



## Priming of pop-out on multiple time scales during visual search

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### ABSTRACT

When target-color repeats in pop-out visual search performance is faster than otherwise. While various characteristics of such priming of pop-out (PoP) are well known, relatively little is known about the temporal character of the memory traces underlying the effect. Recent findings on the perception of ambiguous stimuli show that the percept at any given moment is affected by perception over a long period, as well as by immediately preceding percepts. Intrigued by the existence of various parallels between this perceptual priming phenomenon and PoP, we here investigate whether similar multiplicity in timescales is seen for PoP. We contrasted long-term PoP build-up of a particular target color against shorter-term build-up for a different color. The priming effects from the two colors indeed reflect memory traces at different timescales: long-term priming build-up results in a more gradual decay than brief buildup, which is followed by faster decay. This is clearly demonstrated in Experiment 2 where sustained repetition of one target color is followed by a few repetitions of a second color. Following such a sequence, priming is initially stronger for the second target color, which was primed most recently; however, as more time passes longer-term priming starts to dominate, resulting in better search performance for the first color later on. Our results suggest that priming effects in visual search contain both transient and more sustained components. Similarities between the time courses of attentional priming and perception of ambiguous stimuli are striking and suggest compelling avenues of further research into the relation between the two effects.

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### 1. Introduction

A surprisingly large part of attentional orienting is determined by attentional prioritization from previous trials. A good example is that if the same target repeats in pop-out visual search, responses are faster and more accurate than when the target identity changes (Maljkovic & Nakayama, 1994; Sigurdardottir, Kristjánsson, & Driver, 2008; see Kristjánsson, 2008, for review). This effect, termed “priming of pop-out (PoP)”, has been thought to reflect the operation of a low-level short-term memory system for attentional deployments (Kristjánsson, 2006; Nakayama, Maljkovic, & Kristjánsson, 2004), and has been shown to strongly determine (Brascamp, Blake, & Kristjánsson, 2011) and depend upon (Goolsby & Suzuki, 2001) trial-by-trial attentional selection. This memory system thus takes into account statistics of the recent input, and may use this information to predict future occurrences. Kristjánsson, Wang, and Nakayama (2002) argued that such effects of past history can even account for postulated effects of top-down guidance, which play a major role in theories of visual attention (Duncan & Humphreys, 1989; Treisman & Gormican, 1988; Wolfe, 1994).

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The importance of such history effects for determining attentional orienting makes it all the more important to understand their characteristics. While a lot is known about the various circumstances determining PoP (Ásgeirsson & Kristjánsson, 2011; Becker, 2008; Geyer, Müller, & Krummenacher, 2006; Lamy, Yashar, & Ruderman, 2010; Olivers & Meeter, 2006) and its neural signatures (Campana, Cowey, & Walsh, 2002, 2006; Kristjánsson, Vuilleumier, Schwartz, Macaluso, & Driver, 2007; Saevarsson, Jóelsdóttir, Hjaltason, & Kristjánsson, 2008) much less is known about the temporal characteristics of this repetition benefit.

Studies of priming have traditionally focused on the effects of the most recent trial or a few trials in the past. For instance, Maljkovic and Nakayama (1994) showed that trials as far back as 5 or 6 trials in the past influence current attentional orienting. More recent studies have started to address the time course of build-up and decay of these priming effects in more detail (Maljkovic & Martini, 2005; Martini, 2010).

