



The role of motor response in implicit encoding: Evidence from intertrial priming in pop-out search



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ABSTRACT

Perception and motor control jointly act to meet our current needs. Recent evidence shows that the generation of motor action significantly affects perception. Here, we examined the role of motor response in inter-trial priming, namely, in Priming of Pop-out (PoP): when searching for a singleton target, performance is improved when the target and distractors features repeat on consecutive search trials than when they switch. Although recent studies have shown an interaction between motor response and PoP, the role of motor action on priming has not been fully characterized. Here we investigated whether motor action is necessary during encoding, for PoP to be observed. On *go* trials, observers searched for a color singleton target and responded to its shape, while on *no-go* trials they passively watched the display instead of responding to the target. We observed PoP even when the previous trial had been a *no-go* trial, suggesting that encoding of search-relevant attributes in pop-out displays is not contingent on motor response. Nevertheless, the repetition effect was larger after a *go* trial than after a *no-go* trial, supporting the dual-stage model of PoP, according to which this effect involves both a perceptual and a motor component.

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1. Introduction

The notion that our goals and actions affect how we represent the visual world has gained increasing support in recent years (e.g., Barsalou, 2008). According to this framework, sometimes known as “embedded cognition” or “grounded cognition”, the study of cognitive mechanisms must take into account both the physical environment and the body in which these mechanisms occur. In the present study we examine the perceptual and mnemonic consequences of simple motor actions during a basic perceptual task. Specifically, we investigate whether and how responses to a search display may interact with memory processes known to be involved in visual search (e.g., Chun & Nakayama, 2000; Downing, 2000; Kristjánsson & Campana, 2010; Lamy & Kristjánsson, 2013).

The role of short-term memory in visual search has been extensively studied through inter-trial priming effects in singleton search (e.g., Found & Müller, 1996; Lamy, Bar-Anan, & Egeth,

2008; Maljkovic & Nakayama, 1994). In singleton search, also known as pop-out search, a unique item on a given dimension (e.g., a unique red target embedded in a field of green distractors) is typically detected effortlessly and independently of the number of distractors. To ensure that observers deploy their focal attention to the pop-out target researchers often use a compound search task (Duncan, 1985). Observers are asked to select the target based on one feature (e.g., its color) and to respond to a different feature (e.g., its shape). Thus, in a compound search task the pop-out target is typically detected preattentively (e.g., Treisman & Gelade, 1980) but discrimination of the response feature requires focal attention (e.g. Bravo & Nakayama, 1992; Yashar & Lamy, 2010a).

In such tasks, performance is considerably improved when various aspects of the display repeat from recent trials. In a seminal demonstration of the effect of recent search history, Maljkovic and Nakayama (1994) asked participants to search for an odd-colored diamond, either a red diamond among green diamonds or vice versa. That is, the target and distractors could switch colors unpredictably from trial to trial. One corner of each of the diamonds in the display was chipped and observers had to report whether the left or the right corner of the target was chipped. Responses were faster when the target color repeated than when it changed on successive trials, even though the specific color of the target was

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irrelevant to the task. Similar inter-trial repetition effects also occur when the repeated attribute is the target-defining dimension (e.g., Found & Müller, 1996; Müller, Krummenacher, & Heller, 2004; Müller, Reimann, & Krummenacher, 2003; Töllner et al., 2008), the target's location (Maljkovic & Nakayama, 1996) or its temporal position (Yashar & Lamy, 2013, 2010b). Thus, there is strong evidence that memory of various aspects of previous displays influences visual search performance.

Inter-trial repetition effects have mainly been found when search-relevant attributes repeat, but not when the response-relevant feature repeats (but see Lamy, Bar-Anan, & Egeth, 2008). This finding led Maljkovic and Nakayama (1994) to conclude that PoP facilitates target-selection rather than response-selection processes. The results from several studies (Becker, 2008; Müller, Reimann, & Krummenacher, 2003; Sigurdardottir, Kristjánsson, & Driver, 2008; Wolfe et al., 2003; Yashar & Lamy, 2010a) have supported this view. However, other researchers have suggested that PoP affects post-selection processes. For instance, Huang, Holcombe, and Pashler (2004) showed that repetition of the target-defining attribute and repetition of the response attribute interact, which they took to indicate that PoP takes effect after the target was selected and the response-related attribute was processed.

Relying on the observation that selection and post-selection accounts of PoP are not necessarily incompatible, Lamy, Yashar, and Ruderman (2010) recently suggested a dual-stage account of PoP, according to which PoP affects search at both an early, selection-related stage and a later, post-selection stage. They dissociated the two components by measuring their time course. The results showed that repetition of the target-defining attribute (PoP) affects performance early during search (within 100 ms from display onset), and interacts with response (attribute) repetition only after 200–400 ms.

