

# Permeability of priming of pop out to expectations

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It is well established that repetition of the same target color across consecutive trials enhances search efficiency for pop-out targets; this phenomenon is known as Priming of Pop out (PoP). In three experiments, we addressed whether PoP interacts with top-down expectations in altering target visibility, which was manipulated via metacontrast masking. The target color either remained the same for  $n$  consecutive trials (blocked condition) or changed unpredictably (random condition). The results showed that PoP reduced the efficacy of masking and that its beneficial effect can be either potentiated or attenuated by participants' expectations about the upcoming target color. These findings undermine the view that PoP should be impermeable to top-down factors. In addition, we found evidence that both explicit and implicit expectations interact with PoP. The former can be induced via instructions on the rate of alternation of the target color, and the latter can be induced by random sequences in which repetitions of the same target color exceed those predicted by an internal model of randomness for binary events. In the latter case, more than three repetitions of the same target color led to a decline in target visibility. We speculate that, in the random condition, after few repetitions of the same target, participants developed an expectation for a change; this phenomenon is similar to the “gambler’s fallacy.” Finally, our analyses revealed no effect of expectation on switch trials (i.e., when the target color changed), which casts doubt on the efficacy of top-down control in feature search.

Keywords: priming, attention, expectation, visual search, top-down, bottom-up, gambler’s fallacy

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## Introduction

Decades of research on visual attention have established that the attentive selection process is governed by both top-down and bottom-up mechanisms (Yantis, 2000). Some evidence emphasizes the former by showing the importance of the observer’s expectations and intentions (e.g., Folk, Remington, & Johnson, 1992; Wolfe, Friedman-Hill, & Bilsky, 1994), while other evidence puts more weight on the latter by showing how stimulus salience per se can attract attention regardless of any top-down factor (e.g., Horstmann, 2002; Theeuwes & Burger, 1998; Turatto & Galfano, 2001).

In the domain of feature search, Maljkovic and Nakayama (1994, 1996, 2000) discovered that the deployment of attention is also affected by the repetition of the defining target feature. In their seminal study, Maljkovic and Nakayama (1994) had partici-

pants detect the trimmed side of the pop-out target (i.e., a uniquely colored diamond). To evaluate the influence of top-down knowledge on the search for a pop-out target, the probability of a change in the target color was varied from 0 to 1 across different blocks of trials. The rationale behind this manipulation was as follows: if the observers’ knowledge of the target color played a crucial role in determining visual search performance, then no differences in response times (RTs) for target discrimination would emerge between the blocked (probability of change = 0) and the alternating (probability of change = 1) conditions because, in both conditions, observers could predict with complete certainty the target color on each trial (i.e., red, red, . . . , red in the blocked condition; red, green, red, green, . . . , red, green in the alternated condition). Although the degree of knowledge was comparable in the two conditions, RTs were shorter when the same target feature was repeated instead of alternated. The authors suggested that this was the result of a purely passive

and implicit form of memory that is cumulative, lasts approximately 30 seconds, and whose effects “...are not overcome by knowledge, expectancy, or intentions knowledge” (Nakayama, Maljkovic, & Kristjánsson, 2004, p. 403). The authors termed this phenomenon “Priming of Pop out” (PoP). Although not directly concerned with the PoP phenomenon, a recent study Theeuwes, Reimann, and Mortier (2006) reached a similar conclusion by showing that feature-based knowledge, induced by a valid cue indicating the defining feature of the upcoming target (e.g., color), has no measurable impact on the deployment of attention in singleton search. Rather, the speed with which attention is allocated to the singleton for further in-depth analysis can be completely accounted for by a trial-by-trial bottom-up priming effect. Hence, echoing Maljkovic and Nakayama (1994, 1996, 2000), Theeuwes and colleagues concluded that “in feature search there is no top-down modulation, only bottom-up priming” (Theeuwes et al., 2006, p. 485). In sum, these studies suggest that top-down information, such as feature-based knowledge and expectations, does not influence singleton (or pop-out) search, which seems to be controlled only by bottom-up inter-trial priming.

Interestingly, more recent studies seem to challenge this conclusion. For example, Leonard and Egeth (2008) provided evidence in favor of an effect of top-down guidance in singleton search. In their study, participants were engaged in the same search task used by Maljkovic and Nakayama (1994). However, in each trial, participants were presented with a written cue that was either informative or uninformative with respect to the upcoming target color. The results showed that informative cues significantly speed up the identification of the target, thus indicating a top-down modulation in singleton search. Most notably, the results also showed a significant interaction between the number of target repetitions and the cue type (informative vs. uninformative), which indicates that the strength of PoP may depend on target expectancy (Leonard & Egeth, 2008).

The study by Fecteau (2007) also supports the notion of a top-down modulation of PoP. At the beginning of each trial, participants were instructed to search either for a color or a shape singleton, and both singletons were presented in the search array. The results showed that the beneficial effect of repetition of the feature singleton on RTs was only present for the feature that was relevant to the current goal of the observers.

To summarize, on the one hand, it is still debated whether top-down factors can speed up search for a pop-out target regardless of any priming effect (e.g., Theeuwes et al., 2006); on the other hand, the possibility that feature-based knowledge interacts with inter-trial priming, and particularly with PoP, is well documented (e.g., Leonard & Egeth, 2008). However,

previous studies addressing these questions presented the stimuli without any time constraints and used RT as the main dependent variable. Thus, one may wonder whether analogous results can be observed when the effects of top-down and bottom-up factors are evaluated with respect to the visibility of the pop-out target.

In fact, a few recent studies have been primarily concerned with the issue of whether PoP can affect the visibility of a target singleton (Sigurdardottir, Kristjánsson, & Driver, 2008; Yashar & Lamy, 2010). These studies have shown that PoP affects visual perception at early stages by enhancing the target representation (but see Huang & Pashler, 2005). In particular, Sigurdardottir et al. (2008) asked participants to find the odd-colored disk among homogeneously colored distractors and then decide whether the dot inside the disk was displaced to the left or to the right with respect to the disk center. The visibility of the stimuli was constrained by a pattern-masking procedure. The results showed that participants' discriminative capacity increased as a function of the number of same-color target repetitions (Sigurdardottir et al., 2008). Parallel to these studies, other researchers have focused on the influence of feature-based knowledge on target visibility and have provided contradictory results. For example, Moore and Egeth (1998) demonstrated that prior knowledge of the to-be-searched target feature does not improve the processing of that particular feature (see also Shih & Sperling, 1996).