Useful information about the statistics of the visual world can be inferred from what just happened, as well as from what happened in a more distant past. Our question revolves around whether the memory system for attentional deployments can take advantage of information on both such shorter and longer timescales. How, in other words, does the visual attention system

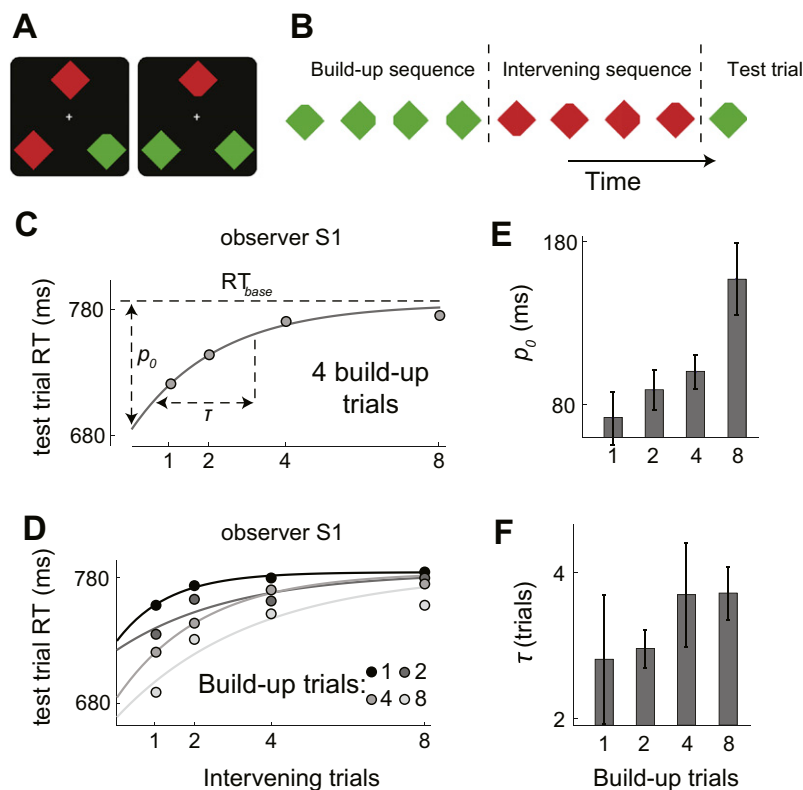
respond when faced with repetition patterns that have both a local, short term structure and regularities across a longer timescale? Does it simply focus on the most recent events or take into account a more elaborate representation of past trials over a longer time period? If the latter is true, then how do long-term information and short-term information combine and interact?

This study was partly inspired by recent work on bistable perception of rivalrous displays. Perception of such displays depends in part on priming traces laid down when the same display was viewed in the past, causing a tendency for the same percept to repeat (Leopold, Wilke, Maier, & Logothetis, 2002; reviewed by Pearson and Brascamp (2008)). One way to put it is that perceiving a rivalrous display in a particular manner leaves a tendency to again perceive the display in the same manner upon subsequent viewing. Brascamp et al. (2008) pointed out the conceptual analogy between this and priming in visual search, noting: “[in priming in visual search] every allocation of attention or gaze to an item simultaneously acts to stimulate reorientation to that item in the future. This is analogous to the accumulating bias that facilitates repeated perceptual dominance [in ambiguous perception]”. More parallels between the two phenomena, such as their implicit nature and their ability to accumulate, have been summarized elsewhere (Brascamp et al., in press; see also Discussion). Recent studies show that ‘perceptual memory’ for ambiguous displays involves multiple mnemonic traces operating at different time scales (Brascamp, Pearson, Blake, & van den Berg, 2009; Brascamp et al., 2008; Pastukhov & Braun, 2008). One concomitant aspect of the present study into the time course of attention repetition priming

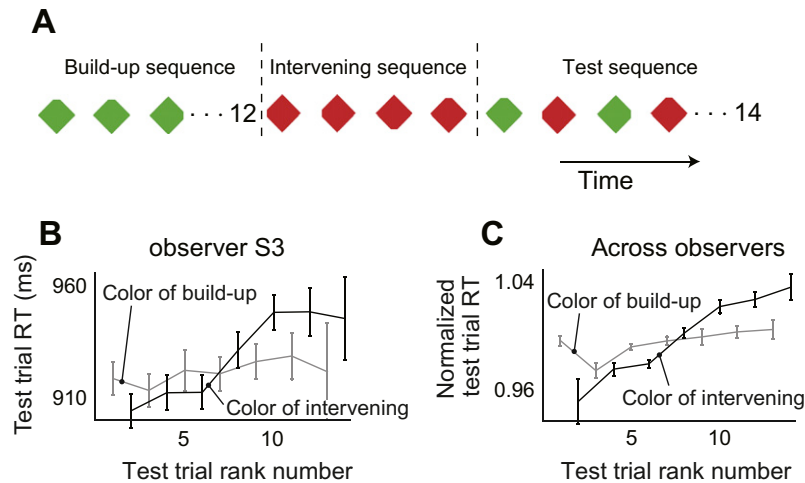
is that it allows us to see how far the analogy between the two phenomena goes.

