Vision Research 51 (2011) 2099–2109

Contents lists available at SciVerse ScienceDirect

Vision Research

journal homepage: www.elsevier.com/locate/visres

The role of search difficulty in intertrial feature priming

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ARTICLE INFO

Article history:
Received 14 February 2011
Received in revised form 10 June 2011
Available online 19 July 2011

Keywords:
Visual search
Attention
Intertrial priming
Priming of pop-out
Episodic retrieval

ABSTRACT

Previous research has shown that intertrial repetition of target and distractors task-relevant properties speeds visual search performance, an effect known as priming of pop-out (PoP). Recent accounts suggest that such priming results, at least in part, from a mechanism that speeds post-selectional, response-related processes, the marker of which is an interaction between repetition of the target and distractor features and repetition of the response from the previous trial. However, this response-based component of inter-trial priming has been elusive, and it remains unclear what its boundary conditions might be. In addition, what information is represented in the episodic memory traces that underlie the response-based component has not yet been characterized.

Here, we show that the response-based component of feature priming reflects an episodic memory retrieval mechanism that is not mandatory or automatic but may be described as a heuristic that subjects sometimes use, in particular when the overall difficulty of the search task is high. In addition, we show that the conjunction of the target and distractor features forms the context that is reactivated during episodic retrieval. Finally, we show that target–distractor discriminability is an important modulator of the selection-based component. The findings are discussed within the framework of the dual-stage model of inter-trial priming (Lamy, Yashar, & Ruderman, 2010).

1. Introduction

Our senses are constantly exposed to more information than our brains can process simultaneously. Selective attention refers to the mechanisms that help us deal with processing capacity limitations by filtering the stream of information. Most models of attention posit that both stimulus-driven and goal-directed factors contribute to directing attention to objects in a visual scene (e.g., Bundesen, 1990; Cave & Wolfe, 1990; Grossberg, Mingolla, & Ross, 1994; Itti & Koch, 2000; Treisman & Sato, 1990; Wolfe, 1994). However, recent research has demonstrated that attention is also directed by past experience: how attention is deployed at a certain moment in time greatly affects how attention will be deployed a moment later (see Kristjánsson and Campana (2010), for a recent review). Such effects have been most often demonstrated in the context of visual search. When the target is defined as the unique item on some dimension, reaction times (RTs) are considerably shorter if, on consecutive trials, the target happens to be unique on the same dimension (dimension repetition effects, e.g., Found & Müller, 1996; Müller, Krummenacher, & Heller, 2004; Müller, Reimann, & Krummenacher, 2003; Töllner, Gramann, Müller, Kiss, & Eimer, 2008), to have the same defining feature (feature priming of pop-out, e.g., Maljkovic & Nakayama, 1994) or to appear at the same location (position priming of pop-out, Maljkovic & Nakayama, 1996). Such repetition effects have also been shown to occur when the target happens to appear at the same temporal position within a rapid serial visual presentation (RSVP) stream on two consecutive trials (Yashar & Lamy, 2010; see Kristjánsson, Eyjólfsdóttir, Jónsdóttir, and Arnkelsson (2010) for related findings). Performance benefits can be very substantial, on the order of several tens of milliseconds. However, it is not clear what processes during visual search are affected by such repetitions. In this article, we focus on the mechanisms underlying the priming of pop-out effect (henceforth, PoP).

1.1. Selection, post-selection and hybrid accounts of PoP

Several accounts of the locus of intertrial facilitation effects in PoP have been suggested, with the main dividing line running between accounts claiming that PoP speeds selection vs. post-selection processes. According to selection-based accounts, repeating the target feature speeds selection of the target either by increasing the target's relative salience (e.g., Becker, 2008; Maljkovic & Nakayama, 1996) or by speeding attentional shifts/engagement (Yashar & Lamy, 2010). According to post-selection accounts PoP is manifested after selection, and speeds either a decision stage that occurs after a candidate target has been located (Huang,

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[1] Support was provided by the Binational Science Foundation (BSF) grant no. 2009425.

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doi:10.1016/j.visres.2011.07.010

Holcombe, & Pashler, 2004; Huang & Pashler, 2005), or selection/execution of the motor response (e.g., Cohen & Magen, 1999). However, newer accounts of PoP suggest that neither selection nor post-selection views on PoP can aptly accommodate the wealth of data that has accumulated.

1.2. The "ambiguity" account of PoP

Meeter and Olivers (2006; see also Olivers & Meeter, 2006) have suggested an ambiguity account of PoP, according to which ambiguity in the stimulus or task underlies the occurrence of intertrial priming. Specifically, they proposed that "if it is ambiguous what the target is, visual selection will rely relatively more on what was selected in previous trials. If it is ambiguous what the response should be, response selection will rely more heavily on what response was coupled with a stimulus on previous trials" (Meeter & Olivers, 2006). In other words, they suggested that PoP facilitates either selection or post-selection mechanisms depending on the stage at which the ambiguity arises. On the one hand, they reported enhanced PoP with small relative to large search set sizes (Meeter & Olivers, 2006, Experiment 1) and when an irrelevant singleton distractor was also present in the display relative to when it was absent (Meeter & Olivers, 2006, Experiment 2). They attributed such modulations to increased ambiguity at the selection level, because they held both manipulations to exacerbate competition between the target and distractors. On the other hand, they also reported enhanced PoP in present/absent tasks relative to compound task (Olivers & Meeter, 2006). They attributed such modulation of PoP to increased uncertainty at a later level, namely, at the level at which the relationship between stimulus and response is assessed, and claimed that such a relationship is more ambiguous in detection than in compound search tasks.

