Visual consciousness and intertrial feature priming

Ziv Peremen Tel Aviv University, Tel Aviv, Israel

Rinat Hilo Tel Aviv University, Tel Aviv, Israel

Dominique Lamy Tel Aviv University, Tel Aviv, Israel

Intertrial repetition priming plays a striking role in visual search. For instance, when searching for a target with a unique color, performance is substantially better when the specific color of the target repeats on successive trials (Maljkovic & Nakayama, 1994). Recent research has relied on objective measures of performance to show that priming improves the perceptual quality of the repeated target. Here, we examined the relation between priming and conscious perception of the target by adding a subjective measure of perception. We used backward masking to create liminal perception, that is, different levels of subjectively conscious perception of the target using exactly the same stimulus conditions. The displays in either probe trials (in which priming benefits are measured, Experiment 1) or in prime trials (in which memory traces are laid down, Experiment 2) were masked. The results showed that intertrial priming improves full access to awareness of the repeated target but only for targets that already achieved partial access to awareness. In addition, they show that full awareness of the target is necessary in both the prime and probe trials for intertrial priming effects to emerge. Implications for the role of implicit short-term memory in visual search are discussed.

Introduction

What we attend to at a given time substantially affects how our attention is deployed next: If you just saw an accident involving a blue car, your attention will be more likely to be caught by another blue car waiting at the traffic light in the few moments that follow than by the yellow or red cars that surround it. An increasing amount of research has shown that we are equipped with an implicit memory system that facilitates reallocation of attentional resources to properties characterizing objects that have recently been the focus of our attention (see Chun & Nakayama, 2000; Kristjánsson & Campana, 2010 for reviews). In order to elucidate the mechanisms underlying implicit memory effects on attentional selection, such research has typically relied on visual search experiments that probe various intertrial repetition effects (e.g., dimension priming, Found & Müller, 1996; feature and location priming of pop-out, Maljkovic & Nakayama, 1994, 1996; contextual cueing, Chun & Jiang, 1998; singleton priming, Lamy, Bar-Anan, Egeth, & Carmel, 2006; Lamy, Bar-Anan, & Egeth, 2008; temporal position priming, Yashar & Lamy, 2013).

Feature priming has been the most extensively investigated phenomenon among these implicit memory effects on visual search performance. In a seminal study, Maljkovic and Nakayama (1994) showed that when there is uncertainty about the target feature, visual search for a discrepant target is speeded when the target's odd feature happens to repeat on successive trials. In their study, the target was defined by its unique color and was unpredictably either the red diamond among green ones or the green diamond among red ones. On each trial, subjects reported which side of the target (either left or right) was chipped. Repeated-color trials were faster than switched-color trials. This effect has been replicated with targets differing from distractors by their shape (e.g., Lamy, Carmel, Egeth, & Leber, 2006), orientation (Hillstrom, 2000), size (Huang, Holcombe, & Pashler, 2004), and facial emotion (Lamy, Amunts, & Bar-Haim, 2008). Maljkovic and Nakayama (1994) called this effect "priming of pop-out" (henceforth, PoP).[1]

Feature priming affects perceptual processes

What stages of visual processing are speeded by feature priming? Do repeated features grab our attention more readily or does feature repetition speed further processing of the object only after it has become

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the focus of our attention? Does priming make objects possessing the recently attended feature appear clearer? Or does it only affect how quickly we can execute a motor response to the object without affecting perceptual processing at all? Recent research has converged on the conclusion that feature priming affects more than just one stage of processing (e.g., Lamy, Yashar & Ruderman, 2010; see also Kristjánsson & Campana, 2010). Several studies have shown that it speeds attentional selection (e.g., Becker, 2008; Bichot & Schall, 2002; Eimer, Kiss, & Cheung, 2010; Goolsby & Suzuki, 2001; Lamy et al., 2010; Maljkovic & Nakayama, 1994; Sigurdardottir, Kristjánsson, & Driver, 2008; Yashar & Lamy, 2010a), and other studies have demonstrated that it also affects later, response-related processes (e.g., Huang et al., 2004; Huang & Pashler, 2005; Lamy et al., 2010; Lamy, Zivony & Yashar, 2011; Yashar & Lamy, 2011; see also Töllner, Rangelov, & Müller, 2012 for response-based effects in dimension priming).

A smaller number of studies have specifically investigated whether feature priming improves perception of the repeated target (Huang & Pashler, 2005; Lamy et al., 2010; Pascucci, Mastropasqua, & Turatto, 2012; Sigurdardottir et al., 2008; Yashar & Lamy, 2010a). Some authors addressed this question indirectly by tracking the time-course of feature priming. For instance, Lamy et al. (2010) showed that feature-priming benefits emerged within 100 ms during the search, that is, at an early, perceptual stage. Other authors relied on the idea that perceptual effects can be isolated from response-related effects by measuring accuracy under data-limited conditions (Moore & Egeth, 1998). To create data-limited conditions, the search display is typically presented very briefly and followed by a mask. Participants are required to extract the task-relevant information before the mask replaces the search display and to respond under no speed stress. Accuracy rate is thought to reflect the quality of the information extracted from the display. Under such conditions, feature-repetition priming was found to improve search accuracy, suggesting that it improves the perceptual quality of the repeated target (Pascucci et al., 2012; Sigurdardottir et al., 2008; Yashar & Lamy, 2010a; see also Huang & Pashler, 2005).

Attention focusing/engagement is a necessary condition for feature-priming effects

Previous research has also delineated boundary conditions of the perceptual effects of feature priming. Specifically, Yashar and Lamy (2010a) showed that such perceptual effects, which were probed by measuring search accuracy with masked displays, occurred in a task that required fine discrimination of the target's response feature but did not occur when subjects were only required to determine the side of the screen in which the target had appeared. Yashar and Lamy concluded that feature repetition speeds focusing/engaging attention on the target (see also Yashar & Lamy, 2010b) because such processes are involved in the discrimination task but not in the left/right localization task. In addition, when the localization and discrimination tasks were interleaved, no priming effect was observed in successive trials. This finding suggests that focusing/engaging attention both in the prime trial (in which the target feature is encoded) and in the probe trial (in which memory traces from the previous trial are retrieved and the repetition effect is measured) is necessary for feature priming to improve perceptual processing in visual search. These conditions were met only for successive discrimination trials (which were separated by a localization trial), and consistent with Yashar and Lamy's (2010a) conclusion, intertrial repetition effects were observed.

