



A dual-stage account of inter-trial priming effects

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ABSTRACT

The study of inter-trial effects in visual search has generated an increasing amount of research in recent years. However, the mechanisms underlying these effects are still a matter of debate. Two rival accounts have been suggested. One view stipulates that inter-trial effects facilitate early perceptual/attentional processes, whereas the other proposes that it affects post-perceptual response-related processes. Here, we focused on the priming of pop-out effect (PoP, Maljkovic & Nakayama, 1994), which refers to the well-established finding that performance on singleton search is faster when the target and distractors features repeat on two consecutive trials than when they switch. We set out to resolve the current controversy surrounding PoP by suggesting a dual-stage account, according to which PoP speeds both an early perceptual stage and a later, response-related stage of visual search. We were able to dissociate the hypothesized components of PoP by tracking their time course.

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1. Introduction

What we attend to at a given time affects how our attention is deployed in the few moments that follow. Such effects of memory on attentional selection are the focus of intensive research and are typically studied by probing various inter-trial repetition effects in visual search (e.g., dimension priming, Found & Müller, 1996; feature and location priming of pop-out, Maljkovic & Nakayama, 1994, 1996; contextual cueing, Chun & Jiang, 1998; singleton priming, Lamy, Bar-Anan, & Egeth, 2008; Lamy, Bar-Anan, Egeth, & Carmel, 2006). For instance, Maljkovic and Nakayama (1994) showed that when there is uncertainty regarding the target feature, visual search for a singleton target is speeded when the target's odd feature happens to repeat on successive trials. In their study, the target was defined by its unique color and was unpredictably either the red diamond among green ones or the green diamond among red ones. On each trial, subjects reported which side of the target (either left or right) was chipped. Repeated-color trials were faster than switched-color trials. This effect, which was called priming of pop-out (henceforth, PoP) has been replicated with targets differing from distractors by their shape (e.g., Lamy, Carmel, Egeth, & Leber, 2006), orientation (e.g., Hillstrom, 2000), size (Huang, Holcombe, & Pashler, 2004) and facial expression of emotion (Lamy, Amunts, & Bar-Haim, 2008).

The stage of processing that is facilitated by PoP remains a matter of debate (e.g., Meeter & Olivers, 2006). According to the perceptual account of PoP, repeating the target feature facilitates

early perceptual/attentional processes (e.g., Chun & Nakayama, 2000). For instance, Maljkovic and Nakayama (1994, 1996) suggested that PoP facilitates the deployment of attention to the target by increasing target salience. They relied on the finding that repetition of features that are important for selecting the target (namely, its defining feature and position) speed search, whereas repetition of other features, such as the response feature, do not affect search (but see Lamy, Bar-Anan et al. (2008) for a report of response repetition effects).

More recently, Goolsby and Suzuki (2001) proposed that PoP mainly facilitates the stage of moving attention toward the target and focusing attention on its location. They based this conclusion on the finding that PoP does not occur when a spatial cue indicates the location of the upcoming target, that is, when attention is already focused on the target location. Furthermore, the results from eye movement studies suggest that PoP affects search before selection of the first item in a display, presumably at the preattentive stage (Becker, 2008). Finally, single-cell recording studies in monkeys showed that, relative to switched-color trials, repeated-color trials were associated with larger neural responses in the frontal eye field, a region thought to be involved in the representation of attentional priority (Bichot & Schall, 2002). Consistent with the perceptual account of PoP, separate target activation and distractor inhibition mechanisms of PoP have been isolated (Lamy, Antebi, Aviani, & Carmel, 2008; see also Kristjansson & Driver, 2008).