## 2. Overview of experiments

We used the classic PoP paradigm of Maljkovic and Nakayama (1994; originally introduced by Bravo and Nakayama (1992)), where observers search for an odd-colored diamond among distractor diamonds of another color (Fig. 1A). When target color repeats responses are faster compared to when target and distractors switch colors across trials (Maljkovic & Nakayama, 1994; reviewed by Kristjánsson (2008)). On a given trial this effect does not rely solely on the target color on the immediately preceding trial, but instead on accumulated effects from a longer preceding sequence. In two experiments we compare the RT effects built up across many consecutive trials that share the same target color with the effects induced by only a few color repetitions. According to our reasoning the former trial sequence conveys a long-term regularity that the visual system might pick up on, whereas the latter reflects a short-term pattern that may not play a role in determining performance in a farther future. Accordingly, we hypothesize that PoP effects that have built up across many repetitions of the same target color will also persist longer once target color changes, compared to PoP effects that have only developed across a few target color repetitions. Given PoP’s cumulative nature more repetitions of the same color will clearly lead to larger RT effects. But will these RT effects also persist longer?



**Fig. 1.** Experiment 1. (A). Schematic depiction of our stimulus. On each trial the observer views three diamonds, and identifies the notch position of the odd-colored item. (B). Trial sequence. Observers viewed a *build-up sequence* with trials of a given target color, during which priming accumulated for that color. This was followed by an *intervening sequence* during which the target had the opposite color, allowing the initially accumulated priming to decay. Finally, we presented a *test trial* during which the target again had the initial target color, allowing us to measure how much of the initially accumulated priming remained. (C). RT values on the test trial (y-axis) for one example observer, following a 4-trial build-up sequence and decay sequences of variable length (x-axis). The curve is an exponential decay function fitted to these RT data, whose parameters (see Methods) are illustrated in this plot. (D). Same as C, but now showing data for all four possible build-up sequence lengths. (E). Cross-observer averages of the initial priming strength (RT reduction  $\rho_0$ ) following various build-up sequence lengths. (F). Cross-observer averages of the time constant of priming decay ( $\tau$ ) following various build-up sequence lengths. Error bars indicate standard errors of the sample mean. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



**Fig. 2.** Experiment 2. (A) Trial sequence. *Build-up sequences* of 12 trials of a given target color were followed by an *intervening sequence* of four trials of the opposite target color. This was then followed by a *test sequence* during which target color alternated from trial to trial, providing a neutral background (i.e. not specifically favoring either target color) for us to “read out” the progression of the priming traces laid down during the build-up sequence and the intervening sequence. (B) RTs on test trials for one representative observer. Although the trials that share the intervening sequence’ target color yield faster RTs initially (black curve) the trials that share the build-up sequence’ color are faster after some time has passed (gray curve). (C) Normalized RTs on test trials averaged across all our observers. The data pattern is the same as in B. In other words, the priming laid down during our combination of build-up sequence and intervening sequence initially favors the target color of the intervening sequence, but then spontaneously reverts to favoring the color of the build-up sequence. Error bars indicate standard errors of the sample mean. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