However, since in PoP studies each possible motor response is typically associated with a unique target feature, motor response repetition is confounded with repetition of the response feature, so that the post-selection component of PoP may pertain either to perceptual analysis of the response attribute or to selection and execution of the motor response. It follows that the so-called response-based component of PoP may not be related to response processes at all but may be perceptual instead. Yashar and Lamy (2011) addressed this issue in a recent study. Using a task that allowed us to dissociate repetition of the response attribute from repetition of the motor response, we showed that repetition of the target-defining feature interacted with the latter but not with the former and thus concluded that the late component of PoP is related to motor processes. Taken together, these findings suggest that intertrial target repetition affects perceptual as well as motor processes.¹

In the present study we investigated whether the perceptual component of PoP is contingent on the execution of a motor response. Previous studies that examined the role of action-related processes on perception have yielded mixed findings. Buttaccio and Hahn (2011) tested whether the requirement to execute a motor response modulates priming effects in visual search. In their first experiment, for instance, a color name, a colored shape (the prime) and a search array were presented one after the other. The search array consisted of four shapes of different colors, each enclosing a line, one of which (the target) was tilted and the others were vertical. Observers were required to press a key when the color name corresponded to the color of the prime and to refrain from responding, otherwise. They were then required to search for the target line and respond to it. Priming was defined as faster search

when the target color was the same as the prime's color, and occurred only on go trials. That is, priming was found only when observers performed a motor action in response to the prime, but not when they merely attended to it.

On the other hand, several studies have shown that information is encoded in implicit memory regardless of whether or not observers explicitly respond to it. For example, Makovski and Jiang (2011) showed that the execution of a motor response did not affect the magnitude of contextual cueing: encoding in implicit long-term memory of the spatial relationship between a target and the distractors surrounding it was independent of whether or not observers had to overtly respond to the target after detecting it. Similarly, Makovski, Jiang, and Swallow (2013) recently showed that response execution does not affect visual long-term memory of faces and objects. Finally, using a rapid serial visual presentation (RSVP) search task, Yashar and Lamy (2013) showed that repetition of the target's temporal position in consecutive visual streams speeded RTs in the second stream even when observers did not respond to the target in the first stream.

According to the dual-stage model (Lamy, Yashar, & Ruderman, 2010), only the motor-based component of PoP should be contingent on the execution of a motor response. However, as there have been reports of perceptual effects that depend on motor action (e.g., Buttaccio & Hahn, 2011) it is not clear whether the perceptual component of PoP can be observed when no motor response is required. In order to address this question, we used a variant of Maljkovic and Nakayama's (1994) paradigm but critically we interleaved go trials with no-go trials. On go trials, observers were asked to search for the color singleton and report the side of its chipped corner as fast as they could. On no-go trials, observers were asked to passively look at the displays, such that no response was required. A precue presented at fixation informed the observers as to whether the upcoming trial was a go or a no-go trial. In line with the terminology suggested by Goolsby and Suzuki (2001), we refer to trial *n-1* as the *encoding* trial of PoP and to trial *n* as the *retrieval* trial. If responding at encoding is necessary for PoP to be observed then we expect a PoP effect only on trials that follow a go trial. Conversely, if the perceptual component of PoP is independent of the execution of a motor response, then we expect PoP to be observed also after no-go trials but to be smaller than following go trials. Indeed, according to the dual-stage model (Lamy, Yashar, & Ruderman, 2010; Yashar & Lamy, 2011), the perceptual PoP effect should be augmented by a response-based component following a go trial but not following a no-go trial.

2. Experiment 1

2.1. Method

2.1.1. Participants

Participants were 11 Tel-Aviv University undergraduate students who participated in the experiment for course credit. All reported having normal or corrected-to-normal visual acuity and normal color vision.

2.1.2. Apparatus

Participants were tested individually in a dimly lit room. The stimuli were presented on a 17" CRT monitor (resolution 1024 × 768). A chin-rest was used to set viewing distance at 50 cm from the monitor.

2.1.3. Stimuli and procedure

The sequence of events on two consecutive trials is presented in Fig. 1. The fixation display consisted of either a plus sign ($0.4^\circ \times 0.4^\circ$) indicating that the participants should respond on

¹ Although motor processes are unrelated to pop out search, we nonetheless keep referring to the "perceptual and response components of PoP" for the purpose of consistency with previous work.

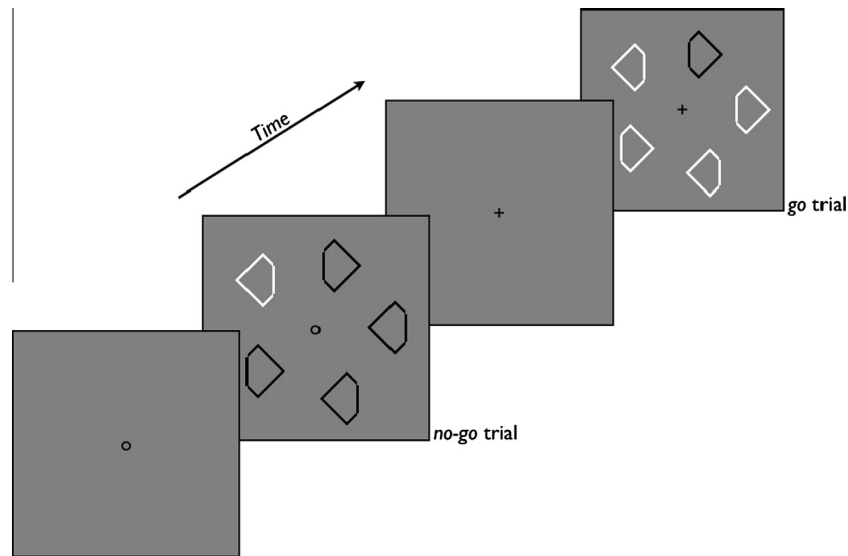


Fig. 1. Sample display sequences for no-go trials (on the left) and for go trials (on the right). The fixation point was a circle on no-go trials and a plus sign on go trials. The background was black (here, gray) and the diamonds were red or green (here, black or white). The task was to report the direction of the chipped side of the color-singleton diamond. Stimuli are not drawn to scale.