The role of visual consciousness in feature priming

In this study, we investigated the role of visual consciousness in feature priming. Specifically, we examined whether a target that is presented for a liminal exposure time is more likely to reach visual consciousness when it repeats from the previous trial relative to when it does not. In addition, we inquired whether feature-priming benefits can emerge when the target is not perceived consciously. As is clear from the foregoing review, previous research has shown that feature repetition speeds a repeated target's perceptual processing by using either direct (Sigurdardottir et al., 2008; Yashar & Lamy, 2010a) or indirect (e.g., Bichot & Schall, 2002; Eimer et al., 2010; Lamy et al., 2010) objective measures of perception. However, in none of these studies were participants asked to report their subjective experience: Even in studies in which masked exposures of the search displays may have impeded conscious perception of the target, only objective measures of perception were examined. It was therefore not possible to determine whether participants were subjectively aware of the target.

Consequently, it is possible that feature priming may affect implicit processing of the target without contributing to bringing it into subjective awareness. This possibility arises because, although attention and conscious vision are closely related (see Dehaene, Changeux, Naccache, Sackur, & Sergent, 2006; Koch & Tsuchiya, 2007, 2011), attention is sometimes dissociated from conscious vision. Indeed, several studies have suggested that attention is not sufficient for subjective awareness (see Lamy, Leber, & Egeth, 2012 for a review): Focusing attention on an invisible object was shown to produce measurable effects on performance without bringing the attended object into subjective awareness (e.g., Kentridge, Nijboer, & Heywood, 2008). Thus, the fact that feature priming speeds attentional engagement (e.g., Yashar & Lamy, 2010a, 2010b) does not necessarily entail that it enhances access to conscious perception.

In addition, feature priming may improve perceptual processing of the target only when observers have some subjective experience of this target—albeit not necessarily a clear experience—either in the prime trial or in the probe trial. Yashar and Lamy (2010a) showed that focusing/engaging attention on the target in both trials is a necessary condition for observing feature-priming effects. Here, we investigated whether an even higher level of target processing may be necessary. On the one hand, consciously perceiving the target in the prime trial may be necessary to create memory traces that can affect perceptual processing of the target in the next trial. On the other hand, feature priming may speed attentional engagement on a repeated target only after this target has been consciously detected.

Objectives and overview of the experimental methods

Our first goal was to determine whether feature priming improves access of the repeated target to conscious awareness. Our second goal was to examine whether conscious perception of the target is necessary in the prime trial, in the probe trial, or in both for feature priming to occur. In order to do that, we presented the search displays for liminal durations such that the same stimulation (in terms of both the stimulus and its duration) led to conscious perception of the target in some trials but not in others. Thus, potential differences in priming between trials in which the participants reported being aware versus unaware of the target could be attributed to the subjective state of the participants rather than to objective stimulation.

In addition, instead of forcing subjects to classify their experience in a binary fashion by responding either "yes, I saw the target" or "no, I did not see the target," we allowed them to report partial awareness. When forced into a "yes/no" response, participants may adopt a lenient criterion and say "yes" whenever they have the slightest feeling that they saw something. Conversely, they may use a conservative criterion and respond "no" unless they very clearly saw the target. Therefore, we used a three-point scale to gauge participants' conscious perception of the target by adding a "partially aware" response. The main purpose of this addition was to minimize the risk that participants would report not seeing the target when they were, in fact, partially aware of it. We reasoned that, in such a case, participants would use the "partially aware" response.

In the present study, participants searched for a unique letter shape (the target) among homogenous letters (the distractors). Half of the letters were in one color and the other half in another color (Figure 1). Subjects were required to report the target color in each trial. Trials were organized in pairs: The first trial in a pair was the prime trial; whereas the second trial was the probe trial. Feature priming was measured as the performance benefit when the target letter repeated from the prime to the probe trial relative to when it changed.

We used pattern visual backward masking (e.g., Breitmeyer & Ögmen, 2000) to impair conscious perception of the search display. Participants' subjective awareness of the target was measured in every masked-display trial. The time interval between the search display and the mask was individually adjusted for each subject in order to obtain liminal awareness of the target (i.e., for subjects to report being clearly aware of the target shape in roughly 50% of the trials).

In Experiment 1, displays were unmasked in prime trials and masked in probe trials. This design allowed us to determine whether feature repetition facilitated access of the target to conscious awareness. In addition, it made it possible to measure the feature-priming effects on objective performance when participants were totally unaware, partially aware, or clearly aware of the target while keeping stimulus conditions identical. We could thus determine whether conscious perception of the target at retrieval is necessary for the perceptual effects of feature priming to be observed. As in previous studies investigating whether feature priming improves perception, conditions in the probe trial were data-limited, and the dependent measure was therefore performance accuracy. In Experiment 2, displays were masked in prime trials and unmasked in probe trials. Thus, as the probe display remained in view until response, the primary dependent measure was reaction time. This design allowed us to assess the necessity of conscious target perception at encoding for feature priming.

Experiment 1

Method

Participants

Participants were 13 Tel-Aviv University students (eight female) who volunteered to participate in the experiment. All were right-handed and reported normal

