trial becomes the target on the current trial. For instance, in Tipper and Cranston's (1985) study, response time to identify one of two overlapping letters was slowed when the to-be-named letter was the same as a letter that was ignored in the immediately preceding display.

Positive priming effects have also been reported when the target repeated from one trial to the next (e.g., Neill, 1997).

Despite clear similarities between priming effects in the context of the PoP and negative-priming paradigms, and between the theoretical models that have been put forward to account for these effects, there has been surprisingly little explicit discussion on how the two phenomena relate to each other[3] (but see Hillstrom, 2000 for an exception). The question arises then, as to whether the two paradigms tap the same priming processes. This question is particularly pertinent from the individual differences aspect, because in contrast with the high reliability of the repetition effects observed in the present study, recent research suggests that both the reliability of the negative-priming measure (e.g., Bestgen & Dupont, 2000; Friedman & Miyake, 2004; Park et al., 1996) and its validity as a measure of inhibition (e.g., Milliken, Joordens, Merikle, & Seiffert, 1998; Neill, 1997) are questionable.

A noteworthy difference between the two paradigms is how strong coupling is between the target-defining property, the response property and the property that repeats from one trial to the next. On the one hand, coupling between the repeating feature and the response feature is typically strong in negative-priming tasks and weak in PoP tasks. Most negative-priming experiments involve naming tasks, such that for instance, the target letter on the current trial is the same as the distractor letter on the previous trial and the task is to name the letter (e.g., Tipper & Cranston, 1985; see also experiments involving superimposed drawings, e.g., Tipper, 1985). Coupling between the repeating feature and the response feature is also strong in negative-priming tasks that do not involve naming. For example, DeSchepper and Treisman (1996) used a same–different judgment task in which participants decided on each trial whether the green shape in an overlapped pair exactly matched a white shape presented to the right of the pair, ignoring the red shape in the overlapped pair. Again, the repeated feature on negative-priming trials was the shape of the ignored distractor, and the response that was subsequently slowed was a judgment concerning the shape of the target. By contrast, the repeating and response features are distinctively separate in PoP experiments. In Maljkovic and Nakayama's (1994) study, for instance, the repeating feature was color and subjects had to respond to the shape of the target.

On the other hand, coupling between the defining feature and the repeating feature is typically strong in PoP tasks and weak in negative-priming tasks. Priming of Pop-out effects were typically observed for repetition of the target-defining feature (e.g., repetition of the target color when the target is defined as a discontinuity along the color dimension), whereas in negative-priming experiments, the repeating feature and the target-defining feature are typically distinct (e.g., the target might be defined by its color with the repeating feature being shape).

These differences suggest that different priming processes might underlie PoP and negative priming, with the former effect occurring mainly at the stage of target selection and the latter occurring mainly at the stage of response selection. This tentative conclusion is consistent with recent neuroscientific research linking negative priming with brain regions associated with episodic retrieval processes (e.g., Egner & Hirsch, 2005), and linking PoP with brain regions related to sensory and attentional processing (e.g., Bichot & Schall, 2002; Kristjansson et al., 2006). Behavioral evidence also suggests that memory processes play an important role in negative priming (e.g., Milliken et al., 1998; Neill, 1997), whereas evidence favoring the post-selection episodic retrieval account of PoP is scarce (Huang et al., 2004).

Thus, by contrast with negative priming, both the high reliability of PoP and the converging evidence from the present study and from the extant literature suggesting that PoP affects selection, promote the modified PoP paradigm presented here as a promising tool for assessing individual differences on activation and inhibition processes involved in selective attention.

[3] Note however that the similarities and differences between spatial Priming of Pop-out and negative priming for location have been discussed (e.g., Maljkovic & Nakayama, 1996).

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