Can a single short-term mechanism account for priming of pop-out?

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A B S T R A C T

Trial-to-trial feature repetition speeds response times in pop-out visual search tasks. These priming effects are often ascribed to a short-term memory system. Recently, however, it has been reported that a 'build-up' sequence of repetitions could facilitate responses over 16 trials later – well beyond twice the typically reported time course (Vision Research, 2011, 51, 1972–1978). Here, we first report two replication attempts that yielded little to no support for such long-term priming of pop-out. The results instead fell in line with the predictions of a previously proposed computational model that describes priming as short-lived facilitation that decays over approximately eight trials (Vision Research, 2010, 50, 2110–2115). In the second part of this study, we show that these data are consistent with a simple formulation of decay with a single timescale, and that there is no significant priming beyond eight trials.

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1. Introduction

Whenever we explore our visual environment or search for a particular target, we are driven both by the visual input, and by what our search goal is, i.e. what we are looking for. The question how these two classes of influences drive visual attention and visual search, as well as how they interact has been hotly debated for decades (Van der Stigchel et al., 2009). However, there is a third class of factors that appears to affect our visual attention and behavior, namely preceding searches. An increasing body of evidence highlights a very important role for the effects of history in visual search, and various authors have suggested that this deserves to be acknowledged as such, and that 'history' deserves its own separate spot alongside the typical dichotomy of 'bottom-up' and 'top-down' factors (Chun & Nakayama, 2000; Awh, Belopolsky, & Theeuwes, 2012).

The extent of the influence history can have on visual search performance is perhaps most clearly demonstrated by research on intertrial priming. This term denotes the finding that trial to trial repetition of features of the target or distractors speeds reaction times. An early exploration of such effects demonstrated that priming occurs in pop-out search tasks, which are believed to be largely driven by bottom-up processes independently of the participants conscious control (Maljkovic & Nakayama, 1994). Later studies revealed that such priming of pop-out affects the direction

and latency of eye movements (McPeek, Maljkovic, & Nakayama, 1999; Bichot & Schall, 1999), and does not only facilitate responses to certain features but also establishes a bias for them (Brascamp, Blake, & Kristjánsson, 2011).

In most studies intertrial priming is merely measured as the immediate effect of feature repetition versus feature switches from one trial to the next. However Maljkovic and Nakayama (1994) already noted that priming effects tend to persist for multiple trials. They reported that repeating the target color of trials up to about seven trials in the past yielded speeded RTs compared to color switches. This finding has contributed to a conceptualization of priming as resulting from a short-term memory system (Kristjánsson & Campana, 2010; Maljkovic & Martini, 2005; Chun & Nakayama, 2000; Kristjánsson & Nakayama, 2003) the amount of priming on a trial is a cumulative effect of the facilitation caused by previous trials, with the facilitation caused by any trial dissipating over the course of 5–8 subsequent trials as their memory fades.

Since priming effects persist for multiple trials, a natural question that arises is exactly how and why these effects fade away. Few studies have systematically explored this time course of intertrial priming of pop-out. Martini (2010) collected data from 50 participants in a standard priming of pop-out task cf. Maljkovic and Nakayama (1994) where target- and distractor colors randomly switched between red and green. The resulting data were formalized by extracting the priming exerted by each trial on every future trial with the same target color see also Maljkovic and Martini (2005). These data yielded a model where every trial independently facilitated future repetitions, and this facilitation decayed over trials. This decay was described by two exponentials:

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one relatively strong but short-lived, and one much weaker but longer-lasting.

