Intertrial repetition affects perception: The role of focused attention

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Implicit short-term memory plays an important role in visual search. For instance, singleton search is faster when the target and distractor features repeat on two consecutive trials than when they switch, an effect called Priming of Popout (PoP). However, whether or not PoP facilitates early perceptual/attentional processes remains controversial. To resolve discrepancies between existing findings, we tested the hypothesis that early effects of PoP occur only if attention is focused/engaged on the target. We measured search accuracy using brief displays for a fine discrimination task, which required focused attention, and for a left/right hemifield localization task, which did not. We found that PoP effects on accuracy occur only in the discrimination task. The theoretical implications are discussed.

Keywords: attention, masking, detection/discrimination, memory, visual acuity, search

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Introduction

Many day-to-day activities require us to repeatedly direct our attention to the same subset of objects in the visual field and to repeatedly ignore potentially distracting information. For example, when crossing a busy street, it is necessary to constantly extract update information regarding traffic lights (to see if they changed) and cars (to see if they stopped) while commercial signs should be ignored. Maljkovic and Nakayama (1994, 1996, 2000) have shown that we are equipped with an implicit memory system that facilitates reallocation of attentional resources to objects that have recently been the focus of our attention. They had participants search for a target defined as the uniquely colored item among homogeneously colored distractors and respond to its shape. Target and distractor colors switched unpredictably from trial to trial, such that observers had to perform their search with no knowledge of the upcoming target color. Response times (RTs) were faster when target and distractor colors happened to repeat on two consecutive trials than when they switched, an effect known as priming of popout (PoP). In subsequent experiments, Maljkovic and Nakayama (1996, 2000) showed that the effect of PoP is implicit, automatic, and independent of top-down expectations. In addition, studies that measured target and distractor repetitions and switches separately revealed that both target activation and distractor inhibition processes contribute to the PoP effect (Kristjánsson & Driver, 2008; Lamy, Antebi, Aviani, & Carmel, 2008).

While PoP is a very robust phenomenon and has been replicated in numerous laboratories (see Kristjánsson & Campana, 2010, for a review), it is not yet clear what stages of processing it affects. The selection-based view suggests that PoP occurs during target selection and affects the speed of target detection and attentional orienting (e.g., Becker, 2008; Goolsby & Suzuki, 2001; Maljkovic & Nakayama, 1994, 1996, 2000). Several findings support this view. For instance, Maljkovic and Nakayama (1994) showed that repetition effects occur only with features that are important for target selection (i.e., target-defining feature and spatial position) but not with features that are important for post-selection processes (i.e., reporting feature). In addition, Goolsby and Suzuki (2001) showed that PoP does not occur when attention is focused at the location of the upcoming target, that is, when search is not required.

Huang, Holcombe, and Pashler (2004) and Huang and Pashler (2005) suggested an alternative account, according to which PoP facilitates decision processes related to response selection. They relied on the finding that PoP interacts with response repetition (Huang et al., 2004), with a larger PoP when response repeats from one trial to the next than when it switches. They reasoned that, as the target response feature becomes available only after the target has been found, such interaction indicates that PoP occurs only after the target has been selected and its response feature identified.

However, in that study, PoP appeared to remain significant when the response switched. This residual effect is inconsistent with a purely response-based account of PoP, which predicts a crossover interaction between

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response repetition and target feature repetition. In a recent study (Lamy, Yashar, & Ruderman, 2010), we showed that PoP emerges early during search (within 100 ms) and interacts with repetition of the response feature only later (after 200–400 ms). A dual-stage model was proposed to account for these findings and suggests that PoP consists of two components: one might reflect perceptual processes and the other, response-related processes.