To state this more concretely, we can determine the magnitude of the PoP effect caused by a “*build-up sequence*” of e.g. four red-target trials by measuring RT on a subsequent “*test trial*” with another red target. Then, we can determine the persistence of this accumulated PoP effect by measuring how much of it remains when we insert, between this build-up sequence and a test trial, an “*intervening sequence*” of trials with a green target, and then systematically vary the length of this intervening sequence (Fig. 1B). When we do this in our Experiment 1, we find evidence that the RT effect of a longer build-up sequence is not only larger than that of a shorter build-up sequence, but that it also decays more gradually, consistent with the idea that patterns learned across longer periods of time are also retained for longer by the memory system. Then, in Experiment 2 we demonstrate a remarkable consequence of this difference in time scale. Here a long build-up sequence with, say, red targets and a brief intervening sequence with, say, green, targets are followed by a neutral “*test sequence*” where target color alternates from trial to trial (Fig. 2A). Here we find that, while RTs for green targets are faster than those for red targets early in the test sequence, later on in the test sequence this pattern spontaneously reverses. This indicates that relatively short-term priming due to the intervening sequence strongly influenced RTs initially, but that more persistent priming effects that had accumulated during the build-up sequence had a larger effect upon attention allocation nearing the end of the test sequence, many trials after these priming effects had been induced.

### 3. Experiment 1

The aim of the first experiment was to investigate whether longer “*build-up*” sequences of same-color trials would cause more persistent priming effects than shorter sequences. For a given length of a build-up sequence (e.g. four trials) we measure priming in terms of RT on a subsequent test trial that has the same target color as the build-up sequence. We then measure the persistence of this priming by inserting an “*intervening sequence*” between the build-up sequence and the test trial. The intervening sequence had the opposite target color and had variable length (Fig. 1B).

#### 3.1. Methods

**Observers:** Nine observers participated; 3 in 10,000 trials each, and 6 in 6000 trials, in blocks of 100 trials. All had normal, or corrected to normal, vision. Testing was spread out over a number of days according to each observer’s convenience. All experiments were approved by the local ethics committee.

**Equipment:** The experimental display was programmed in C using 8-bit graphics mode and presented on a 75-Hz CRT display controlled by a 400-MHz G4 Apple computer.

**Stimuli and procedure:** Each trial started with the presentation of a white (56.6-cd/m<sup>2</sup>) fixation cross for 1200–1700 ms (randomly determined for each trial) on a dark background (0.5 cd/m<sup>2</sup>) followed by a search display containing three diamond shapes (each sized 2.4° by 2.4°, at 4.05° from screen center; see panel A of Fig. 1) on the same dark background. Observers searched for the oddly colored diamond, either a red (12.8 cd/m<sup>2</sup>) target among two green distractors (13.3 cd/m<sup>2</sup>) or vice versa. Observers judged (by pressing the appropriate key) whether the singleton diamond had a notch at the top or the bottom (as in Kiss, Driver, & Eimer, 2009; Kristjánsson, Sigurjónsdóttir, & Driver, 2010).

#### 3.2. Procedure

Our observers participated in a large number of trials where sequences of red-target trials alternated with sequences of green-target trials. This design provided us with build-up sequences (e.g. a given red-target sequence), intervening sequences (e.g. the subsequent green-target sequence) and test trials (e.g. the first trial of the following red-target sequence). However, note that by design any given sequence served all three roles simultaneously, relative to the sequences that preceded and followed it. The length of the trial sequences varied unpredictably throughout a session. We were interested in sequence lengths of 1, 2, 4 and 8 trials, and therefore ensured that these were most common, each making up 20% of all sequences. To increase the unpredictability of our trial order we also included, with lower frequency, other trial lengths of up to nine trials. We asked our observers following participation whether they had noticed any patterns in the presentation order

and none had any idea of the true presentation order. Moreover, although our trial sequence was not fully random, note that priming of pop-out is unaffected by conscious effort, and observers cannot willingly overcome the priming effect even when they know that it is detrimental to performance (Kristjánsson, Mackeben, & Nakayama, 2001; Maljkovic & Nakayama, 1994).