Although these experiments provide compelling evidence that stimulus- and task-related factors can substantially modulate PoP, the concept of ambiguity is rather vague. For instance, Olivers and Hickey (2010) had their participants search for a color singleton target and measured interference caused by a salient distractor that differed from the target either only in color or also in shape and size. They found the two singleton distractor types to interfere with search to the same extent, and yet to be associated with PoP effects that differed in magnitude: the PoP effect was larger when the singleton distractor differed from the target only in color than when it differed from it also in shape and size. Although the authors interpreted their results as supporting the ambiguity hypothesis, it is not clear how one might characterize the ambiguity that is held to have increased the magnitude of the PoP effect in that study. Indeed, interference caused by the presence of an irrelevant distractor is typically thought to reflect the competitive advantage of this distractor relative to the target (e.g., Theeuwes, 1992), yet modulation of the PoP effect in this experiment did not result from differences in the competitive strength of the two distractor types because there was no evidence for such a difference. The conclusion from all this is that failure to come up with a clear *a priori* definition of ambiguity carries the risk of circularity: a manipulation renders the task more ambiguous if it increases the magnitude of the PoP effect.

1.3. The dual-stage account of PoP

Recently, we proposed a dual-stage account of PoP which is also aimed at accommodating the apparently conflicting findings brought forward in support of the selection-based accounts on the one hand and in support for post-selection accounts on the other hand (Lamy, Yashar, & Ruderman, 2010; see Töllner et al. (2008) for a similar account with regard to dimension priming). According to this account, PoP affects search at two different stages of the visual search process: an early, selection-related stage and a later, response-related stage. We tested this conjecture by tracking the time course of the hypothesized components of PoP. We reasoned that a purely perceptual component of PoP should become apparent early in a search trial and should not be affected by response factors. By contrast, we predicted that a response-based component of PoP should be manifested later and emerge as an interaction between repetition of the target defining feature and response repetition. The results of our study (Lamy et al., 2010) confirmed these predictions: we showed that PoP emerged within 100 ms during the search and interacted with repetition of the response feature only later (after 200–400 ms).

It should be noted that the initial finding on which PoP was based was that a target popped out faster when the target's defining feature repeated than when it changed, which led Maljkovic and Nakayama (1994) to label this phenomenon "priming of pop-out". Since their seminal paper, however, several findings have been reported that render this label problematic. First, inter-trial target feature repetition effects have been demonstrated in search tasks in which the target did not pop out (e.g., Hillstrom, 2000; Kristjánsson, Wang & Nakayama, 2002; Lamy, Kosover, Aviani, Harari & Levkovitz, 2008). In addition, as the dual-stage model suggests (Lamy et al., 2010; Töllner et al., 2008), the PoP effect is best viewed as an aggregate of separate repetition effects that reflect two very different mechanisms: one speeding selection and the other unfolding only after selection. The term "PoP" leaves out the response-based component of the reported effect. Therefore, we suggest that the indubitably less catchy label of "inter-trial defining feature repetition priming" (or its shorter version "inter-trial feature priming") is more appropriate to describe the effect. In addition, this label also underscores the similarity between the effect of repeating the target *defining feature* and the intertrial *dimension* priming effect described by Müller and colleagues (e.g., Found & Müller, 1996; Töllner et al., 2008).

1.4. What may account for the volatility of the response-based component of intertrial feature priming?

The magnitude of the intertrial feature priming effect has been shown to vary greatly from one study to the other (e.g., Hillstrom, 2000; Meeter & Olivers, 2006; Olivers & Meeter, 2006). According to ambiguity theory, uncertainty in the task accounts for such variability. Yet, as we claimed above, the notion of uncertainty is not constrained or precise enough to clarify the mechanisms that underlie feature priming and how they are affected by the variables that were shown to modulate the effect. Thus, to provide a meaningful account of feature priming in visual search, the dual-stage model should relate these modulating variables to its selection- and response-based components and specify the conditions under which the effects of each component can be observed.

In a recent study (Yashar & Lamy, 2011), we pursued this goal and investigated under what conditions the perceptual component of inter-trial feature priming is manifested. In the present study, we investigated under which conditions the response-based component is manifested. The interaction between repetition of the defining feature and response repetition is a marker of the response-related component of inter-trial priming. When repetition of the target defining feature and repetition of the response interact, feature priming is larger when the response also repeats than when it does not; in addition, if the target feature does not repeat, performance is worse if the response repeats than if it does not (e.g., Huang et al., 2004). According to the dual-stage model of inter-trial priming (Lamy et al., 2010; see also Töllner et al., 2008), this effect occurs because the previous search episode is retrieved before responding: if there is a match between the traces from the previous trial and the properties of the current trial, the same response is activated and same-response trials are faster than different-response trials. If there is a mismatch, the opposite effect is observed.