Brascamp, Pels, and Kristjánsson (2011) probed the decay of priming via an experimental design where target- and distractor roles reversed with systematic patterns, producing periods that consisted of a 'build-up' sequence of one target color, followed by an 'intervening' sequence of the opposite target color, and then 'test' trials on which potential priming effects of these sequences could be tested. Their experiment 1 showed how longer build-up sequences, compared to shorter ones, produced stronger priming and subsequently required longer intervening sequences to fully decay. In their experiment 2, which is the focus of the present study, build-up sequences always lasted for twelve trials, followed by four intervening trials of the opposite color. After that, a test-sequence followed where target colors alternated between the build-up and intervening color Critically, they found that early in the test sequence, the intervening color-trials appeared primed with facilitated RTs, but later in the test sequence this pattern reversed, with shorter RTs for the trials with the build-up color (Fig. 1, inset). Their explanation of this finding was that the intervening sequence yielded only short-lived priming observed early in the sequence, but that the build-up sequence had established a long-term priming effect that became apparent after the strong short-term priming-effect had decayed. This was interpreted to be in line with the model of Martini (2010), because this model assumes two components to priming, one with a short time scale of decay, and one with a longer time scale.

However, a simulation of this paradigm using the model yields a different prediction (Fig. 1). During the test sequence, the model predicts no appreciable consequence of the build-up sequence. This is the case because for the priming of color, the contribution of the longer-term component in the model is actually much weaker than that of the short-term component, so that feature priming is largely driven by short-term priming alone[1] Therefore, under this model the RTs of the alternating trials in the test sequence are predicted to differ only early in the sequence: near the end of the sequence they converge, as the recent history will be nearly identical for both colors.

Here, we performed two experiments aimed at studying the putative role of longer-term effects in priming of pop-out, and at investigating what could account for the discrepancy between Brascamp and Pels et al. (2011)'s data and the predictions of the model by Martini (2010). The first experiment investigated whether factors independent of long-term priming could have accounted for the crossover effect found by Brascamp et al. In particular, we explored whether the predictability of the sequences in the original study might have affected the results, and attempted to replicate the original findings in an experiment with less predictable sequences (Experiment 1). To preview the results, this experiment suggested that the build-up sequence did not lead to any facilitatory effect for that particular target color during the test sequence, contrary to the original report.

When carefully examining the differences between Experiment 1 and the original experiment, we identified a coding error in the original experiment file that might account for the crossover effect found in Brascamp and Pels et al. (2011), which we will further address in the Discussion section below. To verify this possibility, we ran another experiment, virtually identical to the original experiment. In line with Experiment 1 and in conflict with the orig-

inal study, no detectable long-term priming effect was observed in this experiment. These results are consistent with a scenario in which priming of pop-out relies overwhelmingly on a relatively short-term effect.

The second part of the study formally addresses whether the results support a dual or single-timescale account of priming of pop-out, by examining our data in the context of the model of Martini (2010) These analyses demonstrate that the results are consistent with the time course for priming of pop-out proposed by Martini (2010), despite differences in experimental designs. This suggests that the Martini-model may very well generalize to other priming of pop-out tasks. By extension, these data support the view that priming of pop-out is dominated by short-term facilitation. In fact, the results indicate that priming of pop-out is well described as decaying with a single time scale.

2. Materials and methods

As both experiments were intended to replicate (experiment 2 Brascamp & Pels et al., 2011), they were highly similar and their methods and results will be presented together. Any differences are specifically noted below.

2.1. Participants

Six students from the Vrije Universiteit participated in Experiment 1, aged 19–26 ($M = 21.8$). Four were female, and all reported normal or corrected-to normal vision. The experiment was conducted in accordance with the local ethics committee of the Vrije Universiteit, Faculty of Psychology and Education.

Six observers participated in Experiment 2, five of whom were female students from Utrecht University and the remaining one was an author (JB). Their age range was 22–35 years ($M = 26.2$), and all observers reported normal or corrected-to-normal vision. Experiments were performed in accordance with the local ethics guidelines of Utrecht University.