However, to date, no study has jointly examined both the effects of PoP and feature-based knowledge on the visibility of a target singleton. It is worth noting that, while some previous studies (Huang & Pashler, 2005; Sigurdardottir et al., 2008; Yashar & Lamy, 2010) focused on the role of PoP without manipulating any top-down factors, other studies (e.g., Moore & Egeth, 1998) measured the impact of top-down guidance without considering priming effects. In light of these shortcomings, the aim of the present study was to examine whether, in a pop-out search task, early modulations of target visibility can be ascribed only to the effects of PoP or, instead, can also be due to top-down factors. More specifically, we addressed whether the interaction between feature-based knowledge and PoP reported by Leonard and Egeth (2008) and Fecteau (2007) with RTs can be observed also in the domain of visibility.

To explore this issue, we used the same visual search paradigm devised by Maljkovic and Nakayama (1994) and manipulated target visibility via metacontrast masking. We compared the observers' visual performances in two different conditions: a “blocked” condition, in which the target color was completely predictable, and a “random” condition, in which the target color was completely unpredictable. From this comparison, one can obtain relevant information about

the interactions between the effects of PoP and the effects of top-down guidance (feature-based knowledge or expectation). This information may enrich our understanding of the mechanisms and processes involved in pop-out search.

## Experiment 1

This experiment was intended as a first step to evaluate whether and how stimulus visibility can be altered by top-down information and PoP. We adopted the same stimuli as in the original study of Maljkovic and Nakayama (1994). The task was to report whether the odd-colored diamond was trimmed to the left or to the right (see Figure 1). In this and the following experiments, we manipulated the visibility of the target using a brief display presentation combined with metacontrast masking; thus, accuracy, rather than RT, was our dependent variable. In the “Blocked” condition, the features that defined the target and distractors were kept constant across a block of trials (e.g., red target and green distractors), whereas in the “Random” condition, the color assignment swapped randomly on a trial-by-trial basis.

## Methods

### Participants

Twenty-four students (18 females; mean age =  $22.7 \pm 3.14$ ) from the University of Trento, Italy, participated in the experiment for monetary payment (7€) or course credits. All participants had normal or correct-

ed-to-normal vision and were naïve as to the purpose of the experiment. Written informed consent was obtained from all participants, and the experiment was carried out in accordance with the Declaration of Helsinki.

### Apparatus

The apparatus was identical in all of the experiments. Stimuli were presented on a Dell Trinitron CRT 19” monitor ( $1024 \times 768$ , 75 Hz). The generation and presentation of the stimuli was controlled by a custom-made program written using Matlab and the Psychophysics Toolbox 3.8 (Pelli, 1997) running in Windows 2000 on a Pentium IV Dell PC.

### Stimuli

Stimuli consisted of red or green diamonds (covering approximately  $1.5^\circ$  of visual angle) with a cut of  $.5^\circ$  on the left or on the right (see Figure 1). The luminance of the green and red stimuli was matched using a 21.5-Hz flicker-fusion procedure (Wyszecki & Stiles, 1982). The luminance of the background was  $0.19 \text{ cd/m}^2$ .

The three diamonds were presented at three positions arranged along an imaginary ellipse with major (horizontal) and minor (vertical) axes of  $10.0^\circ$  and  $8.5^\circ$ , respectively. On each trial, the three positions, separated by the same angular distance, were chosen randomly from 12 possible positions on the ellipse. The mask was a  $2.5^\circ \times 2.5^\circ$  outlined diamond of the same color as the target whose inner contours had a separation of 1 pixel from the target. A small white cross ( $.5^\circ$ ) was centered on the ellipse and served as fixation point.

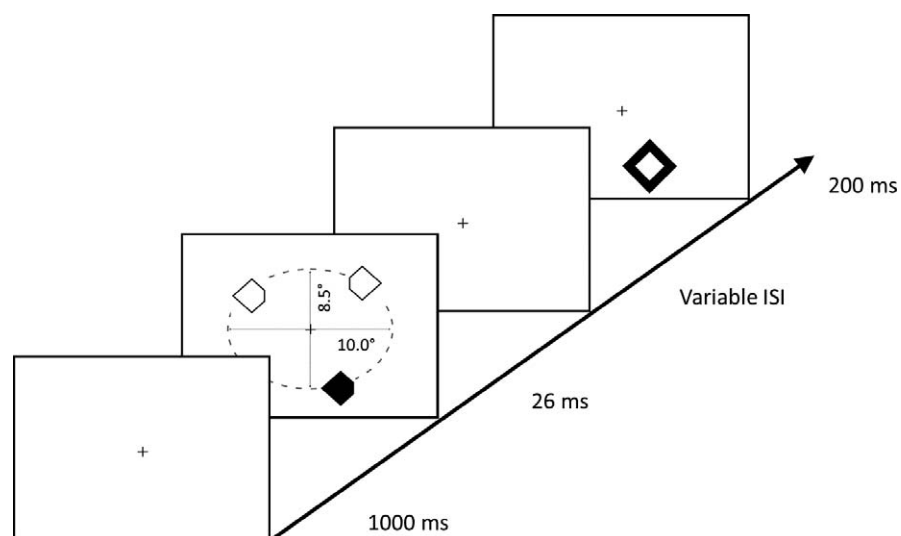


Figure 1. Example of the stimuli and events used in all of the experiments in the present study. The target and the distractors were followed, after a variable ISI (52, 117, or 234 ms), by the mask. Participants were asked to report, without time pressure, which side the target was trimmed. The stimuli are not drawn to scale.