Huang and Pashler (2005) reported additional data that contradict the idea that PoP includes a perceptual component. They relied on the idea that reaction times (RTs) with extended viewing times index both perceptual and post-perceptual stages, whereas accuracy under data-limited conditions (Moore & Egeth, 1998) measures only perceptual stages. To create data-limited conditions, the search display is typically presented very briefly and followed by a mask. Participants are required to extract the task-relevant information before the search display is replaced by the mask and to respond under no speed stress. Accuracy rate is thought to reflect the quality of the information extracted from the display. Huang and Pashler (2005) reasoned that if PoP affects early stages of perceptual processing, then it should improve the perceptual quality of repeated targets.

Participants in their study reported whether the target singleton (defined by its unique orientation) appeared in the left or right hemifield of the screen. To distinguish between effects of top-down expectation and effects of PoP, they used a pre-knowledge condition (in which target- and distractor-defining features either alternated on every trial or repeated on every trial) and a no pre-knowledge condition (in which target and distractors switched unpredictably from trial to trial). The results showed only an effect of pre-knowledge and no PoP effect on accuracy, leading the authors to conclude that PoP affects post-selective processes exclusively.

These findings are inconsistent with the outcomes of a study by Sigurdardottir, Kristjansson, and Driver (2008). Using signal detection theory methodology, they found that streaks (3 or more successive trials) of repetitions increase perceptual sensitivity. However, PoP effects in this study may have been confounded with top-down effects because in order to obtain such streaks, the probability of a repeated-color trial was much higher than that of a switched-color trial.

The objective of the present study was to resolve the contradiction between findings suggesting that PoP affects perceptual/attentional stages (Goolsby & Suzuki, 2001; Lamy et al., 2010; Maljkovic & Nakayama, 1996) and findings showing that PoP affects only post-perceptual processes (Huang et al., 2004; Huang & Pashler, 2005). In a recent study (Yashar & Lamy, 2010), we demonstrated that PoP occurs when the search items are presented successively in a rapid stimulus visual presentation stream rather than spatially distributed, that is, when search occurs in the temporal rather than in the spatial domain. This finding suggests that while PoP requires search (Goolsby & Suzuki, 2001), it can occur in a task that does not require shifts of attention in space. We concluded that PoP facilitates the process of engaging attention in the target.

This finding raises the possibility that the early component of PoP may emerge only when the task requires focused attention but not when it can be performed with distributed attention, that is, in tasks that do not require attentional engagement in the target. Keeping this hypothesis in mind, note that the task used by Huang and Pashler (2005) only required participants to make a coarse localization judgment by indicating whether target appeared in the right or left hemifield. In other words, they only had to detect the target and code its general location. Therefore, the participants did not need to engage their attention in the target in order to respond. By contrast, the task commonly used to demonstrate PoP (e.g., Goolsby & Suzuki, 2001; Lamy et al., 2010; Maljkovic & Nakayama, 1994, 1996) requires fine discrimination of the target shape. Thus, after the target has been detected, attention must be focused on the target location to allow extraction of the responding feature, that is, of the target shape.

Experiment 1

The objective of Experiment 1 was to test the hypothesis that PoP affects perceptual processes but only when the task requires focused attention. Accordingly, we measured the effect of PoP on search accuracy using brief search displays, in a fine discrimination task (held to require focused attention) and in a coarse localization task (held not to require focused attention). We expected PoP effects only in the fine discrimination task.

Methods

Subjects

Participants were 9 Tel-Aviv University undergraduate students who participated in the experiment for course credit. All reported having normal or corrected-to-normal visual acuity.

Apparatus

Displays were generated by an Intel Pentium 4 computer attached to a 17-in. CRT monitor, using 1024 × 768 resolution graphics mode. A chin rest was used to set viewing distance at 50 cm from the monitor.