Informed consent was obtained prior to the experiments and both experiments were conducted in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

2.2. Stimuli

For both experiments, the task and stimuli were modeled after the diamond pop-out task common in studies on intertrial priming (Maljkovic & Nakayama, 1994; Martini, 2010). Each trial started with a fixation display, followed by a search display with three diamonds (sized $2.4° \times 2.4°$) at an eccentricity of $4.05°$. Two of the diamonds were red (12.8 cd/m^2) and one green (13.3 cd/m^2) or vice versa. Each diamond had a notch at the top or the bottom, and participants were instructed to indicate the notch of the singleton colored diamond by pressing a corresponding key on a keyboard. All stimuli were presented on a dark background (0.5 cd/m^2).

Experiment 1 was programmed using the OpenSesame Experiment builder (Mathôt, Schreij, & Theeuwes, 2012). Stimuli were placed at three locations randomly chosen from twelve predefined equidistant positions surrounding fixation, though never at immediately adjacent positions. Experiment 2 was programmed in MatLab using the Psychtoolbox functions (Brainard, 1997). On every trial the three stimuli were assigned to three positions equally spaced on an imaginary circle around fixation but otherwise random.

2.3. Procedure

In both experiments, target colors on each trial (red or green) switched in systematic patterns to constitute build-up-,

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[1] In his study, Martini sought to isolate the effects of repetition in different dimensions, i.e. for the target location, the trial response, and the target selection feature. The effects of repetition in these dimensions were described by two exponentials with different timescales. However, for the selection feature, which shows the strongest repetition effects, the relative contribution of the longer-term component is rather small.
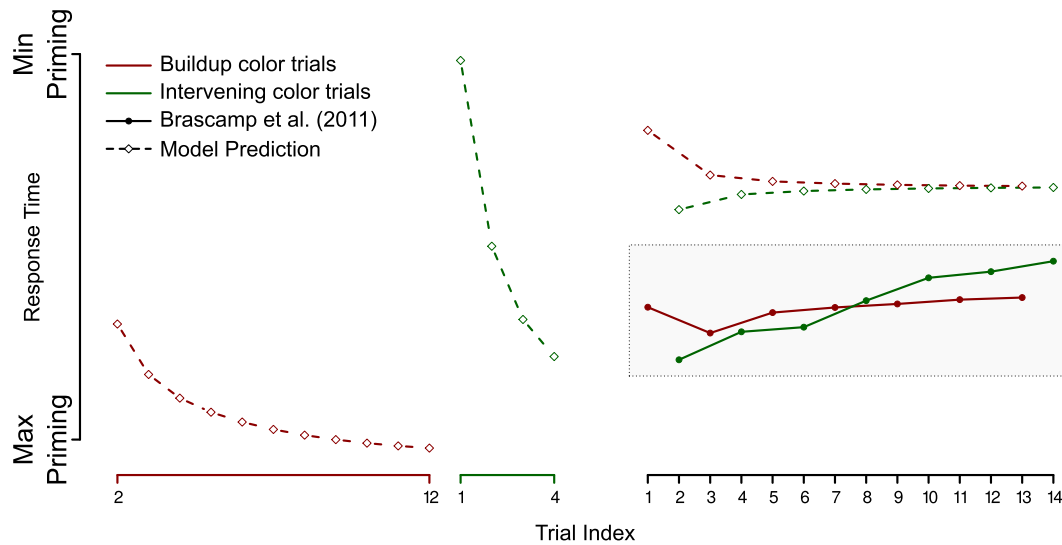
Fig. 1. Predicted outcome of experiment 2 Brascamp and Pels et al. (2011) according to the Martini (2010) model (dashed lines), compared to the outcome reported by Brascamp and colleagues (inset). Sequences consisted of twelve build-up trials, four intervening trials, then fourteen test trials with alternating target colors. Red data points denote trials in which the target has the 'build-up' color, green data points the 'intervening' color. Build-up and intervening colors swapped roles throughout the experiment. The model only predicts relative response times, and the y-axis has no unit. The inset has arbitrary vertical placement and shows normalized reaction times. Of interest here is the qualitative difference between the course of the individual curves at the end of the test sequence. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