However, the few studies which reported whether or not such interaction occurred did not yield a consistent picture. While the interaction was observed in some experiments (e.g., Huang et al., 2004, Exp.1; Becker, 2008; Hillstrom, 2000, Exp. 3; Lamy et al., 2010; Meeter & Olivers, 2006, Exp.1) it did not emerge in others (e.g., Meeter & Olivers, 2006, Exp. 1; Becker, 2008; Olivers & Meeter, 2006, Exp. 1 & 2). Thus, the conditions under which the response-related component is observed remain to be characterized.

Comparison of the displays used in these studies suggests that target–distractor similarity may play an important role in determining whether or not defining feature repetition interacts with repetition of the response. For instance, in studies in which target and distractors features were highly discriminable (e.g., red vs. green, white vs. black, small vs. twice as large) no interaction was observed (Lamy, Bar-Anan, Egeth, 2008; Lamy, Kosover, et al., 2008; Meeter & Olivers, 2006, Exp. 1; Becker, 2008; Olivers & Meeter, 2006, Exp. 1 & 2). By contrast, in studies in which the target and distractors were similar (e.g., purple vs. pink, Hillstrom, 2000, Exp. 1) or display heterogeneity was large (e.g., both the target and distractors varied randomly in size and color, Huang et al., 2004), the interaction was significant. Post-hoc comparisons between different studies, however, do not suffice to validate the notion that the response-related component of PoP may be contingent on low target–distractor discriminability. Therefore, our first objective in the present study was to provide a direct test for this hypothesis.

2. Experiment 1

In this experiment, subjects searched for a target defined as the item with a unique color among homogenously colored distractors. In one condition, target–distractor discriminability, operationally defined by level of color contrast, was low, whereas in the other condition, discriminability was high. Subjects had to respond to the orientation of a rotated T inside the target. We expected (1) inter-trial feature priming to be larger when the task is more difficult (as reported by Meeter and Olivers (2006) and Olivers and Meeter (2006)) and (2) repetition of the target and distractors defining features and repetition of the response feature to interact, with a larger feature priming effect when the response feature repeats than when it changes on consecutive trials (as reported by Huang and Pashler (2005), Lamy et al. (2010), and Olivers and Meeter (2006)). Of main interest, however, was to determine how, if at all, this interaction between defining and response features might be modulated by target–distractor discriminability.

2.1. Method

2.1.1. Subjects

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

2.1.2. Apparatus

Displays were generated by an Intel Pentium 4 computer attached to a 17″ TFT monitor, using 640 · 480 resolution graphics mode. Responses were collected via the computer keyboard. A chin-rest was used to set viewing distance at 50 cm from the monitor.

2.1.3. Stimuli

Examples of the stimulus displays are presented in Fig. 1. The fixation display was a gray plus sign ($0.2° \times 0.2°$ of visual angle), in the center of a black background. The stimulus display consisted of the fixation display with the addition of five colored outline circles, with each circle subtending 0.7° in diameter. Centered inside each circle was a T letter (0.37° in length and 0.25° in width) rotated by 90° and pointing either to the right or to the left. The display always contained either two left-pointing and three right-pointing Ts, or vice versa. T letters were drawn with a 1-pixel stroke and the circles with a 2-pixel stroke. The circles appeared at random locations within an invisible 3×3 matrix centered on the fixation point. No circle ever appeared in the central cell, where the fixation sign appeared. Each cell subtended 2° in side and each circle was centered inside its cell with a random jitter of $-0.15°$ to 0.15°.

Each display contained one circle with a unique color, the target, and four circles in a different color, the distractors. On each block of trials two possible target and distractor colors were drawn randomly from the two sets of four possible colors: In the high-discriminability condition the possible colors were: red (CIE coordinates 0.63/0.34, 18.75 cd/m^2), blue (CIE coordinates 0.20/0.22, 18.67 cd/m^2), green (CIE coordinates 0.28/0.59, 18.44 cd/m^2), and yellow (CIE coordinates 0.42/0.49, 18.32 cd/m^2). In the low-discriminability condition the possible colors were: faint red (CIE coordinates 0.29/0.27, 35.60 cd/m^2), faint blue (CIE coordinates 0.26/0.27, 36.20 cd/m^2), faint green (CIE coordinates 0.28/0.32, 42.10 cd/m^2) and faint yellow (CIE coordinates 0.31/0.33, 40.20 cd/m^2). In each condition of color discriminability, there were six possible target–distractor color pairs (red–green, red–blue, red–yellow, green–blue, green–yellow and blue–yellow).

2.1.4. Procedure

Participants were seated in a dimly lit room. The experimenter instructed them to search for the item with the unique color, defined as the target, and to determine whether the T inside the color singleton target pointed to the right (by pressing the "z" key on the computer keyboard with their right hands) or to the left (by pressing the "3" keypad key with their left hands) as quickly as possible, while maintaining high accuracy. Error trials were followed by a 500-ms feedback beep.

Each trial began with the fixation display. After 500 ms, the stimulus display followed, and remained visible for 3000 ms or until response. The screen went blank for 500 ms before the next trial began. Eye movements were not monitored, but subjects were explicitly requested to maintain fixation throughout each trial.

2.1.5. Design

The experiment included three within-subject factors: target–distractor discriminability, intertrial color repetition and intertrial response repetition. Conditions of target–distractor discriminability (High contrast vs. Low contrast) were run in two different halves of the experiment. Within each condition of color discriminability the six possible target–distractor color pairs were run in separate blocks, the order of which was randomized across subjects. Conditions of color repetition and response repetition were randomly intermixed within each block of trials. Order of color discriminability condition was counterbalanced across subjects.