that trial (*go* trial), or an outline circle (0.4° in diameter) indicating that the participants should withhold their response on that trial (*no-go* trial). It was followed after 500 ms by the search array, which was similar for *go* and for *no-go* trials, and consisted of the fixation sign with the addition of five colored outline diamonds, rotated squares 1.2° to a side and drawn with a two-pixel stroke. Each diamond in the display had either its left or its right corner cut by 0.4° . The diamonds were evenly spaced on the circumference of an imaginary circle with a radius of 4.3° of visual angle. On *go* trials, the search array remained on the screen until response and participants were asked to report the side of the cut corner of the target diamond, as quickly and accurately as possible, using the “Z” and “3” keys. On *no-go* trials, the display remained in view for 750 ms and participants were required to view it passively.

2.1.4. Design

The experiment started with 20 practice trials, followed by eighteen 30-trial experimental blocks. On each trial within each block, conditions of response (*go* vs. *no-go*), color repetition (repeated vs. switched) and target shape repetition (same vs. different) were randomly determined and equiprobable.

2.2. Results and discussion

The data from one participant were removed from the analysis because his mean RT was slower by more than 2 standard deviations than the group’s mean. Accuracy was high: both responses on *no-go* trials ($M = 1.5\%$, $SD = 1\%$) and inaccurate responses on *go* trials ($M = 2.0\%$, $SD = 1\%$) were rare. Only trials preceded by a correct trial were included in all analyses. Error trials were removed from all RT analyses and so were outlier RT trials, in which the RT exceeded the mean of its cell by more than 2.5 standard deviations—fewer than 3% of all correct trials. All analyses included only *go* trials (preceded by either a *go* trial or a *no-go* trial).

A repeated-measures Analysis of Variance (ANOVA) was conducted with response condition on the encoding ($n - 1$) trial (*go* vs. *no go*), color repetition (repeated vs. switched) and target shape repetition (repeated vs. changed) as within-subject factors.

Reaction times: Mean RTs are depicted in Fig. 2 (upper panel). A large PoP effect was observed: repeated-color trials were re-

sponded to faster than switched-color trials, 652 vs. 709 ms, respectively, $F(1,9) = 45.32$, $p < .0001$. The main effect of response condition on the encoding trial was also significant, $F(1,9) = 34.78$, $p < 0.001$, with faster RTs on trials preceded by a *no-go* (658 ms) than by a *go* (703 ms) trial.

The interaction between color repetition and response condition on the encoding trial was significant, $F(1,9) = 19.60$, $p < 0.01$, indicating that the PoP effect was largely reduced when the preceding trial had not required a response (36 ms) relative to when it had (70 ms). Importantly, however, the color repetition effect was significant both when the encoding trial had been a *go* trial, $F(1,9) = 70.91$, $p < 0.0001$ and when it had been a *no-go* trial, $F(1,9) = 11.39$, $p < 0.01$.

In line with previous reports, repetition of the selection dimension (i.e., color) interacted with repetition of the response dimension (i.e., shape), $F(1,9) = 6.35$, $p < 0.04$, with a larger PoP effect when the target shape repeated (68 ms), $F(1,9) = 52.63$, $p < 0.0001$, than when it changed (47 ms), $F(1,9) = 23.72$, $p < 0.001$. Although the 3-way interaction between response condition on the encoding trial, color repetition and shape repetition was not significant, $F < 1$, it is noteworthy that the interaction between color repetition and shape repetition was significant only following a *go* trial, $F(1,9) = 7.38$, $p < 0.03$, and not following a *no-go* trial, $F(1,9) = 2.66$, $p > 0.1$.

Accuracy: The interaction between target-shape repetition and target-color repetition approached significance, $F(1,9) = 4.45$, $p = 0.06$, with a larger PoP effect when the target shape repeated (1.9%) than when it changed (−1.1%). Mirroring the RT results, the interaction between shape repetition and color repetition was significant only following a *go* trial, $F(1,9) = 9.33$, $p < 0.02$, but not following a *no-go* trial, $F < 1$. No other effect approached significance, all $ps > 0.1$.

The results of Experiment 1 are clear: PoP was found even when the encoding trial did not require a motor response, but the effect was larger following a *go* trial than following a *no-go* trial. In line with the dual-stage model of PoP, these findings suggest that the early, perceptual component of PoP is independent of the execution of a motor response, whereas its later, response-related component is contingent on it (Yashar & Lamy, 2011). However, there is an alternative account. One may claim that although observers did not respond on *no-go* trials, they may nevertheless have