intervening- and test-sequences. Build-up and intervening sequences always had lengths 12 and 4, respectively. By definition, the test sequences always started with the build-up color, after which colors alternated. In the original study – and similarly in Experiment 2 – test sequences always had an even length (that is 10, 12 or 14) with equal probability. As a result, the sequence always ended with the intervening color. After each test-sequence, the roles of build-up and intervening color switched: the final test trial was followed by 11 repetitions of the same color, constituting a new build-up sequence. In every sequence, the final test trial thus served a 'double-role' as a subsequent build-up trial.

In Experiment 1, sequences were implemented slightly differently to reduce their predictability. Test sequences could have any length from 10–14 with equal probability, which yielded no constraints on the final color in the test-sequence. The test sequence was then always followed by 12 build-up trials, which could have either color (counterbalanced across the experiment). Note that this means that the resulting build-up sequence could be effectively 13 trials long. To present data that are nevertheless comparable across experiments we adhere to the following standards during the analyses: (1) whenever the first build-up trial is a color switch trial, it is interpreted as the last test-trial; (2) the first repetition following a test-sequence is considered the build-up trial with index 2; (3) only build-up trials 2–12 are reported, and any 13th build-up trials were ignored.

In Experiment 1, participants completed two sessions, one of 2240 trials and one of 1960 trials (based on 80 and 70 full sequences, respectively), preceded by 10 and 5 practice trials. Both sessions were held at the same day with at least 30 min of rest in between. In Experiment 2, every participant completed 12 sessions of on average 542.6 trials (based on 20 full sequences), spread out over multiple days to their convenience.

2.4. Trial Inclusion and preprocessing procedures

Both datasets were processed identically. First, incorrect trials were discarded ($M = 5.1\%$, $SD = 2\%$ trials in Experiment 1; $M = 6.5\%$, $SD = 7.4\%$ in Experiment 2). After discarding incorrect

trials, outlier trials were defined separately per subject using a procedure similar to Brascamp and Pels et al. (2011): a modified z-score for every RT was computed, defined as $M = 0.6745 \frac{(x - \bar{x})}{\text{MAD}}$, where $\bar{x}$ was the sample median, and MAD is the Median Absolute Deviation. Trials with a modified $z > 3.5$ were considered outliers and excluded from further analysis ($M = 1.1\%$, $SD = 0.3\%$ of trials for Experiment 1, $M = 1.0\%$, $SD = 0.8\%$ of trials for Experiment 2).

Apart from analyzing regular RTs, we computed normalized RTs and z-scored RTs. Normalized RTs were computed to compare the current results to those of the original study, and were defined for every participant by dividing RTs by the mean of RTs of trials in the Test sequence. z-scored RTs were computed for our follow-up analyses to compare the results to those of Martini (2010), by subtracting each participant's mean RT from each individual RT and dividing this by the standard deviation, both defined over all trials (i.e. Build-up-, Intervening- and Test- trials).

3. Results

3.1. Response times in the sequence

The results of the full sequence are plotted for both experiments in Fig. 2. As expected, the pattern of response times in the build-up and intervening sequences is in line with the predictions made by the model (in Fig. 1). Crucially, this was also the case for the pattern of results during the test sequence. Early on in this sequence, build-up-colored trials have slightly higher RTs than trials of the intervening color, but this effect quickly fades. Throughout the rest of the test sequence, both colors elicit similar response times. There appears to be no evidence for long-term facilitation at the end of the sequence – build-up colored trials do not seem to be primed more than intervening colored trials.