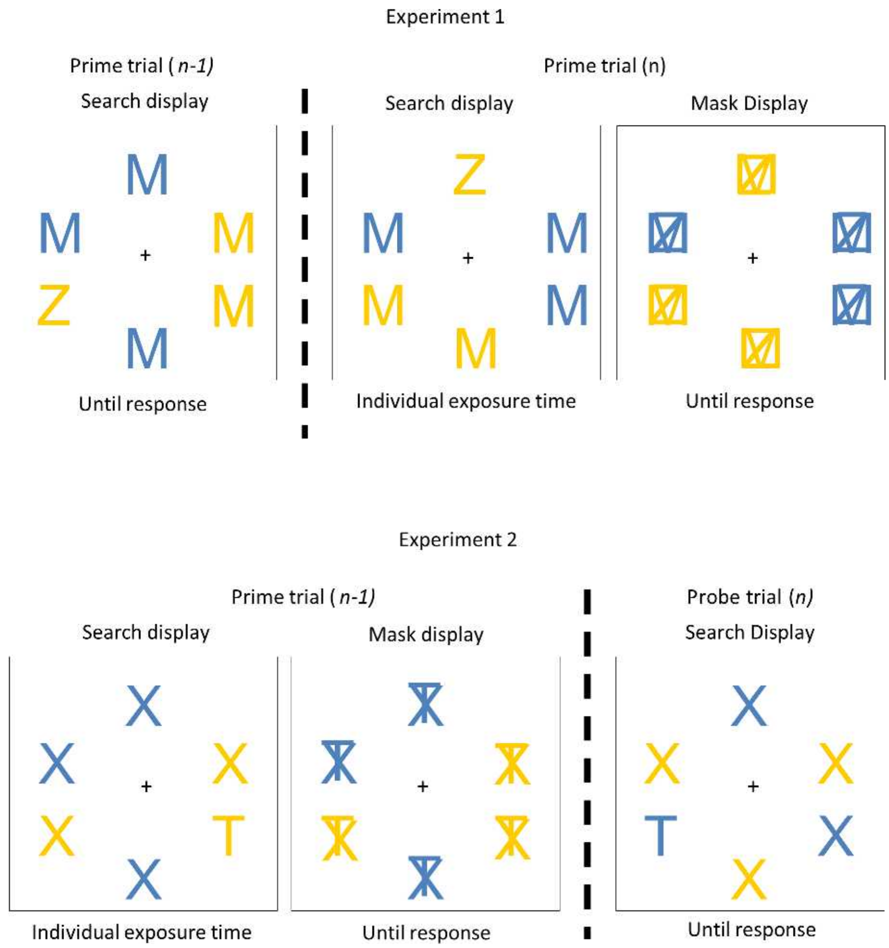

Figure 1. Sample search displays and sequence of events in Experiments 1 (upper panel) and 2 (lower panel).

or corrected-to-normal visual acuity and normal color vision.

Apparatus

Displays were generated by an Intel Pentium IV computer using software by E-prime. The stimuli were presented on a 17-inch color monitor, using a 1024 × 768 resolution graphics mode with an 85 Hz refresh rate. Responses were collected via the computer keyboard. A chin rest was used to set the viewing distance to approximately 50 cm from the monitor.

Stimuli

The fixation display was a gray 0.2° × 0.2° plus sign (+) in the center of a black background. Each search display consisted of six uppercase letters (1° in length and 0.8° in width) with one unique letter, the target, among five homogenous distractors. The target and distractor letters were randomly selected from a set of 14 letters (A, E, H, I, K, L, M, N, T, V, W, X, Y, and Z). Each target display included exactly three blue letters (RGB 130, 39, 152) and three yellow letters (RGB 149, 54, 56). The letters appeared within an imaginary 3 × 3 matrix with each cell subtending a 2.4° visual angle in side. Each letter was centered inside its cell with a random jitter of up to 0.15°. The masking display was similar to the search display except that both the target and distractor letters that had appeared in the search display were superimposed in each of the filled locations and were of the same color as the single letter that had appeared at that location.

Procedure

In each trial, the participants had to make a forced-choice response as to whether the unique letter (the target) was blue or yellow by pressing the appropriate keys as quickly as possible with their right hands while maintaining high accuracy. Key-to-response mapping was counterbalanced between participants. Trials were organized in pairs: a prime trial in which the search display was not followed by a mask and a probe trial in which the search display was followed by a mask. In each pair, the two letters were the same for both trials, and their assignment to the roles of target or distractor either remained the same or switched.

Each trial began with the fixation display, which appeared for 1000 ms. In unmasked-display (prime) trials, the fixation display was followed by the search display, which remained on the screen for 200 ms and after which a blank screen appeared until the participant's response to the target's color. In masked-display (probe) trials, the search display remained visible for an individual exposure time, the duration of which was determined during the calibration block, described below. Then, the masking display was presented until the participant's response to the target's color. It was followed by a question mark, which prompted the participants to report their awareness of the target shape. Using their left hands, they had to report whether (a) they had clearly seen the target letter in the masked display, (b) they had seen fragments of it or were unsure about whether they had seen it, or (c) they had not seen it or any part of it at all by pressing designated keys. Thus, there were three possible awareness responses (henceforth, "fully aware," "partially aware," and "fully unaware," respectively).

Note that presenting the unmasked displays for a fixed amount of time rather than until response ensured that the exposure duration of the prime displays was not confounded with reaction time (RT) on the prime trial. Also note that the masks had the same colors as the letters they replaced. Thus, the difficulty in this task resided in finding the target, not in discriminating its color.

The experiment began with a 40-trial calibration block. The calibration trials were similar to the experimental trials except that the search display duration in the masked-display trials was varied according to the participant's awareness report. Initial duration was set to 200 ms. Using a staircase procedure (Levitt, 1971), the display duration in the masked trials was decremented by 13 ms if the participant had made a "fully aware" response on the previous trial and incremented by 13 ms if the participant had made either a "fully unaware" or a "partially aware" response. Using this procedure, we aimed at obtaining roughly 50% of "fully aware" trials. The mean duration across the last 10 trials of the calibration phase was saved as the individual exposure time to be used in the experimental phase.

Design

All possible letter pairs were equiprobable, and each of the letters had an equal probability ($p = 0.07$) of appearing in a given trial pair. In the probe trial, the target and distractor letters were equally likely to repeat or switch relative to the prime trial. In order to prevent priming effects between unmasked-display trials separated by a masked-display trial, a minimum of four trial pairs separated repetition of the same letter between trial pairs. All letters, including the target, were equally likely to be blue or yellow.

The calibration phase was followed by 20 practice trials. The experimental trials that followed consisted of 10 blocks of 30 trials each. Participants were allowed a short rest after each block.

Results and discussion

Three participants were excluded from the analysis because they were at chance on their responses to the probe (masked) trials when they had reported being fully aware of the target shape.[2] Thus, the data from 10 participants were analyzed. Trial pairs in which the subjects made an incorrect response in the prime trial were excluded from the RT analyses (12% of all trials).

The distribution of the subjects' reports of their awareness of the target letter confirms the efficiency of our calibration procedure: Subjects reported being fully aware of the target in the probe (masked) display in 53.50% of the trials, partially aware in 15.85% of the trials, and fully unaware in 31.64% of the trials. The mean display exposure duration set during the calibration phase and used in the probe trials of the experimental phase was 123 ms ($SD = 42$ ms).