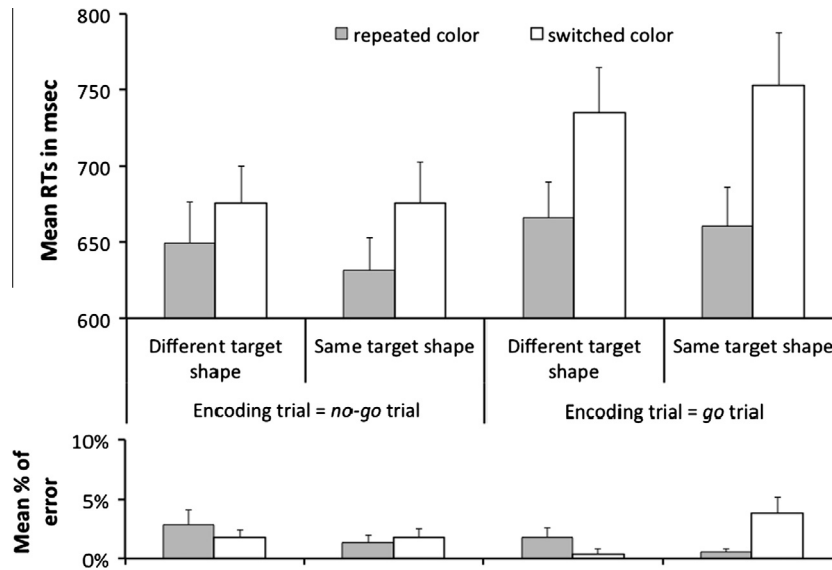


Fig. 2. Experiment 1: Mean reaction times (top panel) and percentage of errors (bottom panel) for repeated and switched target-color trials by conditions of response feature repetition (target shape) and conditions of response on the encoding trial (go vs. no-go). Error bars represent within-subject standard errors.

programmed the appropriate response without carrying it out. Because there was uncertainty as to whether the upcoming trial would be a *go* or a *no-go* trial, observers may have adopted the strategy of first searching for the target and preparing the appropriate motor response on all trials and only then decide whether or not to execute the response.

Note however, that following a *no-go* trial, target-color repetition (i.e., repetition of the selection feature) did not interact with shape repetition (i.e., repetition of the response feature), that is, with repetition of the corresponding response, had both successive trials been *go* trials. This finding invalidates the claim that observers programmed the appropriate response without carrying it out on *no-go* trials. However, because the 3-way interaction that underlies this claim was not significant, we conducted an additional experiment as a further test.

3. Experiment 2

The goal of Experiment 2 was to minimize the possibility that observers would prepare a response on *no-go* trials. For this purpose, we enhanced the distinction between *go* and *no-go* trials and reduced the cognitive load associated with trial-by-trial tracking of the response cue. Experiment 2 was similar to Experiment 1, except that it included two separate blocks: In the mixed-condition block, *go* and *no-go* trials followed a predictable ABAB alternating sequence instead of being randomly intermixed; in the blocked condition, all trials were *go* trials. Thus, observers knew in advance, with 100% certainty, whether or not they would have to respond on the upcoming trial. Moreover, in order to further discourage observers from programming a response on *no-go* trial we included a short display duration (250 ms). To determine whether this reduction indeed affected the probability that observers may program a response, we also included longer display durations (500 and 1000 ms).

3.1. Method

3.1.1. Participants

Participants were 12 undergraduate students from the University of Minnesota who participated in the experiment for course

credit. All reported having normal or corrected-to-normal visual acuity and normal color vision.

3.1.2. Apparatus, stimulus, procedure and design

The experiment was similar to Experiment 1 except for the following changes. First, a 19" instead of a 17" CRT monitor was used. Second, in addition to trials in which displays were presented until response, limited-duration display trials were included, on both *go* and *no-go* trials. On these trials, displays were presented for 250, 500 or 1000 ms and were followed by a blank screen that lasted until the end of the trial (that is, until response on *go* trials and until 1000 ms had elapsed on *no-go* trials). Thus, for instance, on a *no-go* trial with a 250-ms search display duration, the blank screen lasted for 750 ms.

The experiment consisted of two blocked conditions: an alternating *go/no-go* condition and a fixed *go* condition. In the alternating condition, each *go* trial was preceded by a *no-go* trial, whereas in the fixed *go* condition, each *go* trial was preceded by a *go* trial (because all trials were *go* trials). Display duration was equally likely to be 250, 500, 1000 ms on *no-go* trials and 250, 500, 1000 ms or until response on *go* trials. The order of the blocked conditions was counterbalanced across participants. Each blocked condition began with 20 practice trials and consisted of 480 experimental trials divided into 16 blocks.

3.2. Results and discussion

The data from one participant were removed from the analysis because her mean RT was slower than the group's mean by more than 2 standard deviations. Accuracy was high, with few false responses on *no-go* trials ($M = 1.7\%$, $SD = 1.0\%$) and few inaccurate responses on *go* trials ($M = 3.2\%$, $SD = 1.0\%$). Only trials preceded by a correct trial were included in all analyses. Error trials and outlier RT trials (fewer than 3% of all correct trials) were removed from all RT analyses.

Mean RTs and percentage of errors are depicted in Fig. 3 and Table 1. A repeated-measures ANOVA with encoding trial response condition (*go* vs. *no-go*), encoding trial display duration (250, 500, and 1000), color repetition (repeated vs. switched) and target shape repetition (same vs. different) as within-subject factors was conducted.