In line with Brascamp and Pels et al. (2011), we first assessed these observations through paired t-tests on the average of the first three points of each curve, as well as on the last three points on each curve. For both datasets, one-sided tests supported that trials of the build-up color had higher RTs early on in the sequence than those of the intervening color. At the end of the sequence, no evidence for a difference was found (see Table 1).
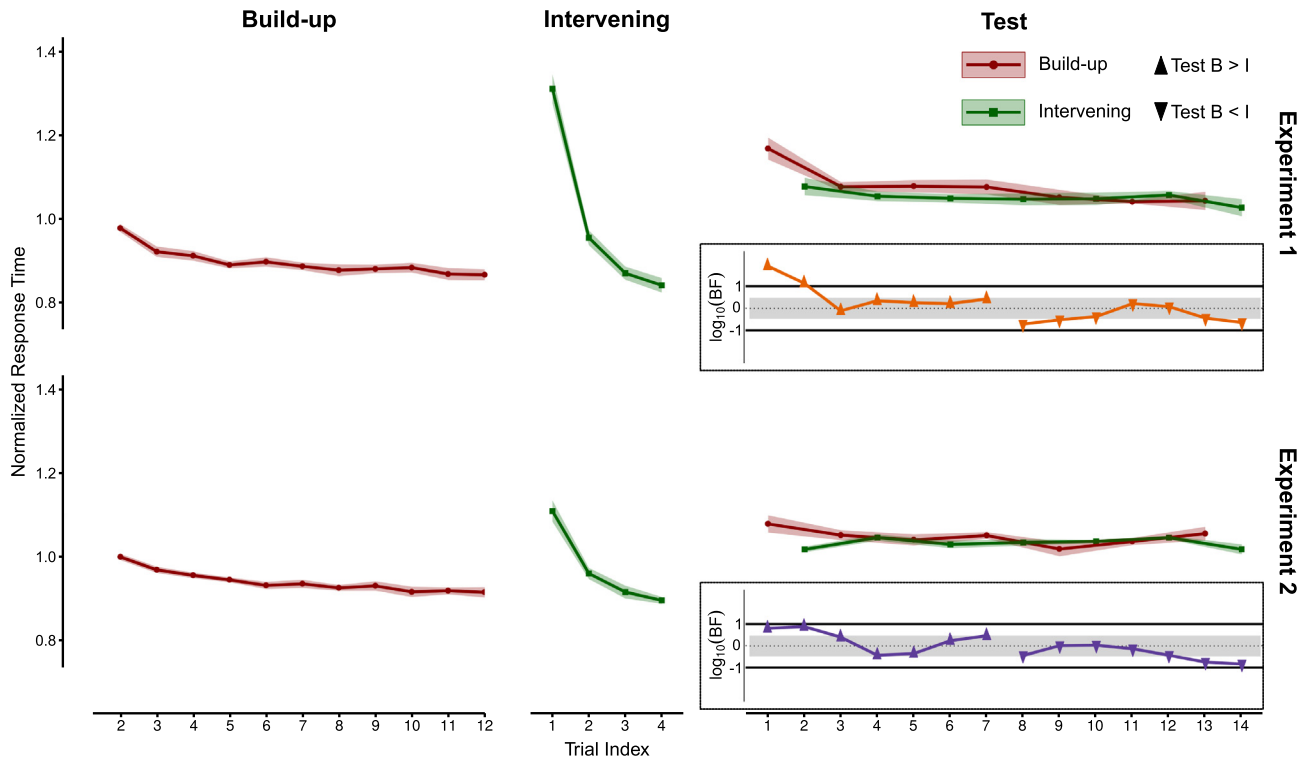
Fig. 2. Results of Experiment 1 (top) and 2 (bottom). Ribbons reflect the sample standard error of each data point. The pattern of results of both experiments qualitatively matches the pattern predicted by Martini (2010): cumulative priming effects are observed in the build-up and intervening sequences, and these result in a brief benefit for intervening trials in the beginning of the Test-sequence. However, this benefit quickly disappears and no differences are found between both colors as the test sequence progresses. The insets depict the $\log_{10}$ Bayes Factor from Bayesian t-tests at each index, to assess whether build-up- and intervening colors differed (see text for details). Values greater than zero indicate evidence for a difference, those below zero for the null-hypothesis. The shaded region indicates Bayes Factors that are considered inconclusive ($BF < 3$), and borders at 1 and −1 indicate strong evidence for either hypothesis ($BF = 10$).