Each experiment half consisted of 30 practice trials followed by the 6 experimental blocks, each including 10 practice trials followed by 60 experimental trials. Subjects were allowed a short rest after each block and were required to take a break of a few minutes between the two discriminability conditions (i.e., after six blocks), during which the instructions were repeated.

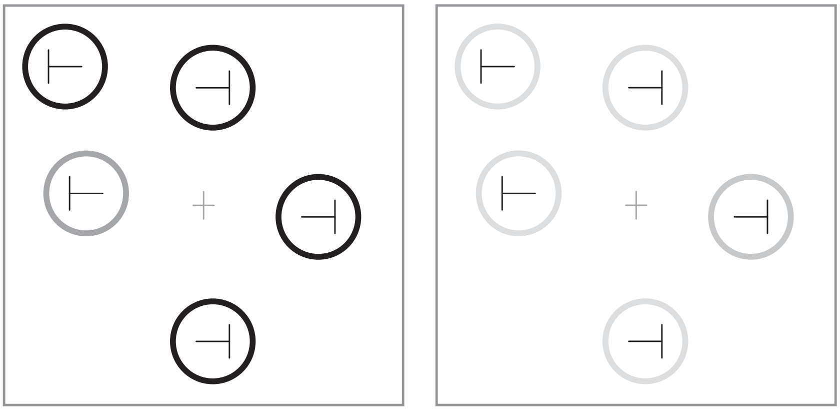

Fig. 1. Sample stimuli in Experiments 1 and 2. Left panel: High-contrast condition (target–distractor discriminability is high). Right panel: Low-contrast condition (target–distractor discriminability is low). In each condition of color discriminability, there were six possible target–distractor color pairs (red–green, red–blue, red–yellow, green–blue, green–yellow and blue–yellow), which were either strong (left panel) or faint (right panel).

2.2. Results and discussion

In all RT analyses, error trials (3.5% of all trials) and trials preceded by an error trial were removed from analysis, and so were outlier trials (less than 1% of all trials).

We conducted an ANOVA (Analysis of Variance) with color repetition (repeated target and distractors colors vs. switched target and distractors colors), response repetition (same vs. different response) and target–distractor discriminability (high vs. low) as factors. Mean RTs and accuracy rates are presented in Fig. 2.

2.2.1. Reaction times

Responses were faster when color contrast was strong than when it was weak, $F(1,7) = 50.59$, $p < 0.0003$, and when the target and distractors colors repeated than when then switched, $F(1,7) = 35.16$, $p < 0.0007$. There was no main effect of response repetition, $F(1,7) = 1.21$, $p > 0.3$. Color repetition interacted with response repetition: as expected, the color repetition effect was larger when the response repeated from the previous trial than when it changed, 139 ms vs. 97 ms, $F(1,7) = 5.82$, $p < 0.05$. The interaction between color repetition and color contrast was also significant: as expected, the color repetition effect was larger when color contrast was weak than when it was strong, 148 ms vs. 88 ms, $F(1,7) = 6.41$, $p < 0.04$. The interaction between color contrast and response repetition did not reach significance, $F(1,7) = 3.97$, $p < 0.09$. Crucially, the 3-way interaction was significant, $F(1,7) = 6.65$, $p < 0.04$.

In order to clarify this interaction, separate analyses were conducted for each level of target–distractor discriminability. For both high and low color-contrast trials, the main effect of color repetition was significant, $F(1,7) = 35.72$, $p < 0.0001$ and $F(1,7) = 25.56$, $p < 0.002$, respectively. The main effect of response repetition was non-significant in the high-contrast condition, $F < 1$, and marginally significant in the low-contrast condition, $F(1,7) = 5.44$, $p < 0.06$. Most importantly, the interaction between color repetition and response repetition was significant only when color contrast was low. Specifically, color repetition effects were larger on same- than on different-response trials, 180 ms vs. 117 ms, when color contrast was low, $F(1,7) = 6.99$, $p < 0.04$, but not significantly so when color contrast was high, 98 ms vs. 78 ms, $F(1,7) = 2.55$, $p > 0.15$.

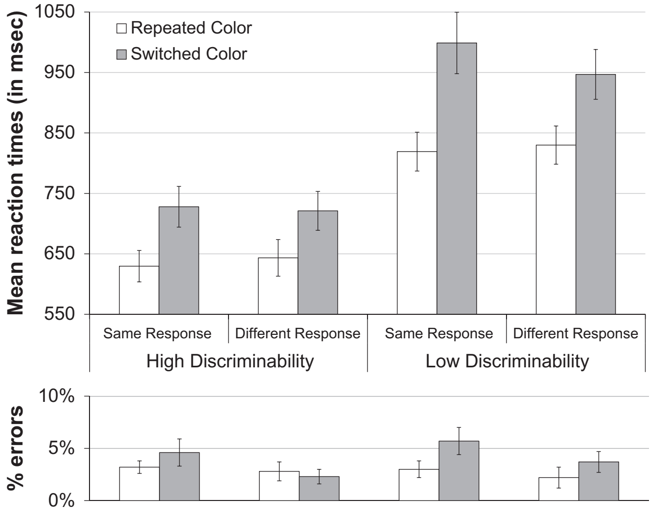

Fig. 2. Mean RTs (upper panel) and percentage of errors (lower panel) for repeated and switched-color trials, by condition of response repetition (same response vs. different response) for each condition of target–distractor color discriminability in Experiment 1. In this experiment, conditions of discriminability were run in separate blocks of trials. Error bars indicate the standard errors.