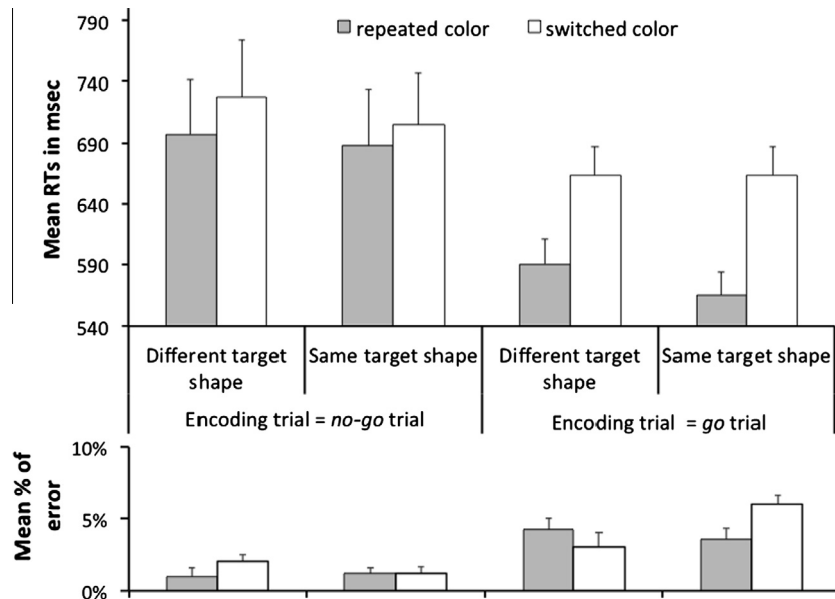


Fig. 3. Experiment 2: Mean reaction times (top panel) and percentage of errors (bottom panel) for repeated and switched target color trials by conditions of response feature (target shape) repetition and conditions of response on the encoding trial (go vs. no-go). Error bars represent within-subject standard errors.

Reaction times. The main findings of Experiment 1 were fully replicated. There was a significant PoP effect, $F(1,10)=64.62$, $p < 0.0001$, with faster RTs on repeated- than on switched-color trials (638 ms, SE = 11 ms vs. 691 ms, SE = 11, respectively). This factor interacted with response condition on the encoding trial, $F(1,10) = 33.32$, $p < 0.0003$, indicating that the color repetition effect was larger when the encoding trial had been a go trial than when it had been a no-go trial. Again, PoP was significant both when the preceding trial had been a go trial $F(1,10)=73$, $p < 0.0001$, and when it had been a no-go trial, $F(1,10)=13.05$, $p < 0.01$.

The main effect of shape repetition was significant, $F(1,10) = 15.32$, $p < 0.01$, with faster RTs when the target's shape remained the same than when it changed ($M = 653$, SE = 11.7 vs. $M = 675$ ms, SE = 11.5, respectively). This factor did not interact with PoP, $F < 1$.

In this experiment, the three-way interaction between color repetition, shape repetition and response condition on encoding trial was significant $F(1,10)=16.6$, $p < 0.01$. As in Experiment 1 when the encoding trial had been a go trial, the interaction between target color repetition and target shape repetition was significant, $F(1,10) = 8.48$, $p < 0.05$. By contrast, when the encoding trial had been a no-go trial, this interaction was not significant, $F(1,10) = 2.43$, $p > 0.1$. Finally, although the main effect of display duration on the encoding trial was significant, $F(2,20) = 7.74$, $p < 0.01$, such that RTs were faster as display duration on encoding trial was shorter, this factor was not involved in any significant interaction, all $ps > 0.3$ (Table 1).

Accuracy. In contrast to the RT data the main effect of response condition on the encoding trial was significant with higher error rate on trials following go trials than following no-go trials, $F(1,10) = 90.90$, $p < 0.0001$, $M = 4.2\%$ SE = 0.4%, vs. $M = 1.4\%$, SE = 0.2%, respectively. However, the remaining accuracy data mimicked the RT data, thus removing any concern of speed-accuracy trade-off in the critical effects. The interaction between response condition on encoding trial and shape repetition approached significance, $F(1,10) = 4.91$, $p > 0.05$, and was modulated by a three-way interaction with color repetition, $F(1,10) = 9.89$, $p < 0.02$. Follow-up analyses showed that the interaction between shape repetition and color repetition was significant

only when the encoding trial had been a go trial, $F(1,10) = 8.11$, $p < 0.01$, but not when it had been a no-go trial, $F(1,10) = 2.92$, $p > 0.1$. The main effect of display duration on the encoding trial approached significance, $F(2,20) = 2.65$, $p > 0.09$. There was no other significant effect, all $ps > 0.05$.

The results of Experiment 2 replicated the main finding from Experiment 1: PoP occurred even when no response had been performed or required on the encoding trial. In addition, the response component (reflected in a significant interaction between color repetition and shape repetition) was again observed only when the encoding trial had been a go trial and not when it had been a no-go trial. This pattern was even sharper than in Experiment 1 indicating that our attempt to discourage observers from programming a response on no-go was successful: indeed, the three-way interaction between color repetition, shape repetition and response on the encoding trial reached significance in the present experiment. This finding suggests that on go trials only, the appropriate motor response was associated with the target color.

There was a speed-accuracy trade-off in the effect of the response condition on the encoding trial (go vs. no-go): RTs were faster but accuracy was lower on trials following a go trial relative to trials following a no-go trial. This effect might be due to the fact that when the preceding trial was a go trial, it was in the context of a whole block of go trials. It is reasonable to suggest that in this condition, observers were more prepared to execute a motor response and more likely to do so before all visual information was completely analyzed, thereby producing the observed speed-accuracy trade off. This conjecture is supported by the fact that when go trials and no-go trials were randomly mixed (in Experiment 1), RTs were slower on trials following a go trial than on trials following a no-go trial, with no speed accuracy trade-off. In any event, this result has no incidence on the main findings of this experiment, as there was no speed-accuracy trade-off for any effect involving color repetition.