Note that, while we characterize the intervening sequence as a period during which accumulated priming of one target color decays, it is also true that the intervening sequence causes priming of the alternative target color (indeed, our conceptualization of Experiment 2 focuses more on that aspect). Our rationale does not depend on how one conceptualizes the intervening sequence, however, since an observed relation between build-up duration and the time scale of subsequent RT changes would point to multiple time scales of priming in either case. For the sake of simplicity we therefore conceptualize the intervening sequence as one during which accumulated priming decays.

As a second note of caution, we will consistently refer to each kind of trial as having a particular target color. In reality any target color repetition in our experiment is tied to a repetition of distractor color as well. It is known that both target repetition and distractor repetition contribute to the PoP effect (Geyer, Zehetleitner, & Müller, 2010; Kristjánsson & Driver, 2008; Lamy, Antebi, Aviani, & Carmel, 2008; Wang, Kristjánsson, & Nakayama, 2005) so our observations likely reflect effects of both combined. While we are aware of this, we will designate trial types by their target color for simplicity.

**Analysis:** If the PoP effect operates on only a single time scale this means that its decay conforms to a simple exponential process. This is because an exponentially decaying signal will, by definition, decay by the same proportion across a time interval of a given duration, regardless of where one places this time interval along the decay curve. Indeed, the decay of the PoP effect has been modeled in this way in the past (Maljkovic & Martini, 2005). In the case of such exponential decay, changes in RT can be characterized by two variables. One is the baseline RT, or the limit toward which the RT recovers as priming is allowed to decay fully, and the other is the time constant that determines how fast this recovery takes place (Fig. 1C). It is this latter variable that is of interest to us. That is, if the length of the build-up sequence has no influence on the persistence of priming, then the same two values for these variables should describe priming decay well for build-up sequences of any length. If, on the other hand, persistence changes with the length of priming build-up, then the value of the time constant should systematically increase as the build-up sequence gets longer, even though baseline RT remains the same.

For each build-up sequence length (1, 2, 4 or 8) we determined RT on test trials following 1, 2, 4 or 8 intervening trials. We then fit an exponential decay function to these four data points, given by

$$RT(i) = RT_{base} - p_0 \cdot \exp(-i/\tau)$$

This describes the RT following a given number of intervening trials  $i$ ,  $RT(i)$ , as a function of the baseline RT ( $RT_{base}$ ), the amount of RT reduction, or priming, after zero intervening trials ( $p_0$ ) and the time constant of priming decay ( $\tau$ : the time it takes for priming to decay by a constant factor  $e$ ). These variables are illustrated in Fig. 1C, which plots  $RT(i)$  against the number of intervening trials  $i$ . For each observer, we fixed  $RT_{base}$  at the RT value observed following one buildup trial and eight intervening trials, as RTs would be close to maximal in that situation. We then fit  $p_0$  and  $\tau$  separately for each build-up sequence length. The critical question was whether the fit value of  $\tau$  was the same for each build-up sequence length, or whether there was a systematic interaction. Incidentally, we clearly also expect the accumulated RT benefit,  $p_0$ , to change with build-up length, and we verify whether this expectation is met.

Although the fitting procedure proved robust for most of the curves, a small number of the fitted  $\tau$ 's took on extreme values incomparable to the remaining values. Specifically, in a few cases the RT did not clearly increase as the intervening sequence length increased (as it does in Fig. 1C and D). While this is almost certainly due to measurement error, because it is well established that priming does decay after it has built up, these cases result in highly deviant values for the fitted  $\tau$ 's because a lack of increase in RT (i.e. a flat line) corresponds to a  $\tau$  value of infinity. Since these outliers would therefore have a disproportionately strong effect on our analyses, we performed an outlier analysis to identify them. This caused 3 out of 36 (nine observers times four build-up lengths) fitted  $\tau$  values to be rejected. Specifically, for each length of the build-up sequence we calculated the modified z-score of all nine fitted  $\tau$  values across our nine observers and rejected those observations whose modified z-score had an absolute value of larger than 3.5, following Iglewicz and Hoaglin (1993). Unlike the conventional z-score the modified z-score is itself robust against outliers, because it is based on medians rather than means. The modified z-score  $M_i$  of each observation  $x_i$  is calculated as  $M_i = \frac{0.6745(x_i - \bar{x})}{MAD}$ , where  $\bar{x}$  is the sample median of all nine observations, and MAD stands for the median absolute deviation, or the median absolute distance to the sample median across all nine observations.