Stimuli

Sample stimulus displays are presented in Figure 1. The fixation display consisted of a gray 0.2° × 0.2° "plus" sign, in the center of a black background. The search display consisted of 24 shapes in a virtual matrix (6 columns by 4 rows) centered at the screen center, with 3 columns

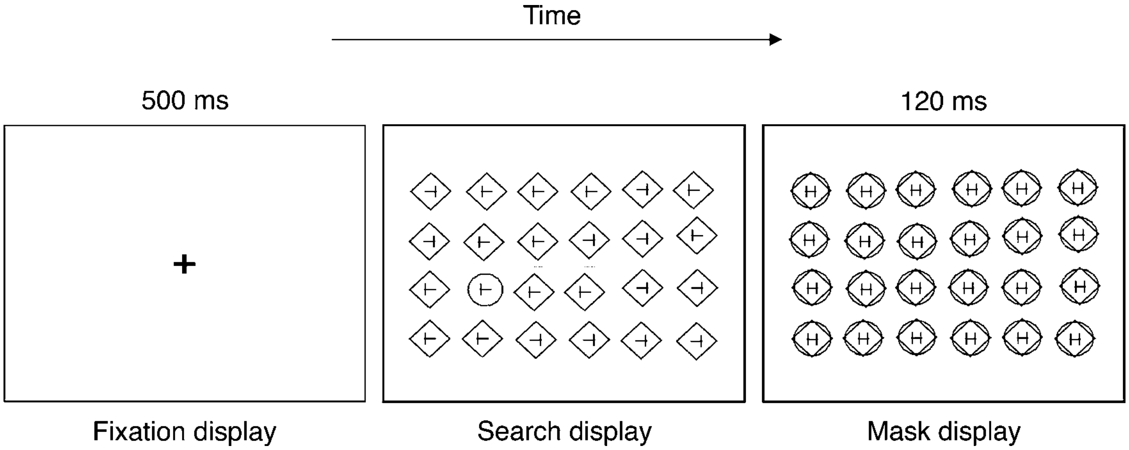

Figure 1. Illustration of the sequence of events in Experiments 1 and 2. In the coarse localization task, participants were required to indicate whether the target appeared in the right or left half of the screen. In the fine discrimination task, participants were required to indicate whether the T inside the target was oriented to the left or to the right. The stimuli were gray and were presented on a black background.

in the left hemifield and 3 columns in the right hemifield. The distance between two adjacent matrix cells was 2.6°. The shapes were outline circles (1.7° in diameter) and outline diamonds (rotated squares, 1.4° in side). Centered inside each shape was a gray T letter (0.6° in length and 0.4° in width) pointing to either the left or right. Each display contained a unique shape (the target) among homogeneous shapes (the distractors). On each trial, the target was randomly chosen to be either a diamond among circles or a circle among diamonds. The mask display contained 24 mask shapes (the outline diamond, outline circle, left-pointing T and right-pointing T, overlapping each other), positioned at the same locations as the stimulus display shapes.

Procedure

Each trial began with the fixation display for 500 ms, followed by the onset of the search display that was replaced by the mask display after a variable time interval, for 110 ms. Then, the screen went blank for 10 s or until the participant made a response by pressing one of two designated keys. The intertrial interval was 500 ms. In the fine discrimination task, participants reported whether the T inside the target pointed to the left or to the right. In the coarse localization task, participants reported whether the target appeared in the left or right hemifield. The participants were urged to respond as accurately as possible with no time pressure.

Design

The two tasks were conducted in two separate sessions. Each session contained 480 trials divided into 8 blocks of 60 trials each. Stimulus duration was recalibrated every 20 trials. If the average accuracy rate had been below 65% or above 85% during the last 20 trials, search display exposure duration was increased or decreased by 35 ms, respectively. Stimulus duration remained the same if the accuracy rate had been between 65% and 85%. Each session began with 20 practice trials for which stimulus duration was set at 470 ms for the discrimination task and to 235 ms for the localization task.

Results and discussion

Trials preceded by an error trial were removed from analysis. Mean error rate scores are depicted in Figure 2.