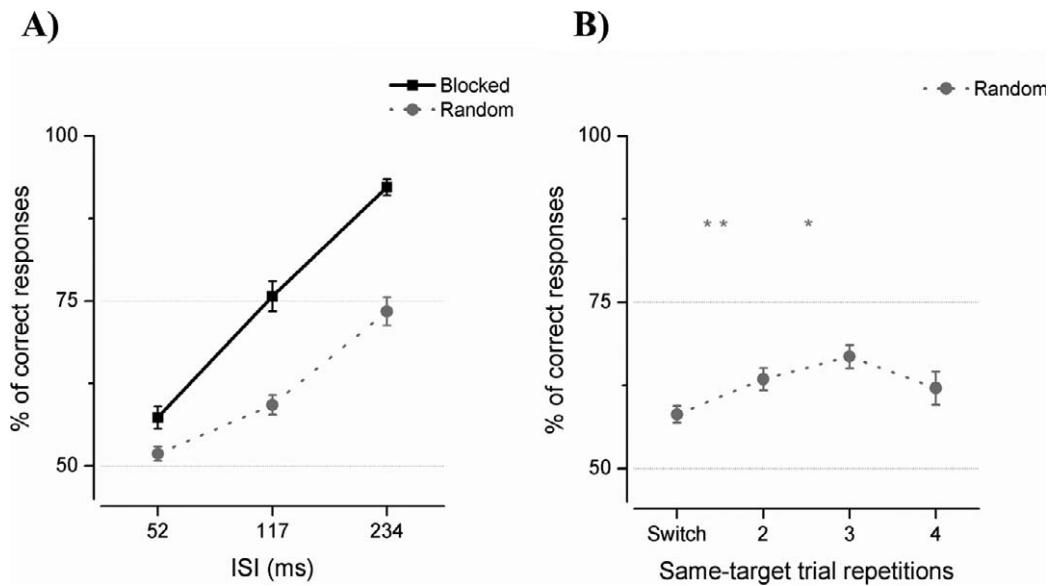


Figure 2. Results from Experiment 1. Panel A: Overall accuracy in the “Blocked” and “Random” conditions as a function of ISI. For all ISIs, participants were more accurate in the “Blocked” condition compared to the “Random” condition. Panel B: Accuracy in the “Random” condition plotted as a function of the number of repetitions (ISIs are collapsed). Target visibility increased from runs of 1 to 3, whereas a drop in visibility emerged for runs of 4 compared to runs of 3 ( $p = 0.08$ ). In this and the following figures, the asterisks indicate a significant difference (\*\*  $p < 0.001$ , and \*  $p < 0.05$ , respectively).

### Procedure

Participants sat approximately 60 cm in front of the monitor in a dimly illuminated room. Before each block of trials, participants were informed about the type of condition (“Blocked” vs. “Random”) they were about to perform. The two conditions were alternated, and the order of presentation was counterbalanced across participants. Each trial started with the presentation of the central fixation mark for 1000 ms, after which the three diamonds were briefly presented for 26 ms. Then, after a variable inter-stimulus-interval (ISI; 52, 117, or 234 ms), the mask appeared for 208 ms at the position previously occupied by the target.

Without time pressure, participants pressed the left arrow on the keyboard to indicate that the target was trimmed to the left or the right arrow to report that the target was trimmed to the right. Errors were signaled by visual feedback.

### Design

A  $2 \times 3$  factorial design was used with Condition (“Blocked” vs. “Random”) and ISI (52, 117, 234 ms) as factors. The experiment consisted of 6 blocks, 3 per condition, with 125 trials per block. Prior to the experimental session, 20 practice trials were administered to participants to familiarize them with the task. The data from these practice trials were discarded from the analyses.

### Results and discussion

The percentage of correct responses was calculated and entered into a two-way repeated-measures analysis of variance (ANOVA). The factors Condition,  $F(1, 23) = 66.02$ ,  $p < 0.001$ , ISI,  $F(2, 46) = 319.07$ ,  $p < 0.001$ , and their interaction,  $F(2, 46) = 15.0$ ,  $p < 0.0001$ , were all significant. As they clearly emerge from inspection of Figure 2 (panel A), the results mirrored those of Maljkovic and Nakayama (1994), although in this experiment, accuracy was the dependent variable. Specifically, target visibility was better in the “Blocked” condition ( $M = 75\%$ ;  $SD = 14\%$ ), when the color of the target remained constant over an entire block of trials, than in the “Random” condition ( $M = 61\%$ ;  $SD = 8\%$ ). In addition and as expected, target visibility was also affected by masking with higher accuracy at the longest ISIs.

The advantage of the “Blocked” condition relative to the “Random” condition could be explained by differences in the amount of priming as suggested by Maljkovic and Nakayama (1994). When the color of the target remains constant over an entire block of trials, the effect of PoP should be maximal, whereas in the “Random” condition, the effect of PoP is often reset to zero by the switches. However, we cannot a priori exclude the possibility that the “Blocked” condition, compared to the “Random” condition, led to improved visibility because of a difference in the degree of knowledge about the target color.



Previous studies (Maljkovic & Nakayama, 1994, 2000; Sigurdardottir et al., 2008) demonstrated that the more the target feature is repeated, the higher the efficiency of target processing, which is consistent with a cumulative effect of PoP. To evaluate this PoP characteristic in the domain of target visibility, we analyzed a subset of the data from the random condition. Accuracy was calculated as a function of the number of consecutive repetitions (runs) of the same target color, up to a maximum of 4. The data were subjected to a two-way repeated-measures ANOVA. The factors ISI,  $F(2, 46) = 70.4$ ,  $p < 0.001$ , and Repetitions,  $F(3, 69) = 7.1$ ,  $p < 0.001$ , were significant, but their interaction was not. Figure 2 (panel B) depicts the accuracy level as a function of the number of repetitions in the random condition. The results show an inverted U-shaped function, with accuracy increasing from runs of 1 (switch trials) to runs of 2 and 3, followed by a drop in performance for runs of 4. This pattern was substantiated by pairwise comparisons ( $t$  tests), which confirmed that accuracy was higher for runs of 2 than of 1 ( $p < 0.001$ ) and higher for runs of 3 than of 2 ( $p < 0.05$ ). The overall gain in performance, with respect to the switch condition, corresponded to approximately 10%. This pattern is entirely consistent with the ideas that PoP reflects a memory trace of the target feature that accrues evidence over time and that this information can be used to guide attention to the target location.

In addition, and quite surprisingly, we observed a marginally significant ( $p = 0.08$ ) decrement in performance (~5%) from runs of 3 to runs of 4. This observation was substantiated by a planned contrast analysis that revealed a significant ( $p < 0.001$ ) quadratic trend for the factor Repetition, confirming the presence of the U-shaped pattern. This decrement in performance for the longest runs might be suggestive of a possible change in expectation of the upcoming target color. In other words, one might hypothesize that after a run of 3 consecutive targets of the same color, participants began to expect a change in the color of the target rather than its repetition based on an internal model of a random sequence. This effect would resemble the well-known “gambler’s fallacy,” a phenomenon that reflects a belief in negative autocorrelation of a random sequence whereby random sequences should exhibit systematic reversals (Croson & Sundali, 2005; Tversky & Kahneman, 1974). In Experiments 2 and 3, we directly addressed this issue by increasing the number of observations in the longest runs. If confirmed, such a decrement in performance would have important implications for our understanding of the interactions between PoP and top-down factors.