2.2.2. Accuracy

The main effect of color repetition was significant, $F(1,7) = 8.88$, $p < 0.03$, with less errors on repeated-color trials than on switched-color trials, 2.8% vs. 4.1%, respectively. The interaction between color repetition and color contrast approached significance, $F(1,7) =$, $p < 0.07$: the color repetition effect tended to be larger in the low-contrast than in the high-contrast condition, 2.1% vs. 0.5%, respectively. There was no other significant effect or interaction, all $ps > 0.2$.

The results support our hypothesis that target–distractor discriminability is an important modulating factor of the magnitude of the response-related component of intertrial feature priming and may explain its apparent volatility in previous studies. When the characteristics of the current trial matched those of the previous trials, subjects were faster to emit the same response as in the previous trial than a different response, but only when target–distractor discriminability was low. Such retrieval and comparison processes, if they occurred at all, did not affect performance when target–distractor discriminability was high.

3. Experiment 2

The objective of Experiment 2 was twofold. First, having delineated conditions in which similarities between the current and previous search episodes speed response-related processes, we set out to characterize the display features that are important during retrieval at the response stage. We investigated what information the episodic traces that underlie the response-related component of feature priming contain: the representation of the target feature, of the distractors feature, of both independently or of the conjunction of the two? Our second objective was to replicate the main finding from Experiment 1, namely, the modulation of the response-related component of feature priming by target–distractor discriminability, using a slightly different design as described below.

In Experiment 1 as in most feature priming experiments, the target and distractors features both either repeat or switch. Thus, target repetition is confounded with distractor repetition. Previous studies have investigated whether repetition of the distractors and repetition of the target yield separate contributions to intertrial feature priming (Kristjánsson & Driver, 2008; Lamy, Antebi, Aviani & Carmel, 2008), but they have not distinguished between the perceptual and response-related components. Here, we aimed at describing what features of the display on the previous and current trials are compared and either speed or slow production of the same response depending on whether or not they match.

In order to dissociate the effects of target and distractor color repetition, target and distractors colors were always randomly drawn from the four possible colors in each discriminability condition. Thus, there were three possible sequences with regard to target-color and to distractor-color variation on successive trials: repeated, switched and new. The combination of the different target and distractors color repetition conditions resulted in seven rather than nine conditions because "*switched* target–*repeated* distractor" and "*repeated* target–*switched* distractor" are impossible conditions (see Lamy, Antebi, et al. (2008) for a more detailed description). The different possible trial sequence types are illustrated in Fig. 3.

We first examined only trials that are relevant to the basic effect, that is, *repeated* target–*repeated* distractors trials and *switched* target–*switched* distractors trials, in order to ascertain that we could replicate the findings from Experiment 1. Then, we examined which of the seven target–distractor color repetition sequences modulated the response repetition effect in order to determine the display properties that drive the response-related component of intertrial feature priming.

3.1. Method

3.1.1. Subjects

Subjects were 24 Tel-Aviv University undergraduate students who volunteered or participated in the experiment for course credit. All reported having normal or corrected-to-normal visual acuity and normal color vision.

3.1.2. Apparatus, stimuli and procedure

The apparatus, stimuli and procedure were similar to those of Experiment 1 except for the following changes. In each condition of discriminability, the target-color pairs were no longer run in different blocks of trials: instead, on each trial, target and distractor colors were randomly drawn from the four possible colors. Each experiment half (corresponding to a different condition of discriminability) began with 60 practice trials followed by 360 experimental trials divided into six blocks.

3.2. Results

In all RT analyses, error trials (4.2% of all trials) and trials preceded by an error trial were removed from analysis, and so were outlier trials (less than 2% of all trials).

3.2.1. Replication of the findings of Experiment 1

We first conducted an ANOVA with color repetition (repeated target and distractors colors vs. switched target and distractors colors), response repetition (same vs. different response) and target–distractor discriminability (high vs. low) as factors. Mean RTs and accuracy rates are presented in Fig. 4.

3.2.1.1. Reaction times. The results replicated the main findings of Experiment 1. All main effects were significant. Responses were faster when color contrast was strong than when it was weak, and $F(1,23) = 124.74$, $p < 0.0001$, when the target and distractors colors repeated than when then switched, $F(1,23) = 142.82$, $p < 0.0001$ and when the response repeated than when it changed, $F(1,23) = 4.37$, $p < 0.05$. Color repetition interacted with response repetition: the effect was larger when the response repeated from the previous trial than when it changed, 116 ms vs. 72 ms, $F(1,23) = 5.49$, $p < 0.03$. The interaction between color repetition and color contrast did not reach significance, although the data