An Analysis of Variance (ANOVA) was conducted with target shape repetition and task as within-participant factors and with accuracy rate as the dependent variable. Although stimulus duration was calibrated according to performance within each task, accuracy rate in the fine discrimination task tended to be lower, yet not significantly so, than in the coarse localization task (77.2% vs. 80.0%, respectively), $F(1,8) = 3.96$, $p < 0.09$. Neither the main effect of target shape repetition nor the main effect of task reached significance, $F(1,8) = 3.94$, $p < 0.09$ and $F(1,8) = 3.96$, $p < 0.09$, respectively. The interaction between the two factors was significant, $F(1,8) = 5.75$, $p < 0.05$. Paired comparisons revealed a significant PoP effect on accuracy in the fine discrimination task, $F(1,8) = 11.45$, $p < 0.01$, but not in the localization task, $F < 1$. Thus, the PoP effect on accuracy is contingent on the task. It does not occur when the task requires detection and coarse localization of the target, but only when it requires the additional process of engaging attention in the target location.

Note that because the calibration procedure was aimed at equating performance between the two tasks within an accuracy range of 65% to 85%, mean display exposure times could differ between the two tasks, which indeed occurred (405 ms for fine discrimination vs. 135 ms for localization). Thus, one may argue that differences in exposure durations rather than in task requirements may underlie the difference in perceptual effects of PoP between

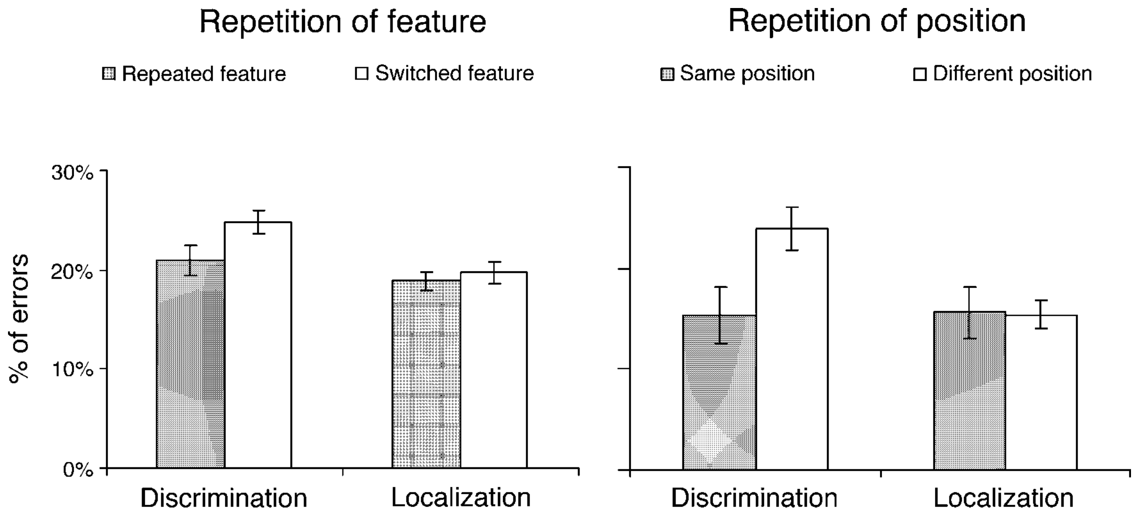

Figure 2. Effects of intertrial repetition on accuracy rate in the fine discrimination task and in the coarse localization task in Experiment 1. The graph shows the mean percentage of error trials as a function (A) of whether the target shape repeated or switched on two consecutive trials and (B) of whether the target was in the same or in a different spatial position relative to the previous trial, separately for each task.

the sessions. However, we claim that the additional processing steps required by the fine discrimination task relative to the localization task (i.e., shifting attention, engaging it in the target, and extracting its response feature) account for the longer exposure times (see also Bravo & Nakayama, 1992; Huang, in press).