## Experiment 2

The results of Experiment 1 have confirmed a significant increase in the visibility of pop-out targets when the corresponding color was repeated rather than changed randomly (e.g., Yashar & Lamy, 2010). The aim of Experiment 2 was to understand which of two alternative explanations could account for the improved visibility in the “Blocked” condition of Experiment 1. On the one hand, following Maljkovic and Nakayama (1994), the number of repetitions (i.e., the amount of priming) should be the only factor affecting search efficiency, whereas expectancy (or predictability) “...is clearly not the factor responsible for the difference between blocked and mixed conditions” (Maljkovic & Nakayama, 1994, p. 660). On the other hand, the observed facilitation could be due to top-down guidance induced by top-down knowledge.

To address these issues, we used the same visual search task as in Experiment 1, with an additional crucial and novel experimental manipulation: the blocked and random conditions were matched in terms of the total number of switches but differed in terms of the target color predictability. Participants therefore performed a “Random” condition and a “Blocked 2” condition in which the color of the target regularly switched every two trials.

The rationale behind this manipulation was as follows: if PoP is the major factor affecting target visibility, then the performance should be better in the “Random” condition than in the “Blocked 2” condition. Indeed, in the latter condition, the beneficial effect of PoP would be limited to only one repetition, whereas the cumulative effects of PoP would be more likely to emerge with longer runs in the random condition. By contrast, if top-down information is the crucial factor, a reversed pattern should be expected; specifically, the performance should be better in the “Blocked 2” condition than in the “Random” condition.

To ensure that the number of switches was the same in the two conditions, we selected a randomly generated sequence that contained the same number of switches as the “Blocked 2” condition, and we used this sequence for all participants. The randomness of the chosen sequence was tested with a battery of four tests (Runs test, Frequency test, Monobit test, and Approximate entropy test) from the suite of NIST (Rukhin et al., 2001). Because probabilistic independence is one of the most basic properties of randomness, we also tested whether the elements of the selected sequence were generated independently of each other. To this aim, we checked that previous events in the sequence did not influence the subsequent events by computing the conditional probabilities given streaks of various lengths (from 1 to 5).

## Methods

### Participants

Twenty-four students (16 females; mean age =  $22.3 \pm 3.7$ ) from the University of Trento, Italy, participated in this experiment for monetary payment (7€) or course credits. All participants had normal or corrected-to-normal vision and were naïve as to the purpose of the experiment. Informed consent was obtained from all participants, and the experiment was carried out in accordance with the Declaration of Helsinki.

### Apparatus and stimuli

The apparatus and stimuli were the same as in [Experiment 1](#).

### Procedure

The procedure was the same as in [Experiment 1](#), with the following exceptions. Participants were tested on two different conditions: “Blocked 2” (i.e., red, red, green, green) and “Random.” Only two ISIs (104 and 234 ms) were used because in [Experiment 1](#), performance was at chance at the 52-ms ISI.

### Design

A  $2 \times 2$  factorial design was used, with Condition and ISI as factors. The experiment consisted of four experimental blocks (two per condition, with 250 trials per block), preceded by 20 practice trials not included in the analyses.

## Results and discussion

The data were entered into a two-way repeated-measures ANOVA. The factors Condition,  $F(1, 23) = 14.0$ ,  $p < 0.001$ , and ISI,  $F(1, 23) = 146.9$ ,  $p < 0.001$ , were significant, but their interaction was not. The results of [Experiment 2](#) ([Figure 3](#), panel A) showed that target visibility for both ISIs was higher when the configuration of the upcoming display was completely predictable (“Blocked 2”) ( $M = 71\%$ ;  $SD = 8\%$ ) than when it varied unpredictably ( $M = 67\%$ ;  $SD = 8\%$ ). Because the number of switches in the two conditions was the same, the results indicate that the amount of priming was not the only critical factor affecting pop-out search. This finding is in contrast with previous studies suggesting that only bottom-up priming is involved in pop-out search (e.g., Maljkovic & Nakayama, 1994, 1996, 2000) and shows that participants were better at identifying the target when its color was predictable. This finding suggests a clear role of top-down information (e.g., Leonard & Egeth, 2008).

To test for possible top-down influences on target visibility during feature search regardless of any contribution of priming, we compared the accuracy of the random and blocked conditions on switch trials, i.e., those trials not affected by PoP. Furthermore, comparisons of runs of 2 allowed us to evaluate a possible interaction between PoP and top-down factors.

Accuracy on switch and repeated trials (runs of 2) was entered into a  $2 \times 2 \times 2$  repeated-measures ANOVA. The factors Condition,  $F(1, 23) = 18.6$ ,  $p < 0.0001$ , ISI,  $F(1, 23) = 136.9$ ,  $p < 0.0001$ , and Repetitions,  $F(1, 23) = 64.0$ ,  $p < 0.0001$ , were all significant. Because the interaction Condition  $\times$  ISI  $\times$  Repetitions,  $F(1, 23) = 5.5$ ,  $p < 0.05$  was also significant, we report the comparisons between the two conditions separately for the different ISIs ([Figure 3](#), panel B). Pairwise comparisons ( $t$ -tests) indicated that, on switch trials, the difference between blocked and random conditions was not significant ( $p > 0.05$ ) at the lowest ISI, whereas it was significant ( $p < 0.05$ ) at the highest ISI. As for repeated trials, target color predictability had a significant effect both at the lowest ( $p < 0.001$ ) and highest ( $p < 0.05$ ) ISI. In addition, the interaction Condition  $\times$  Repetition was significant at the lowest ( $p < 0.05$ ) but not at the highest ( $p > 0.05$ ) ISI. The apparent lack of agreement about top-down modulation on switch trials between the results at the two ISIs was further addressed in a subsequent series of analyses.