In addition to the statistical tests done in the original study, we also quantified the evidence for a difference in priming between build-up and intervening colors at every trial index. To this end, we compared the normalized RT at each test trial to the average of the preceding and subsequent trial using Bayesian t-tests (Rouder et al., 2009). The only exceptions were the first and fourteenth trial, which were compared to the second and thirteenth trial, respectively. We tested whether responses on intervening color trials were faster than on build-up color trials for indices 1–7, and vice versa for indices 8–14. The resulting Bayes Factors are plotted in Fig. 2, after taking the $\log_{10}$ for clearer interpretation. In this graph, positive values indicate evidence for a difference, and negative values indicate evidence for no difference. Although these results are mostly inconclusive due to the conservative nature of Bayesian statistics, they again illustrate how the start and end of the sequence differ: whereas early in the sequence evidence is found for a difference between these colors, later in the sequence the evidence predominantly suggests that both colors yielded similar response times.

Somewhat curiously, regarding the intervening-colored test trials in Experiment 1, it may seem from the graph that response times were greater at index 2 than at index 4, whereas the model predicted a subtle difference in the opposite direction. However, a one-sided t-test, uncorrected for multiple comparisons, did not indicate a difference between these two data points ($t(5) = -1.85$).

3.2. The memory kernel of priming of pop-out

The results of neither experiment replicate the original results of experiment 2 Brascamp and Pels et al. (2011): throughout the test sequence there was no evidence for long-term facilitation from

Table 1
Results of one-sided t-tests, assessing whether build-up colored trials and intervening colored trials differed, both early and late in the sequence. Tests were performed on both raw RTs and normalized RTs (see text for details).

			RT		Normalized RT	
		$\mathcal{H}_1$	$t(5)$	p	$t(4)$	p
Experiment 1	Early	B > I	4.164	**0.004**	4.497	**0.003**
	Late	B < I	0.200	0.575	0.108	0.541
Experiment 2	Early	B > I	2.037	**0.049**	2.207	**0.039**
	Late	B < I	0.442	0.662	0.450	0.664

Boldfaced values indicate significant outcomes at the $p < 0.05$ level.

the long build-up sequence. This suggests the originally reported crossover in the test sequence resulted from the coding error in the experiment file. At least qualitatively, the present results are highly in accordance with the predictions of the computational model put forward by Martini (2010) as depicted in Fig. 1.

As facilitation effects in these data are predominantly short-lived, this raises the question whether a successful description of priming of pop-out requires the inclusion of a longer time-scale at all. Of note, the original formulation of this model successfully captured a range of priming phenomena with just one exponential term (Maljkovic & Martini, 2005). Here, we explore to what extent our data might similarly support this single time scale model, or might require both a fast and a slow component.

In the model, memory kernels describe the amount of facilitation through priming that each trial will exert on subsequent trials of the same color. This value gradually dissipates via a pattern that can be described by a function with either one or two exponential terms, each with a particular gain (w_i) and timescale (τ_i). To estimate this function (termed the 'memory kernel'), Martini z-scored

response times and cross-correlated these with a binary input time series that reflected trials of a particular color. Because this approach assumes that the input reflects uncorrelated noise, this procedure cannot be replicated here, since trial colors varied systematically in the present experiments.

Instead, we used simulations of our experiments, and optimized the parameters of the model with two exponentials to capture the data pattern of each participant. We then used Bayesian parameter estimation procedures to recover the parameters of the kernel underlying priming of pop-out, and to explore whether priming was best described by a function with two exponential terms ($\mathcal{M}_2$) or one ($\mathcal{M}_1$). We constructed a hierarchical Bayesian graphical model in line with $\mathcal{M}_2$, and computed joint posterior distributions for its parameters through Markov chain Monte Carlo (MCMC) sampling (using the `rjags` package; Plummer, 2014), separately for the datasets of both experiments. More detail regarding these analyses is provided in the Supplementary material.