To provide an independent test of the hypothesis that the coarse localization task was indeed performed with attention broadly distributed over the search display, whereas the fine discrimination task involved focal attention on the precise location of the target, we took advantage of the target position repetition effect first reported by Maljkovic and Nakayama (1996). We reasoned that this effect should be observed only when attention had been focused on the same location on successive trials, that is, in the discrimination but not in the localization task. We conducted an ANOVA with target position repetition and task as within-participant factors and with accuracy rate as the dependent variable.[1] The main effect of target position repetition was significant, $F(1,8) = 12.17$, $p < 0.009$, and interacted with the effect of task, $F(1,8) = 5.42$, $p < 0.05$. Paired comparisons revealed that repetition of target position improved accuracy only in the fine discrimination task, $F(1,8) = 12.73$, $p < 0.008$, but not in the coarse localization task, $F < 1$. These findings confirm our hypothesis that the former but not in the latter task required focused attention.

Experiment 2

The findings from Experiment 1 suggest that PoP affects perceptual/attentional processes but only when the task requires attention to be focused/engaged in the target location. Following Goolsby and Suzuki's (2001) terminology, we distinguish between two phases of PoP: encoding during the previous trial ($n - 1$) and retrieval of the encoded information during the current trial (n). In Experiment 2, we examined whether focusing attention is required during encoding, retrieval, or both. We interleaved coarse localization trials with fine discrimination trials, such that whenever trial n was a localization task, trial $n - 1$ was a discrimination task and vice versa. If focused attention is required only during encoding of the target, then PoP should be found only in the localization task because attention was focused on the target in the previous (fine discrimination) trial. If focusing of attention is required only during retrieval, then PoP should be observed only on discrimination trials. If focusing attention is required during both, then no PoP effect should be obtained in either task.

Methods

Subjects

Participants were 9 Tel-Aviv University undergraduate students who participated in the experiment for course credit. All reported having normal or corrected-to-normal visual acuity.

Apparatus, stimuli, procedure, and design

The apparatus, stimuli, procedure, and design were the same as in Experiment 1 except for the following changes. The tasks were interleaved, such that each fine discrimination trial was followed by a coarse localization trial and vice versa. Each session contained 600 trials. Stimulus duration was recalibrated individually and separately for each task, as a function of the participant's performance on the last 20 trials with a particular task.

Results and discussion

Mean error rate scores are depicted in Figure 3. Two participants were removed from analysis, because their error rates were more than 2.5 standard deviations either above or below the group mean (40% and 5% of errors, respectively).

Accuracy rates did not differ between the two tasks (81.4% vs. 82.0% for the fine discrimination vs. coarse localization tasks, respectively, $t < 1$). Mean stimulus duration was 138 ms for the fine discrimination task and 377 ms for the coarse localization task. We first examined the effect of shape repetition from the previous trial ($n - 1$) when the current trial (n) was a fine discrimination trial, and trial $n - 1$ had therefore been a coarse localization trial. There was no significant effect of shape repetition, $t < 1$. However, performance was significantly improved when the target shape repeated from trial $n - 2$, which had been a fine discrimination trial just as the current trial, $t(1,6) = 18.22$, $p < 0.006$. When trial n was a coarse localization trial, there was no significant effect of shape repetition when target shape repeated either from trial $n - 1$, which had been a fine discrimination trial, or from trial $n - 2$, which had been a coarse localization trial just as the current trial, all ts < 1.

These results suggest that PoP facilitates performance only if attention must be engaged in the target location both during encoding and during retrieval, which in the present experiment occurred only for successive fine discrimination trials (despite the fact that these were separated by a coarse localization trial). One may argue that switching from one task to the next may have introduced contextual changes that did not allow priming effects to emerge. However, previous findings (Yashar & Lamy, 2010) strongly argue against this possibility, as we showed that PoP transfers across very different contexts, namely, from temporal search to spatial search and vice versa.