As in [Experiment 1](#), we analyzed performance as a function of the number of repetitions within the “Random” condition. The data were subjected to a two-way repeated-measures ANOVA. The factors ISI,  $F(1, 23) = 170.8$ ,  $p < 0.001$ , and Repetitions,  $F(3, 69) = 6.75$ ,  $p < 0.001$  were significant, but their interaction was not. As shown in [Figure 3](#) (panel C) the pattern of results resembled the inverted U-shaped function observed in [Experiment 1](#) ([Figure 2](#), panel B). Pairwise comparisons ( $t$ -tests) confirmed the initial increase in visibility from runs of 1 to runs of 2 ( $p < 0.001$ ) and from runs of 2 to runs of 3 ( $p < 0.05$ ). The total gain in accuracy relative to the switch condition was approximately 10%. Crucially, the decrement in performance observed in [Experiment 1](#) for runs of 4, compared to runs of 3, was confirmed in the present experiment, where it reached statistical significance ( $p < 0.05$ ). In addition, as in [Experiment 1](#), a planned contrast analysis revealed a significant ( $p < 0.001$ ) quadratic trend for the factor Repetition. Together with the overall advantage observed in the “Blocked 2” condition, this result suggests that both PoP and top-down expectations are crucial in modulating target visibility. In our view, the decrement in performance after a run of 3 (observed in the random conditions of [Experiments 1 and 2](#)) is likely due to top-down factors. A

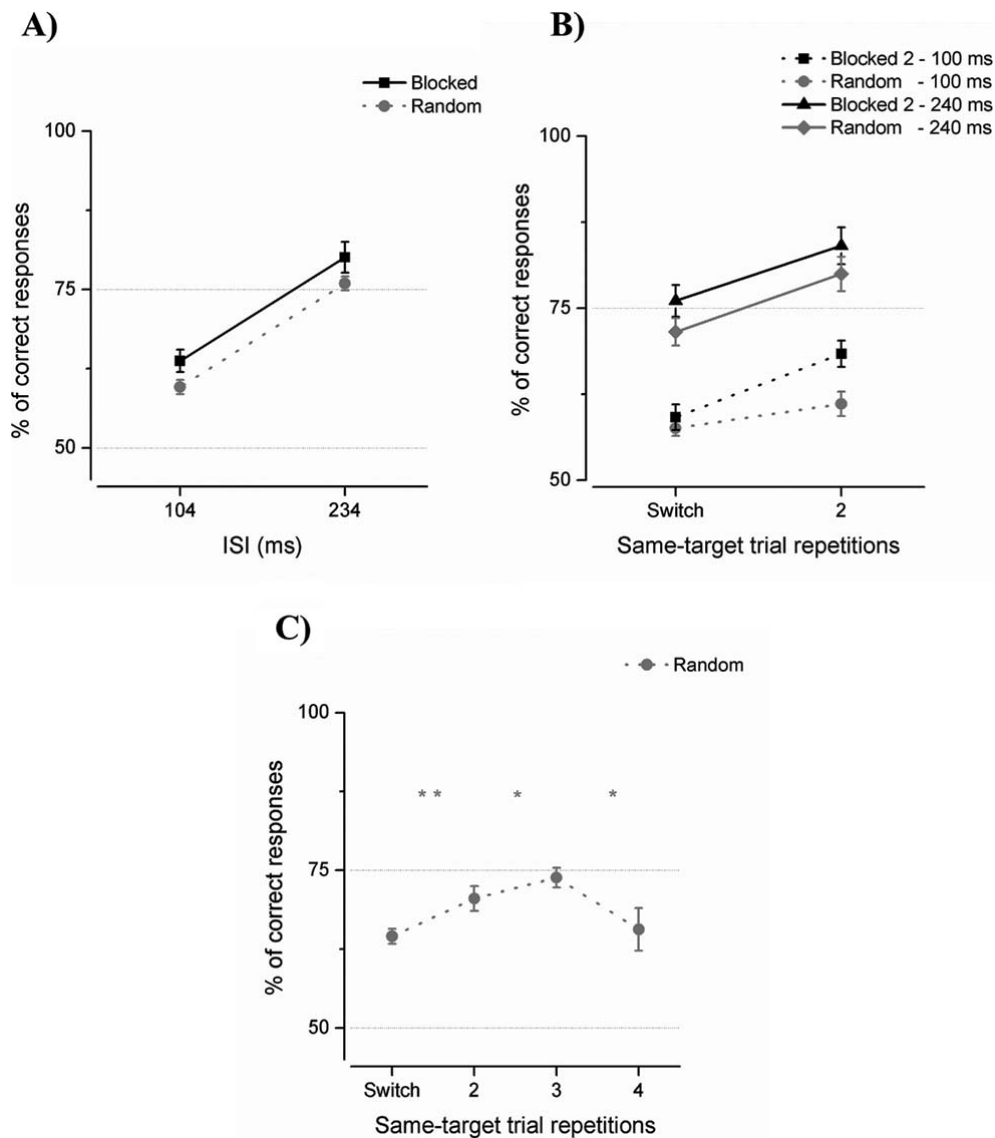


Figure 3. Results from [Experiment 2](#). Panel A: Overall accuracy in the “Blocked 2” and “Random” conditions as a function of ISI. For both ISIs, participants were more accurate in the “Blocked 2” condition compared to the “Random” condition. Panel B: Accuracy plotted as a function of runs of 2 in the “Blocked 2” and “Random” conditions. Panel C: Accuracy in the “Random” condition plotted as a function of the number of repetitions (ISIs are collapsed). Target visibility increased from runs of 1 to 3, whereas a drop in visibility emerged for runs of 4 compared to runs of 3.

possible candidate is predictability or expectation about the upcoming target color that relies on an internal model of a random sequence (Croson & Sundali, 2005; Tversky & Kahneman, 1974).

Following this hypothesis, we further investigated whether the mechanism of implicit expectation can affect target visibility during feature search. To this aim, the accuracy of switch trials was analyzed as a function of the distance between two switches, thus taking into account the number of same-color repetitions that occurred before each switch. If top-down implicit expectation directly affects feature search, target visibility should be better when a switch interrupts a sequence of repetitions longer than 3 (see

above). Yet, a two-way repeated-measures ANOVA, with the factors ISI and Distance, showed that on switch trials, the number of repetitions before a switch had no effect on accuracy,  $F(3, 69) = 2.9, p > 0.05$  (the same analysis was carried out for the “Random” condition in [Experiment 1](#), leading to similar results,  $F(3, 63) = 2.6, p > 0.05$ ; here, two participants were removed from the analysis because they did not have enough data points in some cells of the design).

The results from the analysis of distance, as well as from the comparisons between the “Blocked 2” and “Random” conditions, suggest that top-down information does not impact target visibility in feature search when priming is excluded and only switch trials are



considered. However, there seems to be a robust interaction between PoP and top-down knowledge.

The next experiment was aimed at clarifying how top-down factors and PoP interact in modulating target visibility during pop-out search.

## Experiment 3

In [Experiments 1](#) and [2](#), we provided evidence that PoP is permeable to top-down processes and that previous knowledge or expectation about the target color can explain, at least partially, the difference in accuracy between blocked and random conditions. [Experiment 1](#) allowed only for an overall comparison between blocked and random conditions. In [Experiment 2](#), this comparison was restricted to switch trials and runs of 2. The aim of [Experiment 3](#) was to confirm and extend the results of the previous experiments by studying how top-down factors and PoP interact in runs longer than 2 and by addressing the time-course of priming saturation in the blocked condition. To this aim, we compared the “Random” condition and the “Blocked 5” condition (i.e., red, red, red, red, red, green, green, green, green, green, etc.).