According to the response-based account (sometimes referred to as the retrieval-based account, e.g., Huang & Pashler, 2005; Huang et al., 2004), PoP is manifested later, after selection. After a potential target has been located, the perceptual system seeks to verify that this potential target is indeed the target before responding. This is done by retrieving the properties of the target

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on the previous trial. If these match the properties of the candidate target on the current trial, response is speeded. Response is delayed if there is a mismatch. Supporting this model, Huang and Pashler (2005) failed to observe higher accuracy on repeated- vs. switched-feature trials with brief displays. Relying on the idea that reaction times (RTs) with extended viewing times index both perceptual and post-perceptual stages, whereas accuracy using brief displays measures only perceptual stages (Moore & Egeth, 1998; Santee & Egeth, 1982), the authors concluded that PoP reflects post-selective factors. However, this conclusion has been challenged by recent findings by Yashar and Lamy (2009) who suggested that PoP effects on accuracy are observed in tasks in which discrimination of the response feature requires attention, but not in tasks that can be performed with widely distributed attention (e.g., left/right hemi-field localization).

In addition, Huang et al. (2004) showed that target feature repetition effects interact with response repetition effects. When the target-defining feature repeated from one trial to the next, repetition of the response feature speeded search, whereas it actually slowed search when the target-defining feature switched from one trial to the next. Because there can be no access to the target's non-defining features before the target is found and attention is engaged on it, these findings suggest that PoP occurs after the target is selected. However, it is noteworthy that in that study, PoP appeared to remain significant when response differed on successive trials. This residual PoP effect on different-response trials is inconsistent with a purely retrieval-based account of PoP, which predicts a cross-over interaction between target feature repetition and response repetition. It points to a component of PoP that is independent of the match between stimulus and response pairings on the current and previous trials, and is therefore likely to reflect a perceptual component of PoP.

Here, we tested the idea that PoP affects search at two different stages of the visual search process: an early, selection-related stage and a later, response-related stage. Our objective was to dissociate the hypothesized components of PoP by tracking their time course. We used a variant of a procedure pioneered by Lleras, Kahawala, Wan, and Ariga (2008, Exp. 5), in which the colors of the target and distractors are changed at different times during the trial. In the present study, subjects searched for a color singleton, either a red circle among four green circles or a green circle among four red circles and had to report the orientation of a letter (a rotated T) enclosed in the target circle. On half of the trials (color-change trials), at a variable time (henceforth, SOA) of 100 ms, 200 ms or 400 ms after target display onset, both the target and distractor colors changed, to yellow and blue. Crucially, the location of the target and those of the distractors, as well as the orientation of the T enclosed in each circle and which determined the correct response, remained the same before and after the color change. On the remaining half of the trials (standard trials), the target and distractors remained red and green throughout the trial.

The modulation of the PoP effect as a function of the time of color change onset within the trial was examined from two different perspectives (see Goolsby & Suzuki, 2001, for a similar rationale). In one analysis, we investigated at what stage *during the current trial* repetition of the color and/or response from the previous trial affects search. By examining the effect of color repetition (or PoP) from a standard trial (on the previous trial, henceforth, trial $n - 1$) to a color-change trial (on the current trial, henceforth, trial n) at various SOAs, we could determine what stage of processing is facilitated by PoP. Our central assumption was that any effect resulting from repetition vs. switch of the target and distractors colors from trial $n - 1$ (standard trial) to trial n (color-change trial) could occur only while these colors were available on trial n , that is, before the color change. According to a purely perceptual account, a significant PoP should be observed from the shortest SOA, and should

not interact with response repetition at any SOA. According to the purely response-based account, no PoP should be observed at the shortest SOA but the effect should emerge later, and interact with response repetition. Finally, according to the dual-stage account suggested here, we expected a significant PoP effect across SOAs, that would interact with response repetition only at the latest SOA and not at the shortest one.

In a different analysis, we inspected how length of the exposure to target and distractor colors on the previous trial modulated the effects of target and/or response feature repetition on the current trial. By examining the effect of color repetition (or PoP) from a color-change trial (on trial $n - 1$) to a standard trial (on trial n) at various SOAs, we could determine at what stage the information that underlies the perceptual component of PoP on the one hand and its response-based component on this other hand, is encoded. Our central assumption here was that the representations that are involved in the perceptual component of PoP are modulated by target selection on trial $n - 1$ early during the trial, whereas the bound representation of the target feature and response, that underlies the response-based component of PoP, emerges later during trial $n - 1$, namely, by the time response-based processes unfold.