We first investigated whether repetition of the target letter enhanced subjective awareness of the target shape, that is, whether subjects were more likely to report being fully aware of the target when its shape repeated relative to the previous trial rather than when it did not. The proportion of all trials in which the subjects were fully aware of the target letter was higher when the target repeated relative to when it switched, 55.2% versus 51.8%, $F(1, 9) = 6.13$, $p < 0.04$. Further examination of the data revealed that feature priming did not reduce the overall proportion of trials in which the participants reported not seeing the target at all, $F < 1$: This proportion remained fixed at 30.6%. Thus, feature priming increased the proportion of fully seen targets at the expense of partially seen targets, the proportion of which decreased for repeated- relative to switched-letter trials (Figure 2).

We then investigated participants' accuracy at reporting the color of the unique letter in the probe trial as a function of their reported awareness of this letter. Not surprisingly, the effect of awareness was highly significant, $F(2, 18) = 36.55$, $p < 0.0001$. Paired comparisons revealed that accuracy was higher when the subjects were fully aware of the target shape than when they were partially aware of it, 80.9% versus 58.3%, respectively, $F(1, 9) = 45.38$, $p < 0.0001$, but the difference in accuracy when they were partially aware relative to when they were fully unaware of the target shape did not reach significance, 58.3% versus 53.8%, respectively, $F(1, 9) = 2.22$, $p = 0.17$. T-tests revealed

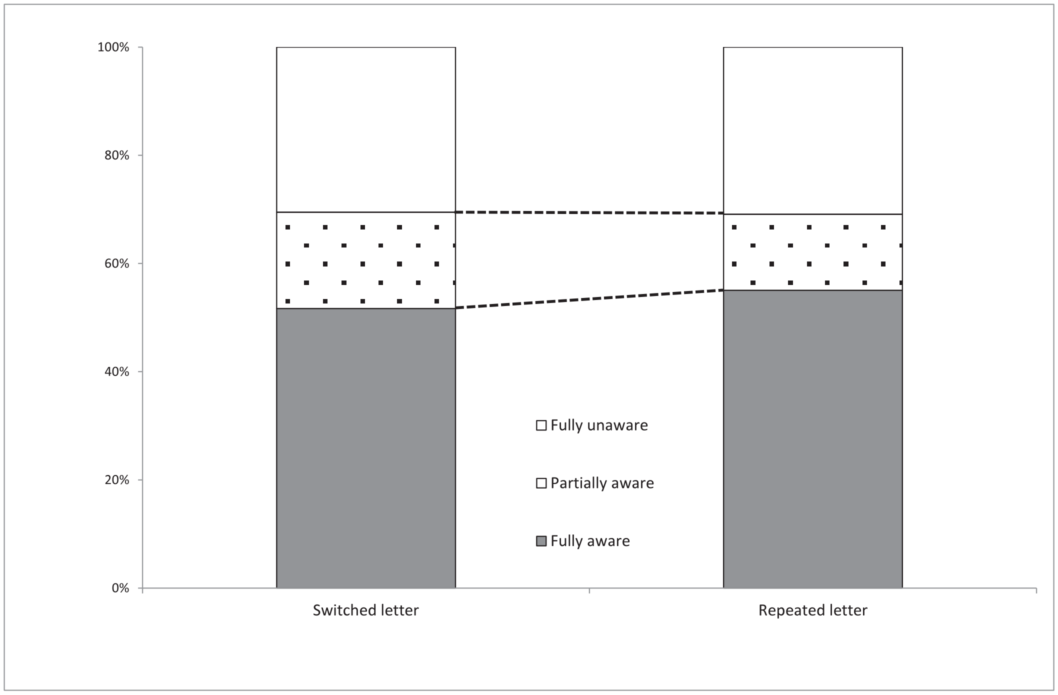

Figure 2. Distribution of probe trials as a function of subjective report of awareness of the target fully aware, partially aware, or fully unaware for repeated- versus switched-letter trials. Repeating the target letter increased the percentage of fully aware trials at the expense of partially aware trials.

that accuracy was above chance in all three conditions of awareness, all *p*s < 0.01.

Finally, we examined the effect of repeating the target letter on the subjects' accuracy at reporting its color in probe trials for each level of awareness (Figure 3). Planned comparisons showed that repetition effects were significant only when the subjects were fully aware of the target shape, $F(1, 9) = 6.81$, $p < 0.03$, with an accuracy benefit of 9.6% in repeated- relative to switched-letter trials. There was no repetition effect in either the partially aware or the fully unaware condition, both *F*s < 1.

Awareness of the target letter in the current trial was highly correlated with accuracy in reporting the target color: Participants were highly accurate when they were fully aware of the target but much less so when they were either partially aware or fully unaware of the target. It is therefore possible to claim that correct performance in the probe trial, even if it is not accompanied by conscious awareness, may be sufficient for priming, but in the present experiment, there was too little processing of the target in partially aware and fully unaware trials to support any priming effect. Indeed, although accuracy was significantly above chance in both trial types, it was only slightly so.

We tested this alternative account using two slightly different procedures. First, we examined whether subjects' accuracy in partially aware trials was correlated with the magnitude of the priming effect. We found no correlation, $r(8) = -0.11$. Second, we also looked at the magnitude of priming for subjects whose accuracy in partially aware trials was above the group's median. We found that while priming in aware trials was still significant for this group, 14.0%, $F(1, 4) = 7.82$, $p < 0.05$, priming in partially unaware trials (in which mean accuracy was 74.9%) was nonsignificant, 2.2%, $F < 1$. Although the foregoing analyses were admittedly conducted on a relatively small number of participants, they are at least suggestive of the conclusion that correct performance is not sufficient for feature priming.

The results of Experiment 1 yielded two main findings. First, they showed that repetition of the target letter increased the proportion of trials in which subjects reported being fully aware of the target at the expense of trials in which they reported partial awareness. This finding suggests that feature priming enhances access to conscious awareness of the target shape only in cases in which the observer partially sees the target shape. Second, we observed dramatically different effects of letter repetition, depending on whether the subjects were aware or unaware of the target shape in the probe trial, despite the fact that stimulus conditions were identical in all conditions of awareness: There was no priming effect at all unless the subjects were fully aware of the target.