### 3.3. Results

Fig. 1C shows, for one sample observer and for the case of only two build-up trials, how RT on the test trial develops as the number of intervening trials increases from 1 to 8 (see trial structure in Fig. 1B). A fitted exponential decay function and variables that constrain this function (see Methods) are also shown. Fig. 1D shows data for the same observer, now showing test trial RTs for all four possible lengths of the build-up trial sequence. From the vertical ordering of the four curves we can clearly see that for this observer longer build-up sequences cause stronger priming. This is entirely expected, and it is confirmed across all observers in Fig. 1E, where we plot the average value across observers of the initial RT reduction immediately following build-up sequences of various lengths, before the intervening sequence starts. This initial priming strength is defined here by the intersection point of the fitted curves with the y-axis, or variable  $p_0$  of the fitted function (see Fig. 1C). The dependence of  $p_0$  on build-up sequence length is significant (Spearman correlation between sequence length and  $p_0$  on individual observers' data:  $\rho = 0.47$ ; one-sided  $p < 0.01$ , one-sided because of our explicit prior hypothesis regarding the direction of the effect).

While the expected dependence of priming strength  $p_0$  on build-up sequence length (Fig. 1E) provides a useful sanity check, the real question here is whether priming persistence also depends on build-up length. In other words, does the time constant estimate  $\tau$  depend on build-up length, or are all decay curves for a given observer (e.g. Fig. 1D) part of the same exponential decay function with a single  $\tau$ , regardless of buildup length? Fig. 1F plots average  $\tau$ 's across observers for various build-up lengths. There is a strong impression that  $\tau$  increases with build-up length, which is consistent with the notion that priming traces become more persistent with longer accumulation. Indeed there is a significant correlation between build-up length and  $\tau$  (Spearman correlation between sequence length and  $\tau$  on individual observers' data:  $\rho = 0.32$ ; one-sided  $p < 0.05$ ) and comparing individual means revealed a significant difference between sequence lengths of 1 and 8 ( $t(8) = 2.52$ ;  $p < 0.05$ ). While these results are suggestive of an influence of priming build-up duration on the time constant  $\tau$  the statistical power of our analysis is modest, in part because of the large variance on parameter estimates such as these (see Methods). In Experiment 2 we present a more direct test of differences

between longer-term and shorter-term priming build-up that does not suffer from this limitation.

The results in Fig. 1 indicate that priming that has accumulated during the build-up sequence decays across the intervening sequence, and that this decay is systematically slower (has a larger  $\tau$ ) as the build-up sequence is longer. This finding is consistent with the idea that the visual attention system retains stable, long-term, regularities in the world for longer periods than more incidental patterns. The present indication that attentional priming traces exist on more than one time scale fits with observations of Martini (2010), who found that two separate exponential processes, each with its own time constant, were needed to accurately model RT data in a PoP paradigm.

#### 4. Experiment 2

In Experiment 1 we found evidence that the decay of priming is slower the longer the build-up of priming lasted. In Experiment 2 we contrast such longer-term and shorter-term priming more directly. The aim was to ask what happens when the memory system first learns a certain scenario over a longer period (e.g. all targets are red for 10 trials in a row) and then briefly has to “relearn” that another scenario is the case (e.g. the following four targets are green). What will the effect of such a sequence be upon performance on immediately following trials, and what will it be farther into the future? Given the present evidence (Experiment 1) that the longer-term learning has a more persistent effect, we made the prediction that, in principle, this type of sequence could result in faster RTs for green targets on the immediately following trials (primed by the immediate history) yet a spontaneous reversal to faster RTs for the red targets on later trials (primed by more global history). In other words, if our reasoning is correct, RTs might initially be faster for the more recently laid-down memory trace, but as more time passes, the attentional memory system might revert to the older memory trace.