1.1. Subjects

Subjects were 12 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.

1.2. Apparatus

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

1.3. Stimuli

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 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. The target and distractors colors were selected from four possible colors as described in procedure. The four colors were matched for luminance 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 $0.42/0.49$, 18.32 cd/m^2).

1.4. Procedure

The stimuli and sequence of events are presented in Fig. 1. The subjects had to determine whether the T inside the color singleton

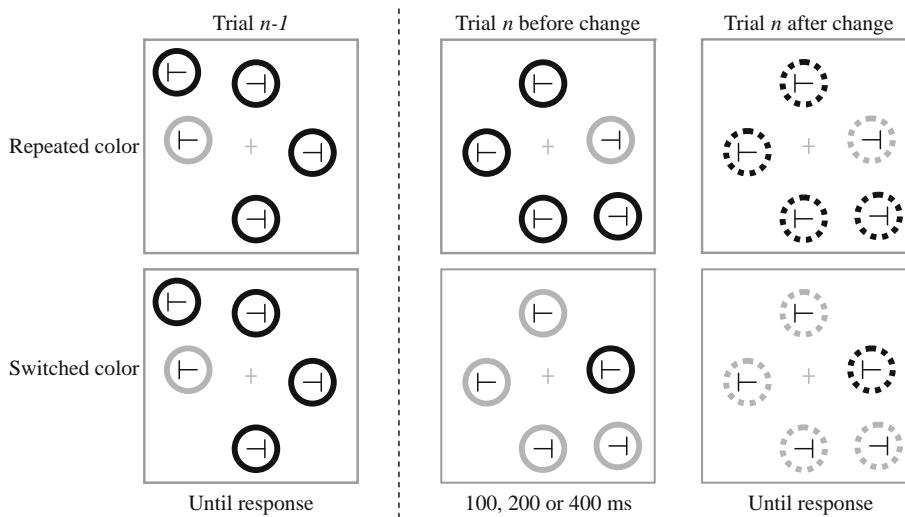


Fig. 1. Sample stimuli and sequence of events. In this example, trial n was a standard trial and trial $n - 1$ was a color-change trial. The upper panel corresponds to the repeated color and different-response condition. The lower panel corresponds to the switched color and same-response condition. The black continuous line was red, the gray continuous line was yellow, and the gray dotted line was blue.

target pointed to the right (by pressing the “z” key on the computer keyboard with their right hands) or to the left (by pressing the “3” keypad key with their left hands) as quickly as possible, while maintaining high accuracy. Error trials were followed by a 500-ms feedback beep. Eye movements were not monitored, but subjects were explicitly requested to maintain fixation throughout each trial.

Each trial began with the fixation display. After 500 ms, the stimulus display followed and remained visible for 2000 ms or until response. On a standard trial, the target was either a red circle among green ones or a green circle among red ones. On color-change trials, the colors of the target and distractors were initially red and green and then changed at various points in time during the trial, 100, 200 or 400 ms after display onset. After the subject's response, the screen went blank for 500 ms before the next trial began. The locations of the circles and the orientations of the Ts inside them (which determine the correct response) remained the same throughout the trial. Before the change, the target and distractors colors were either repeated from trial $n - 1$ or switched (and were therefore red or green), that is, the color of the target on trial $n - 1$ becomes the color of the distractors on trial n and vice versa. After the change, both the target and distractors took on new colors (yellow and blue). Standard trials and color-change trials alternated throughout the experiment. That is, a standard trial always followed a color-change trial and vice versa.

1.5. Design

The design included four within-subject variables: trial type (standard or color change), color repetition (repeated vs. switched color), response repetition (same vs. different response) and SOA on color-change trials (100, 200 or 400 ms). There were an equal number of standard and color-change trials arranged in a fixed alternating sequence. Conditions of color repetition, response repetition and SOA were equally probable and randomly mixed. Thus, target and distractor colors were equally likely to remain the same or to switch from one trial to the next, and subjects were equally often required to produce the same response or the alternative response on successive trials.