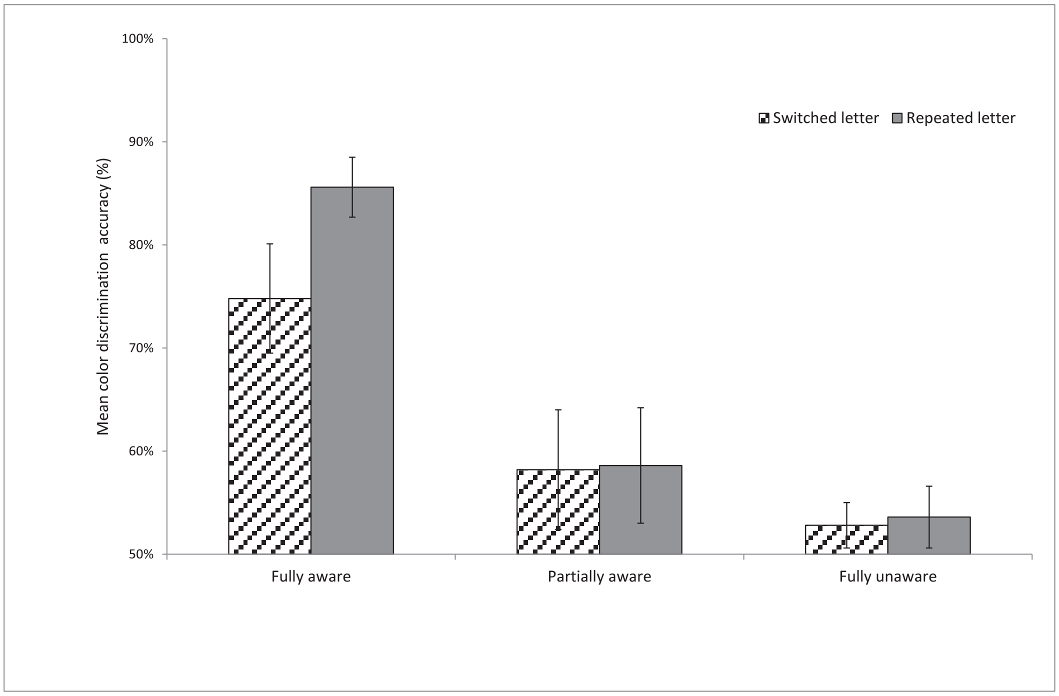

Figure 3. Mean percentage of correct responses for repeated- versus switched-letter trials by condition of subjective report of awareness of the target in the probe trial (fully aware, partially aware, fully unaware) in Experiment 1. Feature priming occurred only when participants were fully aware of the target in the current (probe) trial.

Experiment 2

In this experiment, we investigated whether conscious perception of the target in the prime display is necessary for feature priming. This experiment was similar to Experiment 1 except that the prime display was masked; whereas the probe display was not. Thus, we expected high accuracy in probe trials, that is, in the trials in which priming effects could be measured. The primary dependent measure in this experiment, therefore, was reaction time.

Method

Participants

Participants were 17 Tel-Aviv University students (10 female) who volunteered to participate in the experiment. All were right-handed and reported normal or corrected-to-normal visual acuity and normal color vision.

Apparatus, stimuli, procedure, and design

The apparatus, stimuli, procedure, and design were similar to those of Experiment 1 except for the following changes: In the first trial of each trial pair (prime trial), the search display was masked; whereas in the second trial (probe trial), the search display was not masked and remained visible until response. Participants again responded to the target's color in both prime and probe trials. The primary dependent variable was response latency in probe trials although accuracy data were also analyzed.

Results and discussion

Three participants were excluded from the analysis because they were at chance on their responses to the prime (masked) display in trials in which they reported being fully aware of the target shape. In addition, one participant used the "fully unaware" response in fewer than 5% of the trials. Thus, the data from 13 participants were analyzed. Trial pairs with RTs exceeding the mean RT by more than 2.5 standard deviations were excluded from the RT analyses (2.5% of all trials).

In this experiment, subjects reported being fully aware of the target in the probe (masked) display in 56.91% of the trials, partially aware in 18.93% of the trials, and fully unaware in 24.16% of the trials. The mean display exposure duration set during the calibration phase and used in the prime trials of the experimental phase was 109 ms ($SD = 52$ ms).

Mean accuracy at reporting the color of the target letter in prime (masked) trials varied significantly as a function of the subjects' reported awareness of its

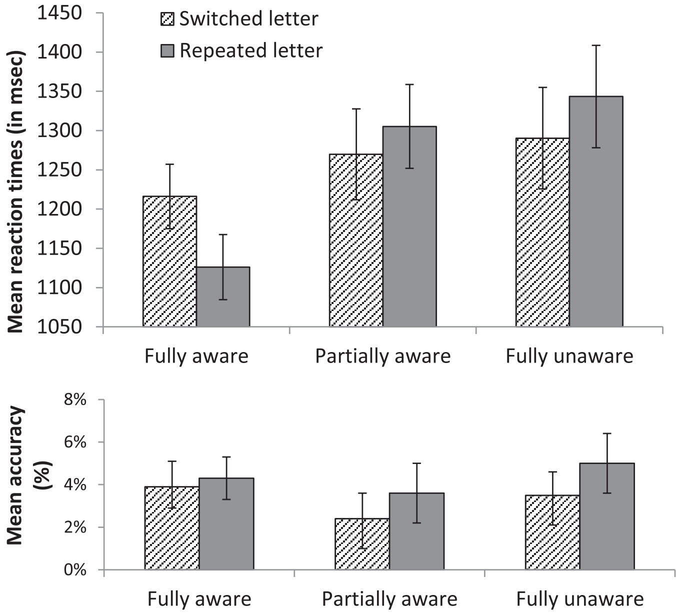

Figure 4. Mean RTs in milliseconds (upper panel) and percentage of correct responses (lower panel) for repeated- versus switched-letter trials by condition of subjective report of awareness of the target in the prime trial (fully aware, partially aware, fully unaware) in Experiment 2. Feature priming occurred only when participants were fully aware of the target in the previous (prime) trial (upper panel).

shape, $F(2, 26) = 83.62$, $p < 0.0001$. Accuracy was higher when subjects reported being fully aware versus partially aware of the target letter, 91.2% versus 68.8%, $F(1, 13) = 61.59$, $p < 0.0002$, and when they reported being partially aware versus fully unaware of it, 68.8%, versus 56.9%, $F(1, 13) = 14.31$, $p < 0.003$. T tests revealed that accuracy was above chance in all three conditions of awareness, all ps < 0.01.

Next, we examined whether awareness of the target letter in the prime (masked) trial was necessary for observing a performance benefit in probe trials when the target letter repeated (Figure 4).