4. General discussion

The results of the present study support the view that repetition of the target's defining feature facilitates two independent processes: perceptual processes and selection/execution of a motor

Table 1

Experiment 2: Mean reaction times and percentage of error rates on repeated- and switched-target color trials by conditions of target shape repetition, response on the encoding trial (go vs. no-go) and display duration on the encoding trial. Error bars represent standard errors.

Display duration on encoding trial	Trial $n - 1$ = no-go trial		Trial $n - 1$ = go trial		All
	Different target shape	Same target shape	Different target shape	Same target shape	
RTS (in ms)					
250 ms					
Switched color	708(44)	691(39)	645(26)	665(25)	
Repeated color	687(40)	687(48)	591(20)	559(19)	
All					654(13)
500 ms					
Switched color	745(50)	715(47)	656(24)	669(32)	
Repeated color	700(50)	687(49)	590(27)	556(20)	
All					665(15)
1000 ms					
Switched color	767(52)	725(50)	679(33)	646(26)	
Repeated color	733(57)	704(46)	614(26)	565(20)	
All					679(15)
% of Errors					
250 ms					
Switched color	3.7(1.2)	0.7(0.4)	1.3(0.9)	4.5(0.9)	
Repeated color	0.6(0.6)	1.1(1.1)	4.1(1.1)	4.6(1.3)	
All					2.6(0.4)
500 ms					
Switched color	0.8(0.5)	1.6(0.7)	5.7(1.7)	8.6(1.6)	
Repeated color	1.5(0.8)	1.9(0.9)	3.9(1.7)	3.8(1.0)	
All					3.5(0.5)
1000 ms					
Switched color	1.8(1.0)	1.3(0.7)	2.5(1.1)	5.1(1.4)	
Repeated color	1.0(0.7)	0.5(0.5)	4.6(1.8)	2.1(0.6)	
All					2.4(0.4)

response. Priming of Pop-out was observed even when no response had been executed or required during encoding, supporting the existence of a perceptual component of PoP that it is not contingent on motor action. In addition, PoP was larger after a motor response had been executed on the encoding trial. This enhancement resulted from trials in which the response repeated on successive trials, supporting the existence of a response-related component of PoP. Crucially, the finding that the effect of repeating the target-defining feature did not interact with response-feature repetition following a *no-go* trial (that is, with repetition of the corresponding response, had both successive trials been *go* trials) strongly suggests that observers did not program the appropriate response without carrying it out on *no-go* trials.²

In apparent contradiction with the present findings, previous research has shown that searching for the target (Goolsby & Suzuki, 2001), and focusing attention on it (Yashar & Lamy, 2010a) is necessary for PoP to be observed. However, Goolsby and Suzuki (2001) showed that PoP is eliminated when a precue makes search unnecessary only during the *retrieval* trial, and not during the *encoding* trial. In the present study in all cases the retrieval trial was a *go* trial (and therefore involved search). Thus, Goolsby and Suzuki's findings are not inconsistent with ours.

With regard to the need for focused attention, we argue that

in the present study, while search was not explicitly required on *no-go* trials, attention was still captured by the color singletons. Indeed, color singletons have been shown to capture transient attention automatically (e.g., White, Lunau, & Carrasco, 2013). Thus, while we claim that observers did not prepare a motor response on *no-go* trials (as corroborated by the absence of the response component of PoP on *go* trials preceded by *no-go* trials), it is most likely that attention was in fact focused on the color singleton. Thus, our findings are compatible with the claim that focusing attention on the target is necessary for the perceptual component of PoP to emerge (Yashar & Lamy, 2010a).

Recently, using manipulation similar to the present study, Kristjánsson, Saevarsson, & Driver, 2013 failed to find a PoP effect when the encoding trial had been a *no-go* trial. One possible reason for the discrepancy between the outcomes of the two studies is that they differed in the size of the standard PoP effect. In Kristjánsson et al.'s study the standard PoP effect (on two consecutive *go* trials) was of only 25 ms (i.e., about 3% of the overall mean RT, reaching only 40 ms after four consecutive repetitions), whereas in the present study the standard effect was of about 70 ms (about 10% of the overall mean RTs). As we found PoP to be substantially smaller following a *no-go* trial (roughly 30 ms in Experiments 1 and 2), it is reasonable to suggest that Kristjánsson et al.'s procedure may not have been sensitive enough to uncover the critical effect. Moreover, while our analyses measured the independent contributions of the perceptual and response components, this was not the case in Kristjánsson et al.'s study. Thus, the PoP effect reported in Kristjánsson et al.'s study might mostly reflect the response component, which was eliminated following *no-go* trials. However, additional research is required to test this hypothesis and to further delineate the conditions required for implicit encoding of PoP.

² The latter conclusion is contingent on the premise that the response-related component of PoP pertains to both response preparation and response execution. However, existing data (Yashar & Lamy, 2011) do not allow one to disentangle the two processes. It is therefore possible to argue that if the response-related component of PoP pertains only to execution of motor action (which would explain why color repetition did not interact with shape repetition) then our current findings do not allow us to reject the possibility that observers did prepare a response on *no-go* trials and the perceptual component of PoP might therefore be contingent on motor preparation. Although such a sharp distinction between effects of motor preparation and motor execution on visual search is unlikely, further research is needed to examine this possibility.