## Methods

### Participants

Twenty-four students (18 females; mean age =  $21.8 \pm 1.8$ ) from the University of Trento, Italy, participated in this experiment for monetary payment (7€) or course credits. All participants had normal or corrected-to-normal vision and were naïve as to the purpose of the experiment. Informed consent was obtained from all participants, and the experiment was carried out in accordance with the Declaration of Helsinki.

### Apparatus and stimuli

The apparatus and stimuli were the same as in [Experiment 1](#).

### Procedure

The procedure was the same as in [Experiment 2](#) with the exception that we used a “Blocked 5” condition instead of a “Blocked 2” condition. To achieve a sufficient number of runs of 5 in the random condition, we created a random sequence that was used for all participants. As in [Experiment 2](#), the randomness of the chosen sequence was tested with a battery of four tests (Runs test, Frequency test, Monobit test, Approximate entropy test) from the suite of NIST

(Rukhin et al., 2001). As in [Experiment 2](#), we also checked the probabilistic independence of the selected sequence.

## Design

A  $2 \times 2$  factorial design was used with Condition (blocked 5 vs. random) and ISI (104,234 ms) as factors. The experiment consisted of four experimental blocks (two per condition, with 250 trials per block) preceded by 20 practice trials not included in the analyses.

## Results and discussion

The data (percentage of correct responses) were entered into a two-way repeated-measures ANOVA. The factors Condition,  $F(1, 23) = 40.8$ ,  $p < 0.001$ , and ISI,  $F(1, 23) = 241.9$ ,  $p < 0.001$  were significant, but their interaction was not. In accordance with the previous experiments, the overall accuracy level ([Figure 4](#), panel A) was higher in the “Blocked 5” condition ( $M = 74\%$ ;  $SD = 7\%$ ) than in the “Random” condition ( $M = 65\%$ ;  $SD = 7\%$ ) at both ISIs. To analyze the effect of repetitions between the two conditions, accuracy from the switch to the fifth repetition of the same color was entered into a  $2 \times 2 \times 5$  repeated-measures ANOVA with the factors Condition, ISI and Repetitions. The factors Condition,  $F(1, 23) = 22.65$ ,  $p < 0.001$ , ISI,  $F(1, 23) = 197.7$ ,  $p < 0.001$ , and Repetitions,  $F(4, 92) = 25.9$ ,  $p < 0.001$ , were all significant. The interactions Condition  $\times$  Repetitions,  $F(4, 92) = 3.23$ ,  $p < 0.05$ , and ISI  $\times$  Repetitions,  $F(4, 92) = 3.73$ ,  $p < 0.05$ , were also significant. In particular, the Condition  $\times$  Repetitions interaction indicated that the number of repetitions had a different impact on accuracy as a function of whether the color of the target changed randomly or remained fixed for five consecutive trials.

As shown in [Figure 4](#) (panel B), in the “Random” condition, we replicated the inverted U-shaped pattern previously observed, which was confirmed by the significant difference ( $t$  test) between runs of 1 (switch) and 2 ( $p < 0.001$ ) and between runs of 2 and 3 ( $p < 0.001$ ); the difference between runs of 3 and 4 was very close to significance ( $p = 0.06$ ), while there was no significant difference between runs of 4 and 5 ( $p > 0.05$ ). However, as in previous experiments, a planned contrast analysis revealed a significant ( $p < 0.001$ ) quadratic trend for the factor Repetition, which substantiated the inverted U-shaped pattern. Most importantly, the accuracy pattern that emerged in the “Blocked 5” condition differed from that obtained in the “Random” condition. Here, accuracy had already reached its maximum for runs of 2 and then remained stable overall, with no signs of decrement, up to runs of 5 (panel C).



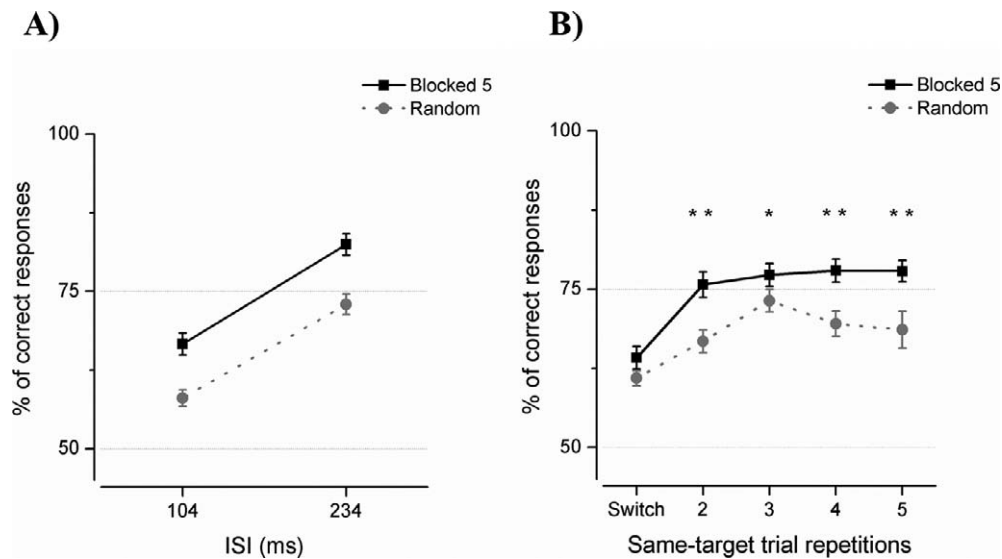


Figure 4. Results from Experiment 3. Panel A: Overall accuracy in the “Blocked 5” and “Random” conditions as a function of ISI. For both ISIs, participants were more accurate in the “Blocked 5” condition compared to the “Random” condition. Panel B: Accuracy plotted as a function of runs of 5 in the “Blocked 5” and “Random” conditions. In the “Random” Condition, target visibility increased from runs of 1 to 3, whereas a drop in visibility emerged for runs of 4 and 5 compared to runs of 3. The inverted U-shaped function in the “Random” condition was substantiated by a significant ( $p < 0.001$ ) quadratic trend for the factor Repetition.