Reaction times

Planned comparisons revealed that repeating the target letter from the prime (masked) trial to the probe trial improved performance only when the subjects had been fully aware of the target letter in the prime trial, $F(1, 13) = 6.19$, $p < 0.03$, but not when they were either partially aware or fully unaware of it, respectively, both Fs < 1.

In the present experiment, awareness of the target letter in the previous trial was highly correlated with accuracy in reporting the target's color. It is therefore possible to claim that correct performance may be sufficient for letter encoding in the prime trial even if it is not accompanied by awareness. Performance in the prime (masked) trials was above chance in both the partially aware and fully unaware conditions with 68.8% and 56.9% accuracy, respectively. If accurate performance was the critical factor for letter-repetition benefits, then some trend toward a repetition effect might become apparent for the subset of the data with correct performance in the prime trial. This is especially so in the partially aware condition because in the fully unaware condition performance was only slightly (albeit significantly) above chance.

We conducted the same planned analyses while excluding trials for which responses in the previous (prime masked) trial had been incorrect. The letter repetition effect was again significant when the subjects had been fully aware of the target letter in the previous trial, $F(1, 13) = 16.01$, $p < 0.003$, yet again not when they had been either partially aware or fully unaware of it, both ps > 0.2.

In addition, as in the previous experiment, we examined whether subjects' accuracy in partially aware trials was correlated with the magnitude of the priming effect and found no correlation, $r(12) = 0.06$. We also looked at the magnitude of priming for subjects whose accuracy in partially aware trials was above the group's median. While priming in fully aware trials was still significant for this group, 143 ms, $F(1, 6) = 41.85$, $p < 0.0006$, priming in partially unaware trials (in which mean accuracy was 79.7%) was nonsignificant, 17 ms, $F < 1$.

Accuracy

No effect approached significance, all Fs < 1.

Taken together, these results suggest that full awareness of the target letter during the prime trial is necessary to create memory traces that affect perceptual processing of the target in the next trial.

General discussion

In the present study, we showed that full awareness is necessary for feature priming. Although stimulation was identical in all respects between the three conditions of awareness, a feature-priming benefit in objective performance (RTs or accuracy) occurred only when subjects reported being fully aware of the target both at encoding (that is, in the prime trial, Experiment 2) and at retrieval (that is, in the probe trial, Experiment 1). In addition, we showed that feature priming improves full access of the repeated target to awareness but only for targets that already achieved partial access to awareness. Taken together, these findings are consistent with the idea that feature priming does not affect attentional priority but later stages of processing in which attention is engaged on the target once it has been detected (e.g., Amunts & Lamy, 2012; Yashar & Lamy, 2010a, 2010b).

The present findings go further by suggesting that attentional engagement may not be sufficient for feature priming. Indeed, objective search performance was above chance when subjects reported being only partially aware of the target (and substantially so for half of the subjects), suggesting that the target was successfully detected and attention was engaged on the target in a large portion of these trials, yet no priming whatsoever was found. Therefore, it seems that speeding of attentional engagement on an object as a result of traces from a previous selection event requires that the object be consciously perceived.

In this study, we used letters, that is, relatively complex stimuli, that may have yielded a serial rather than a parallel search. It is therefore possible to claim that our findings might not generalize to a simple feature search to which most of the research on feature priming pertains. In other words, it may be the case that the effects of target feature repetition are contingent upon conscious perception of the target only in conjunction (serial) search but not in feature (parallel) search.[3]

In order to address this possibility, we divided the set of letter pairs used in our experiments into a "feature set" and a "conjunction set." Relying on previous research (e.g., Beck & Ambler, 1973; Bergen & Julesz, 1983), we assumed that the seriality of search (reflected by slope sizes) depends, at least in part, on the extent to which the target and homogenous distractors can be distinguished by a unique feature. Accordingly, we included letter pairs that can be distinguished by a unique feature in the "feature set." For instance, when looking for a unique V among Ls, a feature (the slanted lines present in the V target and absent in the L distractors) can guide search. By contrast, in letter pairs such as T and L, for instance, both letters include the same features, and they can be distinguished only based on the spatial conjunction of their features. Such letters therefore belong to the "conjunction set."

We reasoned that if conscious perception of the target is required only for target repetition effects in serial search, PoP effects should be observed for letters belonging to the feature set even when observers report being fully (or even only partially) unaware of the target. The results did not confirm this prediction. On the one hand, search, indeed, tended to be easier for letters in the feature set relative to the conjunction set. On the other hand, however, in both experiments, PoP was totally absent in the fully unaware and partially aware conditions (while still significant in the fully aware condition) for both the feature and conjunction set letters. Thus, the data do not suggest that our findings are specific to conjunction search. Admittedly, however, even when letters can be distinguished by a unique feature, letter search may be more complex (and less parallel) than pop-out search, for which the feature-search phenomenon is typically studied. Further research is therefore needed to test this alternative account more directly.

Our study is the first attempt to examine the role of awareness in feature priming in healthy participants. A previous study by Kristjánsson, Vuilleumier, Malhotra, Husain, and Driver (2005) addressed the relationship between conscious perception and feature priming with neglect patients. Visual neglect is a condition that results from unilateral brain damage in the parietal lobe. Neglect patients are characteristically unaware of the contralesional side of space, such that in visual search, they often fail to detect targets that appear in their contralesional field. Kristjánsson et al. (2005, experiment 3) required two neglect patients to search for a color singleton target in a task similar to Maljkovic and Nakayama's (1994, experiment 3) while also reporting whether or not they had consciously perceived the target in each trial.

In one analysis, Kristjánsson et al. (2005) showed that when the target appeared on the contralesional field in the current trial, there was color priming, such that neglect subjects were at chance when the target color changed and reached close to 75% accuracy performance when the target color repeated. However, in this analysis, the authors did not distinguish between trials in which their two neglect patients were aware versus unaware of the target in the current trial (which occurred in roughly equal proportions). Thus, Kristjánsson et al. (2005) did not address the questions we examined in the first experiment of the present study, namely, (a) whether priming increases the probability that the target accesses conscious awareness and (b) whether awareness of the target in the current trial is necessary for feature priming.