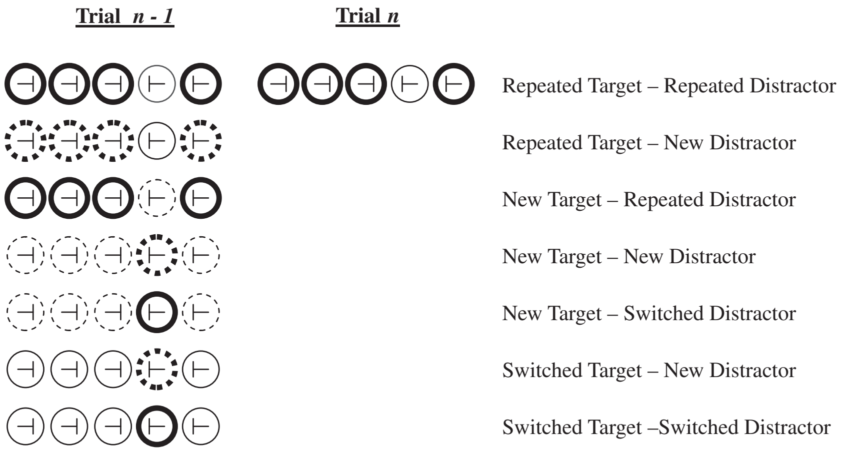

Fig. 3. Sample displays corresponding to the seven possible trial sequence types in Experiment 2. The 4 different line types represent the 4 possible colors. The target is the circle with the unique color and the remaining circles are the distractors. For practical purposes, the displays are depicted as rows, but in the actual experiment, the circles were scattered in an imaginary matrix as shown in Fig. 1."Repeated" refers to when a color repeats from the previous trial and takes on the same role (either target or distractor). "New" refers to when a color did not appear in the previous trial. "Switched" refers to when a color repeats from the previous trial but takes on the alternative role.

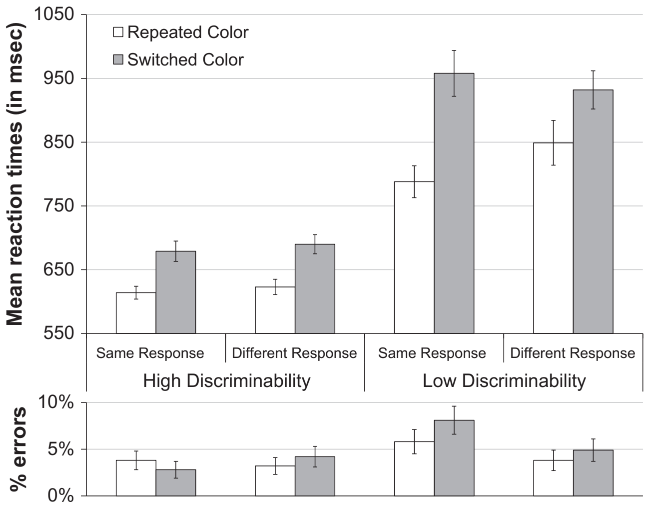

Fig. 4. Mean RTs (upper panel) and percentage of errors (lower panel) for repeated and switched-color trials, by condition of response repetition (same response vs. different response) for each condition of target–distractor color discriminability in Experiment 2. In this experiment, conditions of discriminability were run in separate blocks of trials. Error bars indicate the standard errors.

showed a clear numerical trend for the color repetition effect to be larger when color contrast was weak than when it was strong, 122 ms vs. 66 ms, $F(1,23) = 2.52$, $p > 0.1$. Crucially, the 3-way interaction was again significant, $F(1,23) = 6.80$, $p < 0.02$.

For both low and high color-contrast trials, the main effect of color repetition was significant, $F(1,23) = 67.74$ and $F(1,23) = 64.67$, respectively, $ps < 0.0001$ and the main effect of response repetition was non-significant, $F(1,23) = 2.60$ and $F(1,23) = 2.14$, respectively, $ps > 0.1$. As in Experiment 1, the interaction between color repetition and response repetition was significant only when color contrast was low, $F(1,23) = 8.68$, $p < 0.008$ but not when color contrast was high, $F < 1$. Specifically in the former condition, the color repetition effect was larger on repeated- than on switched-response trials, 168 ms, $F(1,23) = 53.98$, $p < 0.0001$ vs. 87 ms, $F(1,23) = 20.08$, $p < 0.0002$, respectively, but was of equal magnitude whether or not response repeated in the latter condition, 67 ms vs. 63 ms, respectively, both $ps < 0.0001$.

3.2.1.2. Accuracy. There was no significant accuracy effect in either the high color-contrast condition, all $Fs < 1$, or the low color-contrast condition, all $ps > 0.2$.

3.2.2. Characterization of the context relevant for response-based PoP

Having replicated the main findings of Experiment 1, we turned to examine in more detail what display sequences interacted with response repetition in the low target–distractor discriminability condition. That is, we investigated what repetitions or changes from the display in previous trial either speeded or slowed repetition of the same response. To do that, we conducted an ANOVA with color repetition sequence (seven possible sequences depicted in Fig.1) and response repetition as factors. Fig. 5 shows the response repetition effect for each trial sequence type.