Fig. 3 depicts the resulting priming kernel estimates for up to 15 trials, constructed from the posterior distributions of the population parameters. The 95% confidence intervals (CIs) are rather wide due to the small sample sizes, but note that in all cases priming effects have largely faded after ≈8 trials. This matches well with the qualitative estimate given in the earliest study of priming of pop-out (Maljkovic & Nakayama, 1994) and several studies since (see Kristjánsson & Campana, 2010 for a review). To inspect whether long-term effects like the effect explored in our experiments could ever arise from such memory kernels, the sum of the predicted kernel values at indices 8–100 was computed, reflecting the cumulative priming effect that a lengthy sequence of repetitions that lasted from 100 to 8 trials in the past would have. For both datasets, this sum was 0.02 on average, and the CIs were never higher than 0.12 (Experiment 1: $CI = [0.00, 0.06]$; Experiment 2: $CI = [0.00, 0.12]$). Since the unit of this number is z, this can be interpreted as a very small effect. For comparison, the predicted priming effect at index 2 alone (i.e. priming from 2 trials back) far outweighs this cumulative sum (for Experiment 1: $M = 0.27$, $CI = [0.07, 0.44]$; for Experiment 2: $M = 0.16$, $CI = [0.01, 0.34]$ in Experiment 2). Similar outcomes are predicted when the original parameters of Martini are assumed (0.19 at index 2, versus 0.098 for trials 8–100).

In order to determine to what extent our data support a model with multiple time scales, note that model $\mathcal{M}_2$ is equivalent to model $\mathcal{M}_1$ when both timescales τ_i have the same value. Therefore, we expressed the posterior estimate of the difference between both time scale as an effect size (δ), and the posterior distribution of this effect size allowed us to compute a Bayes factor comparing both models (see Wagenmakers et al., 2010). For both datasets, a slight numerical preference for $\mathcal{M}_1$ was observed. (Experiment 1: $BF_{1,2} = 2.00$, Experiment 2: $BF_{1,2} = 2.53$). These results do not rule out a potential contribution of a second exponential. Nevertheless, it is striking that although the priming kernels were produced by optimizing the model with two time scales, a model with a single time scale described the present data at least as well.

4. Discussion

In this study, we have explored whether prolonged repetition of one target type in a singleton search task would yield long-term facilitation effects, as reported by Brascamp and Blake et al. (2011). In two experiments we failed to find such facilitation. Instead, the results were largely in accordance with a mathematical model put forward by Martini (2010), which describes priming of pop-out as subject to swift decay, with only a minor contribution of longer-lasting priming. In fact, the present data are well explained by a simple model of the decay of priming with a single timescale, without a longer-term component.
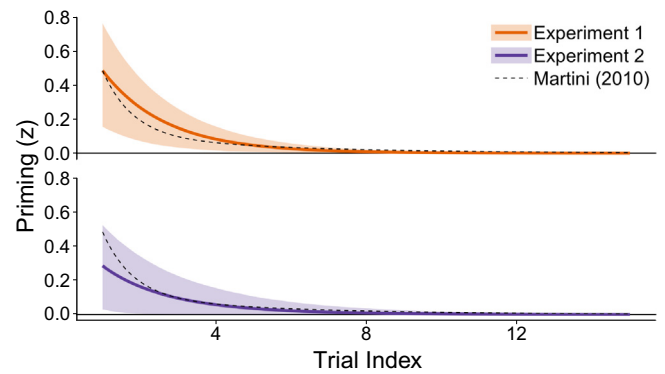

Fig. 3. The memory kernels of priming in both experiments. Shaded areas indicate 95% confidence intervals inferred from the posterior predictive distributions. Note the similarity to the memory kernel inferred by Martini (2010), despite the vastly different approach used to infer the kernel and differing experimental designs. The predicted time course of priming effects is limited to the short term: for both datasets, priming effects drop to baseline over the course of approximately eight trials.