General discussion

The results from the present study provide a resolution of the controversy over the effects of Priming of Popout on perceptual processes during visual search. With a procedure known to tap only perceptual processes (using very brief masked displays), we show, on the one hand, that PoP affects perception, in line with selection-based accounts (e.g., Becker, 2008; Goolsby & Suzuki, 2001; Lamy et al., 2010; Maljkovic & Nakayama, 1994, 1996; Sigurdardottir et al., 2008), but only in a fine discrimination task. On the other hand, we also show that in line with the claim that intertrial repetition facilitates only response-related processes (Huang et al., 2004; Huang & Pashler, 2005) perceptual effects of PoP are not observed in a coarse localization task (Experiment 1). Thus, our results suggest that the apparently contradicting findings reported in previous studies (e.g., Sigurdardottir et al., 2008 vs. Huang & Pashler, 2005) reflect task-related differences.

These results entail that PoP affects processes that are involved in one task but not in the other. In other words, they suggest that (1) PoP does not affect processes that are common to both tasks, and (2) it facilitates one or more stages involved only in the discrimination task.

In both tasks, the target was defined as the unique singleton and finding it therefore required the spatial representation of local contrasts (often referred to as the

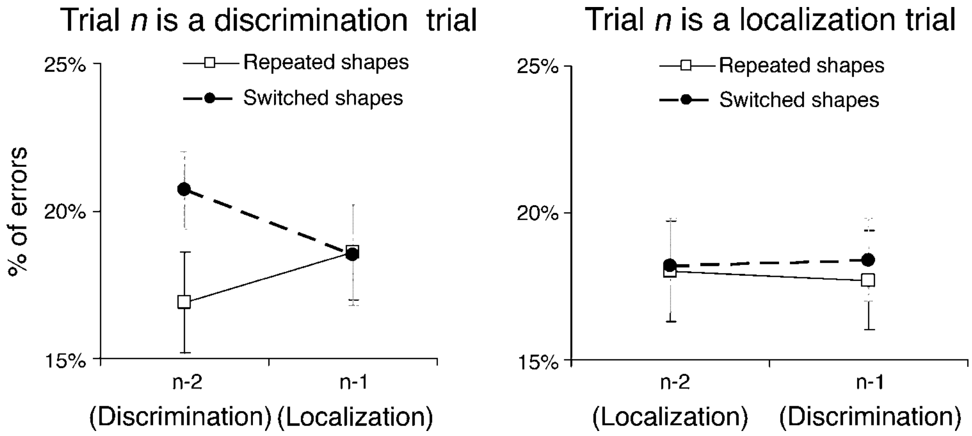

Figure 3. Effects of target shape repetition from trials $n - 2$ and $n - 1$ on accuracy rate on trial n in Experiment 2. The task on trial $n - 1$ is different from that on trial n; the task on trial $n - 2$ is the same as on trial n. The task on trial n was either a fine discrimination task (left-hand panel) or a coarse localization task (right-hand panel).

saliency map, e.g., Itti, Koch, & Niebur, 1998). As PoP was not observed in the coarse localization task, we may infer that PoP does not affect processes related to local contrast representation. That is, repetition of the target- and distractor-defining features does not speed computations of relative salience nor does it enhance the strength of the contrast signal at the location of the target singleton.

The tasks differed in that the fine discrimination task required focal attention to be allocated to the target location in order to extract the response feature, whereas the coarse localization did not. We may thus conclude that PoP facilitates allocation of focal attention. The decision to allocate focal attention is based on the prioritization of locations and/or of stimulus features. However, if we posit that responding to a stimulus entails that this stimulus was selected (prioritized), then we should distinguish between selecting of location(s) (as required by both tasks) and allocating of focal attention to the target (as required by the fine discrimination task alone). A similar distinction has been proposed by Huang (in press), who suggested that the notion of attention includes selection of information and processing optimization. Within this framework, our findings suggest that repetition of the target- and distractor-defining features affects the prioritization process that guides allocation of focal attention but does not affect the prioritization process that underlies the selection of a discrepant location. Note, however, that our findings do not indicate whether PoP speeds the prioritization process per se (e.g., Hillstrom, 2000) or whether it enhances the relative priority of the repeated target (Becker, 2008).