3.2.2.1. Response times. The main effect of sequence condition was highly significant, $F(6,138) = 21.34$, $p < 0.0001$ and the main effect of response repetition approached significance, $F(1,23) = 3.45$, $p < 0.08$. The interaction between the two factors was significant, $F(6,138) = 2.58$, $p < 0.03$. Paired comparisons showed that the effect of repeating the same response as in the previous trial significantly speeded search when both the target and distractors colors repeated, $F(1,23) = 9.54$, $p < 0.006$ and when both took on new colors, $F(1,23) = 5.97$, $p < 0.03$. None of the other comparisons yielded a significant effect, all $Fs < 1$. In particular, despite a clear numerical trend (28 ms), there was no significant cost of repeating the same response when the target and distractors colors switched.

For comparison, the interaction between response repetition and color repetition sequence was not significant in the high target–distractor discriminability condition, $F < 1$, confirming that the response repetition effect was not modulated by repetition of aspects of the displays on the previous and current trials. Note however, that the main effect of response repetition was significant in this condition, $F(1,23) = 9.28$, $p < 0.006$: subjects were faster when they produced the same rather than a different response relative to the previous trial, irrespective of repetitions or changes in the target and distractors colors.

This finding raises the question of what baseline might be more appropriate in order to assess the effects of display sequence on response repetition in the low-discriminability condition.

In the analyses above, we looked at which sequences yield a response repetition effect that is different from 0. Alternatively, however, we may consider the situation in which the display on trial n is unrelated to the display on trial $n - 1$, that is, when both the target and distractors colors are new, as a more appropriate baseline. The rationale is as follows. (1) When response selection is unaffected by display color sequence, as was the case when the task was easy, there was an advantage of repeating the same response. (2) When both the target and the distractors took on colors that did not exist in the previous display, there was not a cost of repeating the response but an advantage (of roughly the same magnitude as in the high-discriminability condition). Taken together, these findings suggest that when the displays are unrelated with regard to the target and distractors colors, the response repetition advantage reflects a baseline, that is, the same response repetition advantage as the one found when there is no interaction between the processes (as was the case in the easy condition).

Following this rationale, we conducted new analyses to compare the response repetition effect in each color sequence condition to this new baseline, that is, to the situation where both colors were new. We found that repeating the target and distractor colors favored a same response over a different response beyond the advantage observed in the baseline condition although the effect only approached significance, $F(1,23) = 3.62$, $p < 0.07$. In addition, a color switch between target and distractors resulted in a cost, $F(1,23) = 4.37$, $p < 0.05$: different responses were faster than same responses. None of the other comparisons to baseline produced a significant effect, all $ps > 0.15$. There was no significant effect in the high-color contrast condition, all $ps > 0.3$.

3.2.2.2. Accuracy. The pattern of errors was consistent with the RT data. In the low color-contrast condition, comparisons of the effect of response repetition against 0 did not yield any significant effect for any of the display sequence conditions, all $ps > 0.1$. Comparisons against the baseline condition, in which both the target and distractors colors were new, yielded only one significant effect: the advantage of same-response trials relative to different-response trials was larger when both the target and distractors colors repeated than when they were new, $F(1,23) = 4.84$, $p < 0.04$, all other $ps > 0.2$. There was no significant effect in the high-color contrast condition, all $ps > 0.3$.

3.3. Discussion

The results from Experiment 2 replicated the main findings of Experiment 1 and thereby confirmed that target–distractor discriminability can indeed determine whether or not the response-based component of intertrial feature priming is observed.