In a second analysis, Kristjánsson et al. (2005, experiment 3) examined the effects of color priming when the current target appeared in the contralesional (bad) field but separately (a) when the previous target had appeared in the contralesional versus in the ipsilesional field and (b) when the target that had appeared in the contralesional side in the previous trial had been consciously detected versus not detected. The authors reported that, regardless of the patients' awareness of the target in the previous trial, there was a significant effect of color priming. They concluded that awareness of the target at encoding is not necessary for color priming, a conclusion that is at odds with the findings of the second experiment of the present study. Curiously, however, when the target had appeared in the ipsilesional (good) field in the previous trial and encoding should therefore have been very good, performance was at chance. This unexpected finding was not accounted for and may therefore invite caution in interpreting the critical results emanating from targets that had appeared in the contralesional field in the previous trial.

It is noteworthy in this regard that neglect is thought to reflect a deficit of attention (e.g., Mesulam, 1981). While some forms of masking are thought to also involve attentional processes (e.g., metacontrast masking, Di Lollo, Enns, & Rensnik, 2000), pattern masking as used in the present study is thought to involve integration between the target and the mask and therefore to degrade the quality of the stimulus (Breitmeyer & Ögmen, 2006). It is therefore possible that our findings may not generalize to cases in which conscious perception is prevented by removing attention from the critical displays rather than by deteriorating the stimulus input. It will be important, therefore, in further research to examine the relationship between conscious perception and priming, using attentional manipulations of conscious perception (as in attentional blindness, e.g., Mack & Rock, 1998; the attentional blink, e.g., Sergent & Dehaene, 2004; or metacontrast masking, Di Lollo et al., 2000).

Finally, our findings may have implications for the relationship between conscious perception and memory. In particular, we interpreted the findings of Experiment 2 as showing that intertrial feature priming is contingent upon conscious perception of the target in the prime trial. However, our findings may also indicate that encoding in the implicit short-term memory store that supports feature priming is a necessary condition for access to conscious perception. In other words, if intertrial priming is viewed as an indicator of successful encoding of the target in short-term memory, then the finding that there is no conscious perception of the target when feature priming is absent may indicate that conscious perception is dependent on access to short-term memory.

Conclusions

Our findings clarify the functional role of the implicit memory system that drives priming effects. While we don't purposefully or successfully remember the properties that characterize recently attended objects, only those objects that were granted attentional resources and conscious access in the recent past benefit from speeded processing. Likewise, if you just saw an accident involving a blue car, you will be faster to process the blue car waiting at the traffic light in the few moments that follow but not unless you attend to it and are at least partially aware of it. In other words, implicit priming does not appear to change our priorities but to increase our efficiency at processing prioritized events.

Keywords: intertrial priming, priming of pop-out, feature priming, visual consciousness, visual awareness

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Corresponding author: Dominique Lamy.
Email: domi@post.tau.ac.il.
Address: School of Psychological Sciences, Tel Aviv University, Ramat-Aviv, Tel Aviv, Israel.

Footnotes

[1] Subsequent research (e.g., Geyer, Müller, & Krummenacher, 2006; Hillstrom, 2000; Kristjánsson, Wang, & Nakayama, 2002; Wang, Kristjánsson, & Nakayama, 2005) has shown that it occurs also during serial search, that is, when the target does not pop out from the display. A more appropriate label would therefore be "intertrial repetition priming of the target's defining feature," but for conciseness purposes, we will refer to it as "feature priming" or "priming" in the remainder of this article.

[2] Such a high exclusion rate is customary in experiments that measure conscious perception with liminal stimulus exposures (e.g., Eimer & Mazza, 2005; Wilenius & Revonsuo, 2007; Woodman, 2010; Woodman & Luck, 2003).

[3] We thank Hermann Müller for this suggestion.

References

Amunts, L., & Lamy, D. (2012). *Inter-trial priming does not affect attentional priorities: An emotional priming of pop-out study*. Manuscript under review.

Beck, J., & Ambler, B. (1973). The effects of concentrated and distributed attention on peripheral acuity. *Perception & Psychophysics, 14*(2), 225–230, doi:10.3758/BF03212381.

Becker, S. I. (2008). The mechanism of priming:

Episodic retrieval or priming of pop-out? *Acta Psychologica, 127,* 324–339.

Bergen, J., & Julesz, B. (1983). Parallel versus serial processing in rapid pattern discrimination. *Nature, 303*(5919), 696–698, doi:10.1038/303696a0.

Bichot, N. P., & Schall, J. D. (2002). Priming in macaque frontal cortex during popout visual search, feature-based facilitation and location-based inhibition of return. *The Journal of Neuroscience, 22,* 4675–4685.

Breitmeyer, B., & Ögmen, H. (2000). Recent models and findings in visual backward masking: A comparison, review, and update. *Perceptual Psychophysics, 62,* 1572–1595.

Breitmeyer, B., & Ögmen, H. (2006). *Visual masking: Time slices through conscious and unconscious vision* (2nd ed.). Oxford, UK: Oxford University Press.

Chun, M. M., & Jiang, Y. (1998). Contextual cueing: Implicit learning and memory of visual context guides spatial attention. *Cognitive Psychology, 36,* 28–71.

Chun, M. M., & Nakayama, K. (2000). On the functional role of implicit visual memory for the adaptive deployment of attention across scenes. *Visual Cognition, 7,* 65–82.

Dehaene, S., Changeux, J. P., Naccache, L., Sackur, J., & Sergent, C. (2006). Conscious, preconscious and subliminal processing: A testable taxonomy. *Trends in Cognitive Sciences, 10,* 204–211.

Di Lollo, V., Enns, J. T., & Rensnik, R. A. (2000). Competition for consciousness among visual events: The psychophysics of reentrant processes. *Journal of Experimental Psychology: General, 129,* 481–507.

Eimer, M., Kiss, M., & Cheung, T. (2010). Priming of pop-out modulates attentional target selection in visual search: Behavioural and electrophysiological evidence. *Vision Research, 50,* 1353–1361.

Eimer, M., & Mazza, V. (2005). Electrophysiological correlates of change detection. *Psychophysiology, 42,* 328–342.

Found, A., & Müller, H. J. (1996). Searching for unknown feature targets on more than one dimension: Investigating a "dimension-weighting" account. *Perception & Psychophysics, 58,* 88–101.

Geyer, T., Müller, H. J., & Krummenacher, J. (2006). Cross-trial priming in visual search for singleton conjunction targets: Role of repeated target and distractor features. *Perception & Psychophysics, 68,* 736–749.

Goolsby, B. A., & Suzuki, S. (2001). Understanding priming of color singleton search: Roles of attention at encoding and "retrieval." *Perception & Psychophysics, 63*(6), 929–944.