##### 4.1. Methods

The trial sequence is shown in Fig. 2A. We used a design of build-up sequences of 12 trials, followed by 4-trial intervening sequences and finally by test sequences of 10–14 trials. The objective of these long test sequences was to measure, across a prolonged time period, the evolution of the priming effects that had been laid down during the preceding trials. Therefore the test sequence itself was not intended to bias RTs in favor of either color, and accordingly target identity during test sequences switched between the two target colors from trial to trial (see Fig. 2A).

We chose build-up sequences of 12 trials and intervening sequences of four trials, based on pilot experiments where we contrasted various sequence lengths, which indicated that this was a likely combination of build-up and intervening trial numbers for finding clear contrasts between long-term versus short-term priming. Despite the regularity in trial sequence in our design, the sequence again had a pseudorandom appearance. Four observers who had not taken part in Experiment 1 participated in this experiment, running 7000 trials each, spread over a few days depending on the convenience of each participant. Otherwise methods were similar to those of Experiment 1.

##### 4.2. Results

Fig. 2B shows the results of Experiment 2 for one representative observer. The numbers along the x-axis indicate trial number, counting from the start of the test sequence. The gray line shows the trials where target color was the same as during the build-up

sequence, and the black line indicates those trials that shared the target color of the intervening sequence (see trial sequence of Fig. 2A). There is a distinct impression that the intervening sequence’ target color (black line) yields faster RTs early on in the test sequence, but that the color of the build-up sequence (gray line) yields faster RTs with more trials of the test sequence. This would mean that, during the first few trials of the test sequence, the more recently laid down memory trace dominates, but that this then reverses as more trials pass. Indeed, this same reversal pattern was apparent for each of our four observers individually, and Fig. 2C shows the same reversal in the across-observer average, obtained after normalizing RTs per observer by dividing by their mean RT. The normalized RTs of Fig. 2C increase significantly faster across trials for the target color of the intervening sequence than for the target color of the build-up sequence (repeated measures ANOVA with factors trial number (matching trial 1 to trial 2, trial 3 to trial 4, etc.) and target color, interaction between factors:  $F(1, 6, 18) = 12.8, p < 0.01$ ; Spearman rank correlation between trial number and the difference between the two curves (again matching trial 1 to trial 2, trial 3 to trial 4, etc.),  $\rho = 0.96$ ; two-sided  $p < 0.01$ ). Indeed, the first part of the black curve lies significantly below the gray curve, whereas the opposite relation is significant for the last portion, demonstrating a cross-over between the curves (paired  $t$ -test on the average of the first three points of each curve for each observer:  $t(3) = 3.17$ ; two-sided  $p(3) = 0.05$ ; same for the last three points:  $t(3) = 4.39$ ; two-sided  $p(3) < 0.05$ ).

These results are consistent with the notion that a long repetition pattern of one color (build-up sequence) followed by a briefer repetition pattern of the second color (intervening sequence) causes priming to initially favor the second color, but to favor the first color in the long term. We argued in the Introduction that the optimal strategy for the memory system for attention deployments might be to assume for a short while that targets are going to have the color of the shorter more recent intervening sequence, but if that is not consistently the case to revert to what has been shown to be the case in the long run. That seems to be exactly what the cross-over in RT in this second experiment demonstrates.

While this overall pattern of results is thus entirely consistent with our hypotheses, it might be surprising that RT seems not to change much across test trials that have the color of the build-up sequence. First, it is important to note that there is, in fact, a significant RT increase there (Spearman rank correlation between trial number and RT,  $\rho = 0.76$ ; two-sided  $p < 0.05$ ). Second we speculate that this effect is relatively small because RT on these trials might reflect a combination of a decaying long-term priming that has built up during the build-up sequence, causing an increase in RT across the test sequence, and the accumulation of a slight short-term priming trace during the test sequence itself, that counteracts this effect. That is, following the four trials of the intervening sequence we might predict there to be little or no short-term priming of the build-up color left, whereas the presence of this target color on half of the test trials should lead to a modest amount of priming of this color during the test sequence itself.