The difference between the accuracy functions in the “Random” and “Blocked 5” conditions was significant for runs of 2 ( $p < 0.001$ ), 3 ( $p < 0.05$ ), 4 ( $p < 0.001$ ), and 5 ( $p < 0.001$ ), whereas there was no significant difference on the switch trials ( $p > 0.05$ ). The results from the comparisons between the “Blocked 5” and the “Random” conditions are not compatible with the idea that, in the random condition, the decrement in performance observed for runs longer than 3 is due to a deterioration of the priming mechanism. If this were the case, then the same decrement should have also emerged in the “Blocked 5” condition.

Alternatively, we propose that in the “Random” condition after a run of 3 participants began to expect a change in the target color and prepared for a switch trial. By contrast, in the “Blocked 5” condition, the complete certainty about the upcoming target color allowed participants to actively maintain the same attentional set, which was reconfigured only after the fifth repetition. As for the ascending part of the curve (from the switch trial to runs of 3), the pattern from the “Random” condition suggests that the accumulation of priming gradually increases target visibility, a result that parallels the cumulative trend of priming described by previous studies (Maljkovic & Nakayama, 1994; Sigurdardottir et al., 2008). However, as emerged from the “Blocked 5” condition, because participants could predict the target color with no uncertainty, top-down influences due to expectation boosted visibility to its maximum in a single trial after the switch.

In addition, as in previous experiments, we performed the analysis of distance between two switches in

the “Random” condition. The results were consistent with those obtained in Experiments 1 and 2. Accuracy on the switch trials did not depend on the number of repetitions before the switch,  $F(3, 69) = 1.7, p > 0.05$ . This result is in agreement with the fact that, on switch trials, performance did not differ between the “Blocked 5” and “Random” conditions, as reported above in the analysis of repetitions.

To summarize, two conclusions can be drawn from the present experiment. First, PoP and top-down factors interact in singleton search (Leonard & Egeth, 2008). Second, the visibility of the target, in the absence of priming (switch trials), does not seem to be modulated by top-down knowledge (also see Moore & Egeth, 1998).

## General discussion

PoP is a form of perceptual priming that affects the deployment of attention (Nakayama et al., 2004). In particular, the PoP phenomenon shows that the visual system tends to give processing priority to the items that have been selected in the recent past. It is therefore important to address whether and how the memory mechanism underlying PoP interacts with other information in the cognitive system to modulate target visibility.

From this perspective, our study represents the first attempt to jointly explore the effects of top-down knowledge and PoP in a singleton-search task in which

target visibility was manipulated by means of meta-contrast masking. The main results can be summarized as follows. First, we demonstrated that PoP and top-down information (feature-based knowledge or expectation) interact to affect target visibility. Hence, contrary to the view that PoP is impermeable to top-down factors (e.g., Maljkovic & Nakayama, 1994), we provided evidence that PoP can indeed be modulated, directly or indirectly, by implicit and explicit expectations (also see Kristjánsson, Sigurjonsdottir, & Driver, 2010). Second, we showed that, on switch trials, there seemed to be a lack of top-down attentional control in feature search.

In [Experiment 1](#), we demonstrated that the visibility of a pop-out target was higher when its defining feature was blocked rather than randomly switched. [Experiment 2](#) showed that if blocked and random trials were made comparable in terms of switches, accuracy remained higher when the feature defining the target was predictable rather than unpredictable. This novel manipulation allowed us to conclude that the mere effect of repetitions cannot entirely account for the advantage of the blocked condition. In [Experiment 3](#), we confirmed that two top-down factors can affect singleton search. One mechanism, which is due to explicit knowledge of the upcoming target color, modulates the visibility of the target during the first repetitions in a run. The second implicit mechanism, which operates for repetitions larger than 3, generates expectations on the basis of an internal model of randomness. This expectation counteracts the beneficial effects of priming by preparing the observer for a switch in the target feature, thus reducing target visibility.

Furthermore, in all three experiments, we found that accuracy on the switch trials did not differ between the blocked and random conditions. In other words, knowing the color of the upcoming target in advance did not lead to any advantage in target discrimination. This finding can be ascribed to an unavoidable cost in performance due to the reconfiguration of the current attentional set, which would mainly be under bottom-up control (e.g., Rogers & Monsell, 1995). Hence, if only the results on switch trials are considered, they seem to support the conclusion of Moore and Egeth (1998), according to whom feature-based knowledge cannot enhance target visibility (also see Carrasco, 2011, for a review on the effects of feature-based attention). These results are also in agreement with the general claim that, in feature search, there is no top-down control (e.g., Theeuwes et al., 2006).

A different scenario emerges when the trials in which the color of the target was repeated are considered. We found an interaction between top-down expectations and PoP that is consistent with what has been reported by Leonard and Egeth (2008). Interestingly, the analysis of target visibility for consecutive repetitions

in the random condition showed an inverted U-shaped function; visibility increased up to runs of 3 and then decreased from runs of 3 to 5. The pattern was completely different when the same number of repetitions occurred in the blocked condition. Taken together, these results suggest that different mechanisms are involved and interact in a singleton-search task like the one used here.

A memory system accumulates information when the same target-singleton feature is repeated over consecutive trials. As a result, the singleton feature representation is enhanced, and priming is observed. In other words, repetition per se leads to priming, here PoP. The effect of priming is evident in the ascending part of the inverted U-shaped function. It is reasonable to assume that, if no top-down factors were involved, the beneficial effect of PoP would follow an asymptotic function, with target visibility reaching the maximum in 3 repetitions and then remaining stable for longer runs. However, such patterns can be modulated by top-down knowledge in two ways. Explicit expectations about the upcoming target color can boost visibility to its maximum on the trial that immediately follows a switch. Implicit expectations of a switch, instead, can reduce target visibility after a run of 3 (or longer). This implicit expectation would be due to a systematic bias of the cognitive system in representing a random series of binary events.

As demonstrated by Kahneman and Tversky (1972), people's perception of randomness departs systematically from the rational laws of chance. When repeatedly flipping a fair coin, a long sequence is generated so that, by virtue of the law of large numbers, the proportions of heads and tails will tend to be 50%. However, people's intuitions about randomness are biased by the so-called "law of small numbers" (Tversky & Kahneman, 1971), whereby the probability distribution in short sequences closely resembles the global distribution. The belief that local and global sequences should share the same essential characteristics (the "local representativeness" heuristic discussed by Tversky & Kahneman, 1974) leads to some decisional biases, such as the "gambler's fallacy." As observed by Croson and Sundali (2005), most casino gamblers believe that, in roulette, the probability of the ball landing in a red space increases as the length of a series of black outcomes increases. Of course, this belief is irrational if the roulette wheel is unbiased; on every trial, red and black are equally probable outcomes because each roulette spin represents an independent event. More recently, however, some authors have noted that the conditional independence of events can be assumed only in few situations in everyday life. When outcomes are sampled without replacement from a finite population, the conditional independence cannot be assumed, and the gambler's fallacy becomes a rational bias (Rabin, 2002). Under these circumstances,

the occurrence of a particular outcome correctly lowers the probability that the same outcome will occur the next time. According to Hahn and Warren (2009), the gambler's fallacy reflects "the subjective experience of a finite data stream for an agent with a limited short-term memory capacity" (p. 454).