Hillstrom, A. P. (2000). Repetition effects in visual search. *Perception & Psychophysics, 62,* 800–817.

Huang, L., Holcombe, A. O., & Pashler, H. (2004). Repetition priming in visual search: Episodic retrieval, not feature priming. *Memory & Cognition, 32*(1), 12–20.

Huang, L., & Pashler, H. (2005). Attention capacity and task difficulty in visual search. *Cognition, 94,* B101–B111.

Kentridge, R. W., Nijboer, T. C., & Heywood, C. A. (2008). Attended but unseen: Visual attention is not sufficient for visual awareness. *Neuropsychologia, 46,* 864–869.

Koch, C., & Tsuchiya, N. (2007). Attention and consciousness: Two distinct brain processes. *Trends in Cognitive Sciences, 11,* 16–22.

Koch, C., & Tsuchiya, N. (2011). Attention and consciousness: Related yet different. *Trends in Cognitive Sciences, 16,* 103–105.

Kristjánsson, A., & Campana, G. (2010). Where perception meets memory: A review of repetition priming in visual search tasks. *Attention, Perception & Psychophysics, 72,* 5–18.

Kristjánsson, Á., Vuilleumier, P., Malhotra, P., Husain, M., & Driver, J. (2005). Priming of color and position during visual search in unilateral spatial neglect. *Journal of Cognitive Neuroscience, 17,* 859–873.

Kristjánsson, A., Wang, D., & Nakayama, K. (2002). The role of priming in conjunctive visual search. *Cognition, 85,* 37–52.

Lamy, D., Amunts, L., & Bar-Haim, Y. (2008). Emotional priming of pop-out in visual search. *Emotion*, *8*(2), 151–161.

Lamy, D., Bar-Anan, Y., & Egeth, H. E. (2008). The role of within-dimension singleton priming in visual search. *Journal of Experimental Psychology: Human Perception & Performance, 34,* 268–285.

Lamy, D., Bar-Anan, Y., Egeth, H. E., & Carmel, T. (2006). Effects of top-down guidance and singleton priming on visual search. *Psychonomic Bulletin & Review*, *13*(2), 287–293.

Lamy, D., Carmel, T., Egeth, H. E., & Leber, A. B. (2006). Effects of search mode and intertrial priming on singleton search. *Perception & Psychophysics*, *68*(6), 919–932.

Lamy, D., Leber, A. B., & Egeth, H. E. (2012). Selective attention. In A. F. Healy & R. W. Proctor

(Eds.), *Comprehensive handbook of psychology: Vol. 4. Experimental psychology* (4th ed., editor-in-chief I. B. Weiner) (pp. 265–294). New York: Wiley.

Lamy, D., Yashar, A., & Ruderman, L. (2010). A dual-stage account of inter-trial priming effects. *Vision Research, 50*(14), 1396–1401, doi:10.1016/j.visres.2010.01.008.

Lamy, D., Zivony, A., & Yashar, A. (2011). The role of search difficulty in intertribal feature priming. *Vision Research, 51*(19), 2099–2109, doi:10.1016/j.visres.2011.07.010.

Levitt, H. (1971). Transformed up–down methods in psychoacoustics. *Journal of the Acoustical Society of America, 49,* 467–477.

Mack, A., & Rock, I. (1998). *Inattentional blindness*. Cambridge, MA: MIT Press.

Maljkovic, V., & Nakayama, K. (1994). Priming of popout: I. Role of features. *Memory and Cognition, 22,* 657–672.

Maljkovic, V., & Nakayama, K. (1996). Priming of pop-out: II. The role of position. *Perception and Psychophysics, 58,* 977–991.

Mesulam, M. (1981). A cortical network for directed attention and unilateral neglect. *Annals of Neurology, 10,* 309–325.

Moore, C. M., & Egeth, H. (1998). How does feature-based attention affect visual processing? *Journal of Experimental Psychology: Human Perception and Performance, 24,* 1296–1310.

Pascucci, D., Mastropasqua, T., & Turatto, M. (2012). Permeability of priming of pop out to expectations. *Journal of Vision*, *12*(10):21, 1–13, http://www.journalofvision.org/content/12/10/21, doi:10.1167/12.10.21. [PubMed] [Article]

Sergent, C., & Dehaene, S. (2004). Is consciousness a gradual phenomenon? Evidence for an all-or-none bifurcation during the attentional blink. *Psychological Science, 15,* 720–728.

Sigurdardottir, H. M., Kristjánsson, Á., & Driver, J. (2008). Repetition streaks increase perceptual sensitivity in brief visual search displays. *Visual Cognition, 16,* 643–658.

Töllner, T., Rangelov, D., & Müller, H. J. (2012). How the speed of motor-response decisions, but not focal-attentional selection, differs as a function of task set and target prevalence. *Proceedings of the National Academy of Science, USA, 109*(28), E1990–E1999.

Wang, D., Kristjánsson, Á., & Nakayama, K. (2005). Efficient visual search without top-down or bottom-up guidance. *Perception & Psychophysics, 67,* 239–253.

Wilenius, M. E., & Revonsuo, A. T. (2007). Timing of the earliest ERP correlate of visual awareness. *Psychophysiology, 44,* 703–710.

Woodman, G. (2010). Masked targets trigger event-related potentials indexing shifts of attention but not error detection. *Psychophysiology, 47,* 1–5.

Woodman, G., & Luck, S. (2003). Serial deployment of attention during visual search. *Journal of Experimental Psychology: Human Perception and Performance, 29,* 121–138.

Yashar, A., & Lamy, D. (2010a). Intertrial repetition affects perception: The role of focused attention. *Journal of Vision*, *10*(14):3, 1–8, http://www.journalofvision.org/content/10/14/3, doi:10.1167/10.14.3. [PubMed] [Article]

Yashar, A., & Lamy, D. (2010b). Intertrial repetition facilitates selection in time: Commonmechanisms underlie spatial and temporal search. *Psychological Science, 23,* 243–251.

Yashar, A., & Lamy, D. (2011). Refining the dual-stage account of intertrial feature priming: Does motor response or response feature matter? *Attention, Perception, & Psychophysics, 73,* 2160–2167.

Yashar, A., & Lamy, D. (2013). Temporal position priming: Memory traces of recent experience bias the allocation of attention in time. *Journal of Experimental Psychology: Human Perception & Performance*.