The current findings also seem to be at odds with Buttaccio and Hahn's (2011) finding that preparation/execution of a motor response is necessary for priming effects to occur. However, the two studies differ in several aspects. One potentially important difference between the two studies is that here, the target in the prime display was embedded within an array of distractors (search display), whereas in Buttaccio and Hahn's (2011) study, it was presented by itself. In both studies, it is reasonable to suggest that the prime was attended, because it was a color singleton in our study and because it was the only item in a blank screen in Buttaccio and Hahn's study. Yet, priming was not contingent on producing a response in the former, whereas it was in the latter. Consistent with this observation, Wolfe et al. (2003, Experiment 6) showed that when the display consisted of just one item, priming occurred only when the repeated feature was relevant for the required response. Taken together, these findings suggest that focusing attention on an item's location during the encoding trial is not sufficient for all its properties to produce priming. Instead, attending to the repeating feature during the encoding trial – either because it is prioritized by its salience (as in our study) or because it is relevant to the response (as in Buttaccio & Hahn, 2011 and in Wolfe et al., 2003, studies) – is necessary for priming.

It is important to underscore that in the present study, 'motor response' refers to the selection and execution of the appropriate manual motor response, based on the target shape. Our findings may not apply to other kinds of motor responses involved in visual search, in particular, to eye movements. Although observers in the current study were specifically instructed to maintain their eyes at fixation, we cannot rule out the possibility that they executed eye movements towards the target on at least part of the *no-go* trials. Indeed, attentional shifts and eye movement are strongly correlated (e.g. see Cavanagh et al., 2010; Gottlieb & Balan, 2010, for review), and PoP, as an attentional effect, is no exception (McPeck, Maljkovic, & Nakayama, 1999).

However, previous research from our lab is inconsistent with the claim that eye movements may account for our results (Yashar & Lamy, 2013). The task consisted in comparing a color singleton target embedded in one rapid visual presentation stream displayed at fixation to a target embedded in the stream that followed, such that the first target was not associated with any response. In that study, we showed an inter-trial priming effect (namely, temporal position repetition priming), despite the fact that all stimuli were presented at fixation and therefore were unlikely to elicit eye movements. The task consisted in comparing a target in a first stream to a target in the stream that followed, such that the first target was not associated with any response. Nevertheless, it remains an open question whether the finding in temporal position repetition effect can apply to feature repetition effect in spatial visual search as in this study. However, whether this characterization of temporal repetition effect can apply to the present study of feature repetition effect remains an open question.

The present results have implications for our understanding of the mechanisms that underlie PoP. Nakayama and Martini (2011) recently suggested that RT fluctuations related to feature repetitions have much in common with fluctuations in motivational salience induced by rewards. Specifically, they suggested that PoP reflects reinforcement learning, such that successfully responding to a target reinforces allocation of attention to the same target, that is, to objects that have the same salient feature as the target. In the experimental psychology literature reinforcement is traditionally associated with behavior and performance rather than with mental processes such as attentional allocation. Here, we dissociated reinforcement of the attentional response from reinforcement of the motor response by showing that PoP is still observed when no motor response is required or executed at encoding (i.e., on the encoding trial), that is, when attentional allocation but not the motor

response was reinforced. Note that the emergence of PoP following a *no-go* trial suggests that observers attended to the target even when they were not required to do so. Such allocation was probably triggered by effortless detection of the pop-out target and was enough to reinforce the conditioned strength associated with the target-defining feature.

Finally, our study also has implications regarding the relation between cognition and motor processes. A growing number of researchers (e.g., Barsalou, 2008) have argued that perceptual and motor processes are closely intertwined. For instance, the Theory of Event Coding proposes that an event file is associated with each perceived visual object, and contains information about the visual properties of the object as well as the planned or executed action towards it (Hommel, 2004; Hommel et al., 2001). Relative to this general framework, the present findings show that some perceptual processes, namely, encoding of the attended feature of an object in short-term memory, are not contingent on motor action.