In the present study, each trial in the random conditions is to be considered an independent event. In a random binary sequence, it would be reasonable to expect that runs of 5 are less frequent than runs of 4, which, in turn, are less frequent than runs of 3, and so on. However, although such a priory expectation is correct, the probability of obtaining one of the two outcomes (here, "red" vs. "green") on any given trial of the sequence remains equal to .5. By contrast, expecting one outcome to be more likely than the other corresponds exactly to the gambler's fallacy.

When the number of same target color repetitions is sufficiently large to produce a strong fallacious expectation of a switch, the beneficial effect of PoP is attenuated. The inverted U-shaped function might seem to be in contrast with the cumulative effect of PoP on visual sensitivity reported by Sigurdardottir et al. (2008). However, the two different results can be easily reconciled by considering that Sigurdardottir et al. manipulated the probability of repeating the color of the target in pseudo-random sequences of trials so that repetitions (~80%) were more likely than switches. This may have led their participants to maintain a high level of expectation for same-color repetitions.

Apparently, providing evidence that feature-based knowledge does not improve target visibility on switch trials may seem to be in contradiction with the fact that expectation modulates target visibility when the same target color is repeated. However, the two findings can be reconciled if one hypothesizes that expectation can become effective in modulating target visibility only once the system has been reconfigured or set on the new target feature, a process that is largely under exogenous control and determined by the stimuli (Rogers & Monsell, 1995).

Different views of the nature of the PoP have been proposed (see Kristjánsson & Campana, 2010 for a detailed review). One view, which dates back to the original studies of Maljkovic and Nakayama (1994, 1996), ascribes PoP to a passive form of memory. The authors clearly stated "...once the memory is established, it facilitates consecutive same-color trials in a passive way – observers' knowledge or an attempt to apply it have no effect" (Maljkovic & Nakayama, 1994, p. 669). This view is consistent with the idea that priming is an automatic bottom-up process impermeable to top-down knowledge (e.g., Posner, 1978; Theeuwes et al., 2006) and emphasizes the fact that PoP itself is impermeable to top-down factors (Maljkovic & Nakayama, 2000). A completely different view

holds that PoP is top-down in nature because it emerges as the result of a learning process and is not solely determined by intrinsic stimulus properties (Wolfe, Butcher, Lee, & Hyle, 2003). A third (intermediate) view considers PoP to be an automatic bottom-up process that depends on or is affected by the observer's goals (Fecteau, 2007) and expectations (Leonard & Egeth, 2008). Although our results do not allow us to clarify the nature of PoP, we tend to favor the automatic bottom-up view. In any case, the results show that target visibility can be affected by both PoP and explicit or implicit top-down expectations. These results challenge the notion that PoP is the only factor involved in singleton search and that its effect cannot be influenced by prior knowledge (e.g., Maljkovic & Nakayama, 2000). Notably, our results do not explain how and where the interaction between expectation and PoP takes place. One possibility is that VSTM is directly affected by top-down information; another possibility is that VSTM is not permeable to top-down factors, and the interaction occurs at a later stage. However, the claim that PoP and expectations interact remains valid, regardless of the nature of PoP (also see Brascamp, Blake, & Kristjánsson, 2011, for a different interpretation of PoP) and the locus of the interaction.

## Open issues

We explained the decrement in target visibility that was observed for runs longer than 3 in the random condition by arguing that, on each trial, the cognitive system was trying to anticipate the color of the next target. This implicit form of expectation would rely both on recent past events and on an internal model of randomness for a series of binary events. The cognitive system would implicitly assume that, when the same target color is excessively repeated, a color change is the most likely event to expect on the next trial. Consequently, the cognitive system would start configuring the attentional set for a change, an expectation that counteracts the beneficial cumulative effect of PoP. Based on these premises, one might be tempted to predict that, on switch trials, performance should be better after runs of 4 than after runs of 2. Yet, the analysis of distance between switches conducted in all three experiments clearly showed that this was not the case. In other words, the pattern of results seems to indicate that, although top-down (implicit) expectation can partially overcome the priming effect, the same information appears unusable to prepare the appropriate attentional set on switch trials. This, in turn, suggests that top-down knowledge interacts differentially with the mechanisms governing priming and feature-based attentional set, an issue that future studies should address in more detail.



The second issue that deserves further investigation is the accuracy pattern (the inverted U-shaped function) observed in the random condition. We believe that this effect might be very important for shedding light on the PoP phenomenon and on its interactions with top-down factors, either implicit or explicit. However, one puzzling aspect is that this result was never reported before by previous studies on PoP.

Different causes may have prevented the occurrence of the inverted U-shaped function in previous studies evaluating the effect of PoP on target visibility. In the study of Sigurdardottir et al. (2008), participants were never presented with a random sequence of events. While Huang and Pashler (2005) used random sequences and analyzed target visibility as a function of repetitions (up to four), the accuracy function was basically flat. However, as shown by Yashar and Lamy (2010), the task adopted by Huang and Pashler (2005) could be performed with distributed attention, a condition that is less than ideal to observe any effect of priming. In their study, Yashar and Lamy (2010) used random sequences but their analysis of the data considered only a maximum of two repetitions.

In a recent study, Leonard and Egeth (2008) used random sequences and analyzed the number of repetitions for lengths of 2 and 3 and combined longer runs into a single condition (4+). However, their findings showed that RTs monotonically decreased as run length increased, with no signs of a decrement in performance (here longer RTs) at the longest runs (4+). Motivated by the discrepancy between the functions obtained with accuracy and RTs, we also conducted a pilot experiment with our stimuli and paradigm with the alterations that the target was not masked, and we recorded the speed of responses. Under these conditions, we also failed to find a U-shaped function mirroring the inverted one that emerged with accuracy in all the present experiments. We do not have a reasonable explanation to reconcile the different findings when accuracy and RTs are used. This is certainly an issue worthy of future investigation; however, this investigation is beyond the scope of the present study.

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