The experiment began with a block of 20 practice trials, followed by 360 experimental trials divided into six blocks. Subjects were allowed a short rest after each block.

2. Results

In all RT analyses, error trials (2.5% of all trials) were removed from analysis, and so were outlier trials (less than 1% of all trials).

2.1. Trial n is a color-change trial (and is preceded by a standard trial)

In order to determine at what stage of the visual search process color repetition from the previous trial modulates search performance, an Analysis of Variance (ANOVA) was conducted on color-change trials with SOA, color repetition and response repetition as factors. Mean RT and accuracy scores are depicted in Fig. 2.

2.1.1. Reaction times

The main effect of color repetition was highly significant, $F(1, 11) = 40.96$, $p < 0.0001$, with faster RTs when the target and distractors colors repeated than when they switched. This effect interacted with response repetition, $F(1, 11) = 15.75$, $p < 0.003$, reflecting that the PoP effect was larger when the response repeated, $F(1, 11) = 40.01$, $p < 0.0001$, than when it did not repeat, $F(1, 11) = 18.78$, $p < 0.003$. This pattern of results was modulated by a 3-way ANOVA, $F(1, 22) = 3.52$, $p < 0.05$.

A separate follow-up ANOVA was conducted for each SOA. With the 100-ms SOA, the effect of color repetition (PoP) was significant, $F(1, 11) = 14.69$, $p < 0.003$, and did not interact with response repetition: the PoP effect was 33 ms vs. 34 ms for different-response vs. same-response trials, respectively, $F = 0$. With the 200-ms, the PoP was also significant, $F(1, 11) = 39.00$, $p < 0.0001$, and the interaction did not reach significance, although a numerical trend became clearly apparent, 31 ms vs. 72 ms for different-response vs. same-response trials, respectively, $F(1, 11) = 2.92$, $p > 0.1$. Finally, with the 400-ms SOA, PoP was again significant, $F(1, 11) = 17.90$, $p < 0.002$, and the interaction with response repetition was highly significant, 23 ms vs. 85 ms, for different-response vs. same-response trials, respectively, $F(1, 11) = 23.93$, $p < 0.0005$.

2.1.2. Accuracy

There was no significant effect.

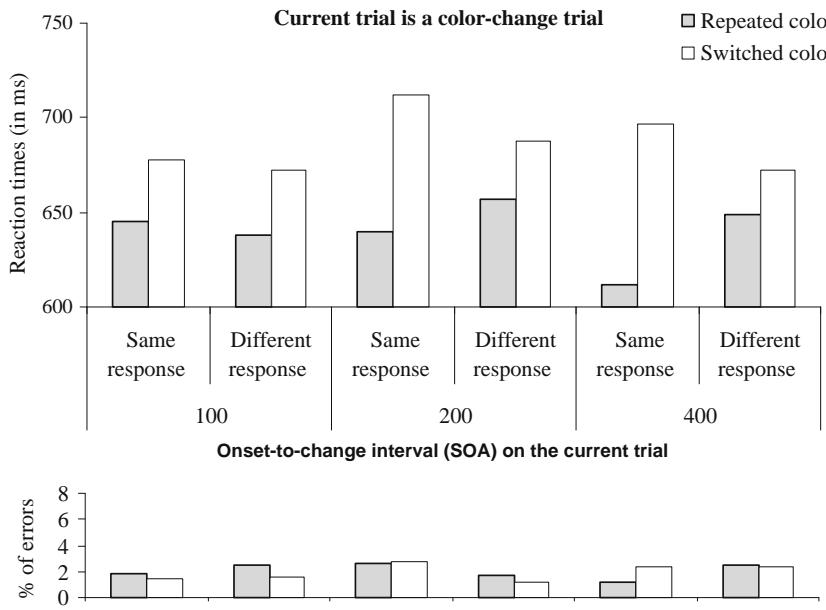


Fig. 2. Mean response times and error rates on color-change trials by conditions of color repetition, response repetition and target display onset to color change time interval (SOA). The previous trial had been a standard trial.