How can these findings be reconciled with those reported by Brascamp and Pels et al. (2011)? As noted above, we uncovered a coding error in the original experiment file when we re-examined the original workflow as part of the present project. This error might provide an explanation for the reported results of that original experiment, and is described in more detail in an erratum to the original paper, submitted in combination with the present study (Brascamp, Pels, & Kristjánsson, 2015).

These results indicate that, at least in simple pop-out tasks like the one studied here, priming can be explained as an effect of short-term feature weighting (Kristjánsson & Campana, 2010; Kruijne & Meeter, 2015; Lee, Mozer, & Vecera, 2009; Maljkovic & Martini, 2005; Maljkovic & Nakayama, 1994). According to this account, selecting a singleton target among distractors on one trial alters 'attentional weights' to favor the target feature(s) over those of the distractor on the next trial. These weight changes are short-lived: priming has been shown to fade after several (five to eight) interfering trials (Maljkovic & Nakayama, 1994; Martini, 2010). Additionally, priming effects subside over time in the absence of any intervening trials, albeit more slowly than in the presence of intervening trials (≈90s, Maljkovic & Nakayama, 2000). Results from a recent thorough exploration (Thomson & Milliken, 2012) revealed that both passive decay over time and interference from other trials attenuate priming effects. Discussing their results, they proposed that decay and interference potentially operate on dissociable time scales, referring to Martini's fast component reflecting decay and slow component reflecting interference. They noted the short- and long-term effects initially reported by Brascamp and Pels et al. (2011) might have reflected this dissociation. The results of this study do not speak to whether decay or interference underlies the decrease in priming, but it does suggest that this decrease cannot be divided into two processes with very different time courses.

In light of present findings, what is the memory mechanism producing priming of pop-out? We propose that a simple, straightforward mechanism may suffice: after completing a trial, activity (or excitability) of neuronal populations that represented the target features will be briefly sustained. Neurophysiological evidence that sustained intertrial activity in feature-selective areas is involved in priming has been found in MEG-, fMRI-, and TMS-studies (de Lange et al., 2013; Yeung, 2006; Campana et al., 2007; Kristjánsson et al., 2007). Circumstantial evidence for this view can also be found in studies of recordings in macaque frontal eye fields (Bichot & Schall, 2002; Fecteau & Munoz, 2003) and in human eye movements (Meeter & Van der Stigchel, 2013): both

showed that the previous trial affects visual signals, before they reach the oculomotor system, suggesting that the previous trial leaves a lingering trace affecting its bottom-up processing.

Sustained intertrial activity as the cause of intertrial priming would be subject to both temporal decay as well as interference from intermediate trials, in line with the conclusions of Thomson and Milliken (2012). However, these processes would be intertwined, and would both contribute to rapid decay in conventional priming of pop-out tasks. This is illustrated in the experiments here, where only a few intervening trials were sufficient to abolish accumulated repetition effects from the build-up sequence. Note that the view outlined above predicts that interference might be limited when intervening trials have very different features, a manipulation that has been shown to produce longer-lasting priming effects (Thomson & Milliken, 2012, but see Thomson & Milliken (2013) for a different account).

5. Conclusion

The data from these experiments contradict earlier findings from Brascamp and Pels et al. (2011): in the present experiments there was no evidence of appreciable long-term priming effects, and the priming effects decreased over the course of 5 to 8 trials as has been consistently found before. We conclude that such swift decay supports the view that priming of pop-out results from sustained intertrial activity that decays both over time and over interfering trials.

Acknowledgments

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.visres.2015.03.011.

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