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References

- Barsalou, Lawrence W. (2008). Grounded cognition. *Annu. Rev. Psychol.*, 59, 617–645.
- Becker, S. I. (2008). The mechanism of priming: Episodic retrieval or priming of pop-out? *Acta Psychologica*, 127(2), 324–339.
- Bravo, M. J., & Nakayama, K. (1992). The role of attention in different visual-search tasks. *Attention, Perception, & Psychophysics*, 51(5), 465–472.
- Buttaccio, D. R., & Hahn, S. (2011). The influence of action on visual search: Behavioral response toward stimuli modifies the selection process. *Attention, Perception & Psychophysics*, 73(5), 1453–1466. <http://dx.doi.org/10.3758/s13414-011-0121-y>.
- Cavanagh, P., Hunt, A. R., Afraz, A., & Rolfs, M. (2010). Visual stability based on remapping of attention pointers. *Trends in cognitive sciences*, 14(4), 147–153.
- Chun, M. M., & Nakayama, K. (2000). On the functional role of implicit visual memory for the adaptive deployment of attention across scenes. *Visual Cognition*, 7(1–3), 65–81.
- Downing, P. E. (2000). Interactions between visual working memory and selective attention. *Psychological Science*, 11(6), 467–473.
- Duncan, J. (1985). Visual search and visual attention. In M. I. Posner & O. S. M. Marin (Eds.), *Attention and performance XI: Mechanisms of attention* (pp. 85–105). Hillsdale, NJ: Lawrence Erlbaum Associates Inc..
- Found, A., & Müller, H. J. (1996). Searching for unknown feature targets on more than one dimension: Investigating a "dimension-weighting" account. *Attention, Perception, & Psychophysics*, 58(1), 88–101.
- Goolsby, B. A., & Suzuki, S. (2001). Understanding priming of color-singleton search: Roles of attention at encoding and "retrieval". *Perception & Psychophysics*, 63(6), 929–944.
- Gottlieb, J., & Balan, P. (2010). Attention as a decision in information space. *Trends in Cognitive Sciences*, 14(6), 240.
- Hommel, B. (2004). Event files: Feature binding in and across perception and action. *Trends in Cognitive Sciences*, 8(11), 494–500.
- Hommel, B., Müsseler, J., Aschersleben, G., & Prinz, W. (2001). The theory of event coding (TEC): A framework for perception and action planning. *Behavioral and Brain Sciences*, 24(05), 849–878.
- Huang, L., Holcombe, A. O., & Pashler, H. (2004). Repetition priming in visual search: Episodic retrieval, not feature priming. *Memory & Cognition*, 32(1), 12–20.
- Kristjánsson, Á., & Campana, G. (2010). Where perception meets memory: A review of repetition priming in visual search tasks. *Attention, Perception, & Psychophysics*, 72(1), 5–18.
- Kristjánsson, Á., Saevarsson, S., & Driver, J. (2013). The boundary conditions of priming of visual search: From passive viewing through task-relevant working memory load. *Psychonomic Bulletin & Review*, 1–8.
- Lamy, D., Bar-Anan, Y., & Egeth, H. E. (2008). The role of within-dimension singleton priming in visual search. *Journal of Experimental Psychology: Human Perception and Performance*, 34(2), 268.
- Lamy, D., & Kristjánsson, Á. (2013). Is goal-directed attentional guidance just inter-trial priming? A review. *Journal of Vision*, 13(3), 14.
- Lamy, D., Yashar, A., & Ruderman, L. (2010). A dual-stage account of inter-trial priming effects. *Vision Research*, 50(14), 1396–1401.

- Makovski, T., & Jiang, Y. V. (2011). Investigating the role of response in spatial context learning. *The Quarterly Journal of Experimental Psychology*, 64(8), 1563–1579.
- Makovski, T., Jiang, Y. V., & Swallow, K. M. (2013). How do observer's responses affect visual long-term memory? *Journal of Experimental Psychology: Learning, Memory, & Cognition*, 39, 1097–1105.
- Maljkovic, V., & Nakayama, K. (1994). Priming of pop-out: I. Role of features. *Memory & Cognition*, 22(6), 657–672.
- Maljkovic, V., & Nakayama, K. (1996). Priming of pop-out: II. The role of position. *Attention, Perception & Psychophysics*, 58(7), 977–991.
- McPeck, R. M., Maljkovic, V., & Nakayama, K. (1999). Saccades require focal attention and are facilitated by a short-term memory system. *Vision Research*, 39(8), 1555–1566.
- Müller, H. J., Reimann, B., & Krummenacher, J. (2003). Visual search for singleton feature targets across dimensions: Stimulus-and expectancy-driven effects in dimensional weighting. *Journal of Experimental Psychology: Human Perception and Performance*, 29(5), 1021.
- Müller, H., Krummenacher, J., & Heller, D. (2004). Dimension-specific intertrial facilitation in visual search for pop-out targets: Evidence for a top-down modifiable visual short-term memory effect. *Visual Cognition*, 11(5), 577–602.
- Nakayama, K., & Martini, P. (2011). Situating visual search. *Vision Research*, 51(13), 1526–1537.
- Sigurdardottir, H. M., Kristjánsson, Á., & Driver, J. (2008). Repetition streaks increase perceptual sensitivity in visual search of brief displays. *Visual Cognition*, 16(5), 643–658.
- Töllner, T., Gramann, K., Müller, H. J., Kiss, M., & Eimer, M. (2008). Electrophysiological markers of visual dimension changes and response changes. *Journal of Experimental Psychology: Human Perception and Performance*, 34(3), 531.
- Treisman, A. M., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, 12(1), 97–136.
- White, A. L., Lunau, R., & Carrasco, M. (2013). The attentional effects of single cues and color singletons on visual sensitivity. *Journal of Experimental Psychology: Human Perception and Performance*. <http://dx.doi.org/10.1037/a0033775>.
- Wolfe, J. M., Butcher, S. J., Lee, C., & Hyle, M. (2003). Changing your mind: On the contributions of top-down and bottom-up guidance in visual search for feature singletons. *Journal of Experimental Psychology: Human Perception and Performance*, 29(2), 483.
- Yashar, A., & Lamy, D. (2010a). Intertrial repetition affects perception: The role of focused attention. *Journal of Vision*, 10(14).
- Yashar, A., & Lamy, D. (2010b). Intertrial repetition facilitates selection in time common mechanisms underlie spatial and temporal search. *Psychological Science*, 21(2), 243–251.
- Yashar, A., & Lamy, D. (2011). Refining the dual-stage account of intertrial feature priming: Does motor response or response feature matter? *Attention, Perception, & Psychophysics*, 73(7), 2160–2167.
- Yashar, A., & Lamy, D. (2013). Temporal position priming: memory traces of recent experience bias the allocation of attention in time. *Journal of Experimental Psychology: Human Perception and Performance*, 39(5), 1443–1456.