#### 5. Discussion

The usefulness of a memory system for attention deployments is obvious, keeping our attentional system focused on whatever task is important. Here we have investigated the temporal characteristics of the memory traces laid down by recent history of attention deployments.

What our results conclusively show is that the memory system involved in PoP is not solely dependent upon what occurred on the past few trials. Priming of pop-out reflects a more nuanced representation of presentation history than this. The “strategies” of this

memory system reflect both recent attentional priorities as well as a longer lasting effect of older presentation sequences.

In our conceptualization of the results we have consistently attributed the combination of transient and more persistent components in the observed *RT* effects to the presence of several distinct priming ‘traces’ that each have a different timescale of operation, and that accordingly differ in manifest *RT* effects depending on the temporal statistics of the input (faster traces being more pronounced following brief sequences and slower ones catching up when a particular target color repeats for a longer time). Another interpretation that is consistent with our findings, is that a given priming trace can change its temporal properties depending on the temporal statistics of the input, fading fast following brief repetition sequences but becoming more persistent after more repetitions. Our findings do not clearly discriminate these two conceptualizations and it could, in fact, be argued that the distinction between them depends on what, on a molecular or cellular level, we designate as ‘the priming trace’. What both conceptualizations have in common is our most important conclusion, namely that priming of pop-out can ‘learn’ the statistics of the environment and adapt to them by adjusting its temporal characteristics.

Our pattern of results is reminiscent of recent findings on temporal characteristics of the perception of ambiguous displays (Brascamp et al., 2008). They found that perception of such displays depended on mnemonic traces on a number of different timescales. When ambiguous displays are viewed continuously, perception alternates between the two stimuli, as both cannot be perceived at the same time. But when these stimuli are presented intermittently, perception tends to stabilize and the same percept is perceived repeatedly (Leopold et al., 2002). Brascamp et al. found that prolonged dominance of one percept leaves a persistent memory trace, whereas a short period of dominance leaves a more transient memory trace. The question which percept will be experienced when an ambiguous stimulus reappears is then determined by a seconds-long influence of the latest percept, and a more persistent influence based on the relative proportion of dominance during a longer preceding period. The fact that our present results for PoP mirror this pattern of results adds to several other parallels between the two phenomena that have been noted elsewhere (Brascamp et al., in press). Briefly, these parallels can now be summarized as follows: both effects occur implicitly without a need for explicit recall of stimulus history, both accumulate across trial repetitions, both bias the allocation of processing resources to either one or another competing element within the visual display (manifested as either the direction of attention to that element or the exclusive perception of that element), and both evolve on several timescales simultaneously. It is also interesting to note, in this context, that priming of attention shifts has recently been found to influence figure-ground assignment in ambiguous displays (Kristjánsson, 2009). We find these parallels intriguing and of potential importance for a deeper understanding of both priming of pop-out and priming of ambiguous stimulus perception. Further research is needed to determine whether these parallels also reflect a neural similarity or not, perhaps research that focuses on interactions between the two phenomena within a single experiment.

Martini (2010) argued that the evolution of *RTs* during PoP was best modeled using two different time constants (a longer-term time constant of about five trials and a short-term, fast component). Our results agree with this: implicit memory traces at multiple timescales are responsible for the observed priming effects. The crossover pattern demonstrated in Experiment 2 shows this quite conclusively. Martini (p 2114) noted: “It remains for future studies [to manipulate] performance in different lags’ ranges, thereby establishing whether the [separate model time scales] reflect true

separate influences”. Our study answers this call for direct manipulation, contrasting different build-up and intervening sequences to study the separate influences of longer term and shorter term history on attention priming.

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