2.2. Trial n is a standard trial (and is preceded by a color-change trial)

We then looked at the time-course of feature encoding on the previous trial by measuring PoP on a standard trial as a function of the time the relevant colors (red and green) had remained visible on trial $n - 1$. An ANOVA was thus conducted on standard trials with SOA on the previous trial, color repetition and response repetition as factors. Mean RT and accuracy scores are depicted in Fig. 3.

2.2.1. Reaction times

The main effect of SOA on the previous trial was significant, $F(1, 22) = 10.30, p < 0.0007$, reflecting that RTs were slower when the interruption had occurred at a later stage in the previous trial, 630 ms, 637 ms, and 649 ms for the 100-ms, 200-ms and 400-ms

SOAs, respectively. The main effect of color repetition was significant, $F(1, 11) = 17.28, p < 0.002$. No other effect approached significance, all $p > 0.3$. In particular, there was no effect involving response repetition, all $Fs < 1$.

2.2.2. Accuracy

The effect of color repetition approached significance, $F(1, 11) = 4.02, p = 0.07$, indicating that repeated-color trials tended to be more accurate than switched-color trials, thus paralleling the RT finding. This trend was modulated by an interaction between color repetition and response repetition, which also approached significance, $F(1, 11) = 3.50, p < 0.09$, with a larger PoP effect on same-response trials than on different-response trials. However, further inspection of the data revealed that this interac-

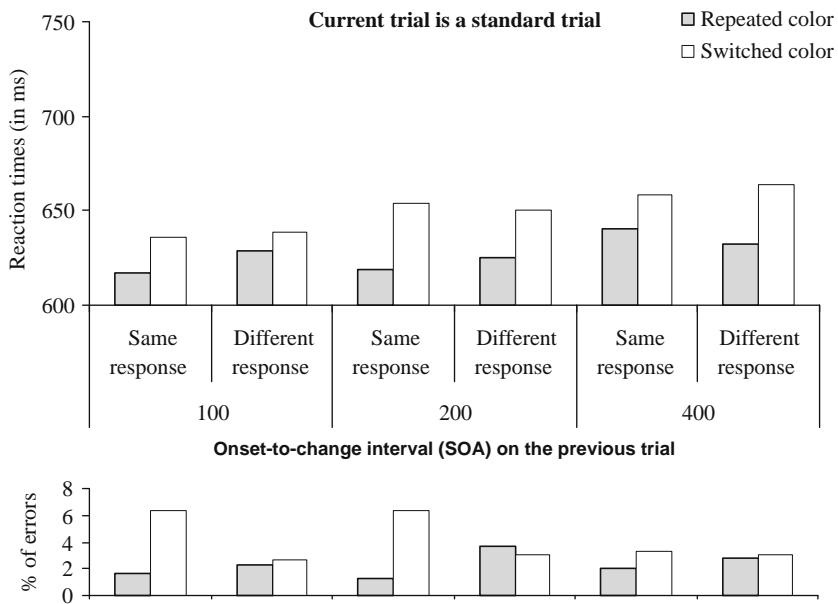


Fig. 3. Mean response times and error rates on standard trials by conditions of color repetition, response repetition and target display onset to color change time interval (SOA) on the previous trial. The previous trial had been a color-change trial.

tion was mainly due to the fact that for three subjects, accuracy was at ceiling on different-response trials, whereas this happened for no subject on same-response trials. When these subjects were removed from analysis, the color repetition effect became similar for same- and different-response trials, 1.6% vs. 1.9%, $F < 1$. Finally, the interaction between color repetition and SOA on the previous trial was marginally significant, $F(1, 22) = 3.28$, $p < 0.06$. Follow-up comparisons revealed that the PoP effect on accuracy was significant with the 200-ms SOA, $F(1, 11) = 20.57$, $p < 0.0008$, but not with either the 100-ms or 400-ms SOA, $p > 0.2$.