Several authors have shown that allocation of focal attention can be further decomposed into two different processes (Folk, Ester, & Troemel, 2009; Posner & Petersen, 1990; Yashar & Lamy, 2010): it entails shifting (or narrowing) of attention to the target location as well as engagement of attentional resources in the target. Accordingly, our results suggest that PoP facilitates attentional focusing, attentional engagement, or both. In a recent study, we already showed that PoP affects engagement of attention. Indeed, we observed PoP in an RSVP task, that is, when attentional shifting/narrowing was not needed (because attention remained focused on the same location), but engagement in the target was needed to extract task-relevant information. Note, however, that this finding did not preclude the possibility that in addition to facilitating attentional engagement, PoP might also affect earlier stages of processing.

In addition, no PoP effect was observed when the two tasks were interleaved (Experiment 2). On the one hand, PoP was not observed when the task was fine discrimination on the current trial and coarse location on the previous trial. Thus, perceptual effects of PoP were also contingent on attention being focused on the target during encoding (that is, on trial $n - 1$). This finding suggests that while spatial representation of local contrasts can be extracted when displays are presented for a brief time interval and attention is distributed over the display, the features that underlie the local contrasts are poorly encoded (if at all).

On the other hand, PoP was not observed when the task was coarse localization on the current trial and fine discrimination on the previous trial. This finding suggests that failure to observe PoP in the coarse localization task of Experiment 1 did not result only from failure to encode the target and distractor features. Instead, it reinforces our claim that PoP facilitates stages of processing not involved in the coarse localization task.

To summarize our conclusions, the present study shows that PoP does not affect early preattentive stages during which local contrasts are computed. Instead, PoP affects feature prioritization for the allocation of focal attention. Further research is needed to determine whether such effects on prioritization facilitate only engagement of attention or may also speed shifts of attention to the target.

It is important to note that the rationale of the present study rests on the notion that focal attention is needed in tasks that require discrimination of a subtle feature of the target but not in tasks that do not require such discrimination, such as the coarse localization task used here, or absent/present detection tasks. While the idea that a target can be selected and responded to without focal attention has been supported by several authors (e.g., Bravo & Nakayama, 1992; Huang, in press), it was recently challenged by Theeuwes, Van Der Burg, and Belopolsky (2008). They showed that detecting the presence of a singleton was speeded when the target shape (which was irrelevant to the task) repeated relative to when it changed on consecutive trials, suggesting that a simple detection task involved focused attention on the target location. However, our finding that repetition of the target location facilitated performance only in the discrimination task and not in the coarse localization task strongly indicates that attention was focused on the target location in the former but not in the latter task. Thus, we may speculate that selection in a detection or coarse localization task may be accompanied by a shift of attention to the target location only in certain circumstances, for instance, under conditions of unlimited viewing time (e.g., Theeuwes et al., 2008).

The conclusion that PoP does not affect search unless the task requires allocation of focal attention seems to be at odds with several reports of PoP effects on search latencies in detection and coarse localization tasks (e.g., Huang & Pashler, 2005; Lamy, Carmel, Egeth, & Leber, 2006). However, the apparently contradictory findings can be accommodated within the framework of our dual-stage model (Lamy et al., 2010). We suggest that while target feature repetition does not affect perceptual processes when attention is distributed over the search display, it speeds response-related processes. The outcomes of such response-related processes can be assessed by RT measures with unlimited viewing time but not by accuracy with brief displays (e.g., Moore & Egeth, 1998), which is why they did not emerge in the present study. Recent findings from our laboratory confirm this prediction (Yashar & Lamy, in preparation).

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Footnote

[1] Note that in the localization task target position repetition is confounded with motor response repetition, because whenever the target position repeats, so does the response. Thus, whereas the same response condition included both same and different location trials, the different response condition included only different location trials. Therefore, to measure position repetition effects on similar conditions of response repetition in both tasks, we included only repeated-response trials in the analysis.

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