3. Discussion

In the present research, we attempted to resolve the current controversy between perceptual and response-based accounts of PoP by suggesting a dual-stage account of PoP, which includes an early perceptual component of PoP and a later, response-based component. Our findings support this dual-stage account.

3.1. Support for the dual-stage account of PoP

In line with the recent literature on PoP (e.g., Huang & Pashler, 2005; Meeter & Olivers, 2006; Yashar, 2009), we assumed that a purely perceptual component of PoP should become apparent early in a search trial and should not be affected by response factors. By contrast, we assumed that a retrieval- or response-based component of PoP should be manifested later and emerge as an interaction between color repetition and response repetition. The data showed that PoP effect was significant at the 100-ms SOA and was of the same magnitude whether or not the response feature repeated from the previous trial. This effect thus corresponds to the perceptual component of PoP. At the 400-ms SOA, the PoP effect was also significant but it was much larger when the response feature repeated from the previous trial than when it did not. Therefore, it reflects the sum of the perceptual and response-based components of PoP. At the 200-ms SOA, the pattern was intermediate: the PoP effect tended to be larger for same- than for different-response trials, yet not significantly so, and to a lesser extent than for the 400-ms SOA. A likely explanation for this finding is that the transition from the perceptual to the response stage occurred at different times between subjects and between different trials within subjects.

Note that the procedure employed in the present study allows one not only to dissociate between the perceptual and response-based components of PoP, but also to estimate their relative magnitude. In a classical PoP experiment with no color change manipulation, the PoP effect is smaller on different-response trials than on same-response trials. According to the retrieval-based account of PoP (Huang et al., 2004), which we hold to reflect the processes that underlie the response-based component of PoP, “when all the feature dimensions cohere in their implications (all favoring the same judgment or all favoring a different judgment), the judgment is easy”, and inconsistency across dimensions will have a cost (Huang et al., 2004, p. 20). Thus, due to response-related factors, the magnitude of the PoP on different-response trials is an underestimate of the perceptual PoP: RTs are speeded on switched-color trials and slowed on repeated-color trials. Likewise, the magnitude of the PoP on same-response trials is an overestimate of the perceptual PoP: RTs are speeded on repeated-color trials and slowed on switched-color trials. As there is no principled reason to assume that the gain of a match between the different target features (e.g., defining and response features) is of equal magnitude to the cost of a mismatch between them, one cannot assess the relative contributions of the perceptual and response-based components.

However, in the present study, we could have a glimpse at the purely perceptual PoP component by observing it at the 100 ms, that is, at a time in which its measure was not contaminated by response-based effects. The magnitude of this effect was 33 ms, to the extent that it was fully developed 100 ms after target display onset. By comparing it to the effect observed with the 400-ms SOA, one can conclude that a mismatch between the color and response features reduced PoP by 10 ms (to 23 ms in the different-response condition), whereas a match increased it by 52 ms (to 85 ms in the same-response condition). Although these observations are not supported by statistical analyses, they open the way to further investigations of the effects of perceptual and response-based PoP by providing a method to assess their magnitude. In particular, it will be important to identify variables that selectively modulate the relative contributions of these factors.

3.2. Tracking the time course of the encoding processes that underlie PoP

While previous theorizing on PoP has mainly focused on processes occurring on trial n (e.g., Meeter & Olivers, 2006), Goolsby and Suzuki (2001), have highlighted that the PoP effects on trial n are a consequence of processes that took place on trial $n - 1$. Here, we suggested that the perceptual component of PoP results from the modulation of the representations of the task-relevant features associated with the target and distractors following target localization/selection on trial $n - 1$, and that likewise, the response-based component results from the coupling of the target-defining feature with the response feature or the motor response associated with it on trial $n - 1$.

Accordingly, the present study allowed us to investigate how encoding time in the previous trial affects PoP on the current trial. The data suggest that a 100-ms long exposure to the target and distractors colors on trial $n - 1$ suffices to speed search on the next trial when the colors repeat relative to when they do not. Furthermore, longer exposure to the relevant colors on trial $n - 1$ did not seem to increase the magnitude of the repetition effect as measured on trial n . Finally, color repetition did not interact with response repetition, for any of the three SOAs.

Taken together, these findings have two main implications. First, they suggest that the process of selecting the target is completed or at least well under way as early as within 100 ms after target display onset. This process results in a change in the representation of the target color (and/or of the distractors color) that speeds selection of the same target (and/or rejection of the same distractors) on the trial that follows, and reflects the perceptual, selection-based component of PoP.

Second, the present findings suggest that during trial n , the representation that is retrieved at a post-perceptual stage and on which the response-based component of PoP relies, is formed at a late stage during trial $n - 1$, later than within 400 ms from target display onset. In other words, the process that binds the defining feature of the target and its response feature or motor response into a common representation that is retrieved after target selection on the next trial, seems to occur later than the process during which this representation is retrieved on trial n . On the one hand, a 400-ms long exposure to the critical target and distractors colors during trial $n - 1$ was not associated with a significant interaction between color repetition and response repetition on trial n . On the other hand, color repetition already interacted with response repetition within 400 ms into trial n . In future research, in order to further characterize the encoding and retrieval processes that underlie the response-based component of PoP, one could manipulate the difficulty of response-related mechanisms that might be involved or serve as temporal landmarks, namely, response feature discrimination and motor response selection. By lengthening these

stages independently of each other, one could isolate and possibly dissociate the stage at which the to-be-retrieved bound representation of target defining and response features is formed, from the stage at which it is retrieved in the next trial.

3.3. Relation to other inter-trial priming effects

The debate around the locus of inter-trial priming effects on search performance has also emerged with respect to effects other than PoP, namely, negative priming (Neill, Valdes, & Terry, 1995; Tipper, 2001), the distractor-preview effect (e.g., Lleras et al., 2008) and dimension-repetition effects (e.g., Cohen & Magen, 1999; Mortier, Theeuwes, & Starreveld, 2005; Müller & Krummenacher, 2006).

While accounts of negative priming and of the distractor-preview effect have typically postulated a mechanism operating at a single stage, either attentional selection (e.g., Lleras et al., 2008; Tipper, 2001) or retrieval from episodic memory (e.g., Neill et al., 1995), Müller and his colleagues (Pollmann, Weidner, Müller, Maertens, & von Cramon, 2006; Töllner, Gramann, Müller, Kiss, & Eimer, 2008) have recently proposed that dimension-repetition effects result from the interaction of selection- and response-based processes, in line with the dual-stage account suggested here with regard to PoP. In Töllner et al.'s (2008) study, subjects had to search for a singleton that was unique on either the shape or the color dimension, unpredictably, and to report its orientation. Event-related potentials (ERPs) were recorded while the subjects performed the task. Dimension repetition and response repetition effects were also found to interact, but by contrast with the findings reported in the present study, dimension-repetition effects on the behavioural measures were observed only on same-response trials and did not emerge on different-response trials. Thus, in Töllner et al.'s study, the perceptual component of dimension priming was small (rather than non-existent – taking into account that their magnitude was underestimated when measured on different-response trials, as explained in the foregoing discussion in the "Support of the dual-stage account of PoP" section). Repeated-dimension trials were associated with shorter latencies and enhanced amplitudes of the N2pc relative to changed-dimension trials, which suggests that dimension priming indeed facilitated allocation of attentional resources to the target (e.g., Eimer, 1996). In addition, different-response trials were associated with larger lateralized readiness potentials (LRPs) than same-response trials, suggesting that response repetition facilitates the activation and execution of motor responses (e.g., Hackley & Valle-Inclán, 2003).

Further research employing the procedure used here should clarify whether the dual-stage account tested in the present study with regard to PoP and suggested by Müller and colleagues with regard to the dimension-repetition effects (e.g., Müller & Krummenacher, 2006; Pollmann et al., 2006; Töllner et al., 2008) provides a general account of inter-trial priming effects on visual search.

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