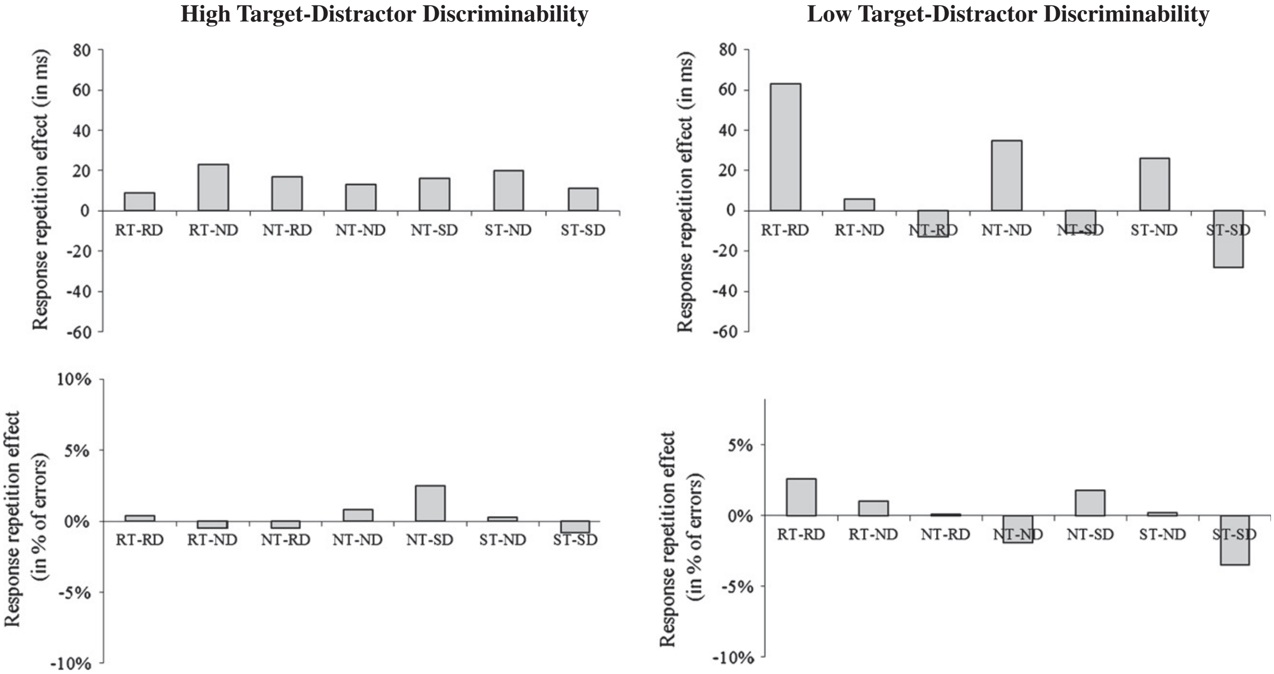

Fig. 5. Mean response repetition effect (mean difference between performance on different-response trials and performance on same-response trials) by trial sequence type (RT = Repeated Target color; RD = Repeated Distractor color; NT = New Target color; ND = New Distractor color; ST = Switched Target color; SD = Switched Distractor color) in Experiment 2. Upper panels show RT data and lower panels show accuracy data.

In addition, we showed that the display features which form the search context that is retrieved during the response stage are both the target and distractors features on the singleton dimension (here, their color). Indeed, response repetition affected performance only when either both the target and distractors colors repeated or both switched – with no discernable effect of partial repetition (i.e., repetition of only one color) on response repetition. Note that here, targets and distractors varied only on color, which was the task-relevant dimension. Thus, it is theoretically possible that repetition of other, task-irrelevant, display characteristics may also affect response-related processes. However, the findings reported by Huang et al. (2004) make this possibility unlikely. In their study, subjects searched for a target line defined by its unique size and responded to its orientation. Each item in a display was randomly either red or green and color was irrelevant to the task. Repetition of response interacted with repetition of the defining feature (size) but not with repetition of the irrelevant feature (color).

Finally, we found a general response repetition effect that was independent of intertrial feature priming. In the high color contrast condition, there was a main effect response repetition that did not interact with feature priming. A response repetition advantage of the same magnitude also emerged in the low-contrast condition when both the target and distractors colors changed to new colors (and were therefore unrelated to the colors in the display in the previous trial). This finding did not show up as clearly in Experiment 1: the effect of response repetition was not significant in the high color contrast condition – despite a small numerical trend in the expected direction.

4. Experiment 3

The results of Experiments 1 and 2 clearly show that the response-based component of intertrial feature priming (indexed by the interaction between color repetition and response repetition) is contingent on low target–distractor discriminability. The objective of Experiment 3 was to determine why similarities between the current and previous search episodes speeded response-related processes only when target–distractor discriminability was low, that is, when the search was difficult. We compared two possible accounts.

According to one account, the processes that underlie the response-based component of feature priming are mandatory and automatic, and do not depend on the search difficulty per se. The critical impact of lowering target–distractor discriminability is simply that is lengthens the time it takes for the subjects to complete the stages of the task preceding response selection. As the response-based component of feature priming is thought to reflect retrieval processes that affect the stage of response selection (Lamy et al., 2010), its effects on performance can be measured only if these retrieval processes terminate before a response is selected. In the low-discriminability condition, search takes more time and is therefore less likely than it is in the high-discriminability condition, to terminate before retrieval is complete: therefore in Experiments 1 and 2, the critical interaction was observed in the former but not in the latter condition.

According to an alternative account, however, the response-based component of intertrial feature priming might not reflect mandatory processes but instead a heuristic or shortcut that observers use when the task at hand is demanding. Indeed, high cognitive load is generally thought to increase reliance on heuristic processing strategies. Accordingly, when the search context on the current trial is similar to that of the previous trial, the shortcut consists in reactivating the response associated with the previous trial.

In Experiment 3, we tested these alternative accounts against each other by randomly mixing conditions of search difficulty. Thus, subjects did not know whether the upcoming trial would be easy or difficult. If the contingency of the response-based component on low target–distractor discriminability hinges on how long it takes to find the target, then in the present experiment, we should replicate our previous findings: the critical interaction should emerge on difficult-search trials and not on easy-search trials. However, if such contingency reflects a heuristic which subjects tend to use when under high cognitive load, then we should observe a similar pattern of results on easy and difficult-search trials because subjects are unlikely to change their strategy on a trial-by-trial basis: the critical interaction should occur either on both or on neither type of trials (depending on whether or not they resorted to the heuristic processing strategy).

4.1. Method

4.1.1. Subjects

Subjects were 24 Tel-Aviv University undergraduate students who volunteered or participated in the experiment for course credit. All reported having normal or corrected-to-normal visual acuity and normal color vision.

4.1.2. Apparatus, stimuli and procedure

The apparatus, stimuli and procedure were similar to those of Experiment 1 except for the following changes. (1) Conditions of target–distractor discriminability were randomly mixed within each block of trials rather than run in different blocks of trials. (2) Instead of receiving all six color pairs resulting from the four possible colors within each condition of target–distractor discriminability, each subject received only one color pair within each condition. This change was necessary in order to ensure that randomly mixing color pairs would yield a sufficient amount of repeated- and switched-color trials. For half of the subjects, the low-discriminability colors were faint blue and faint yellow and the high-discriminability colors were red and green. For the other half, the low-discriminability colors were faint red and faint green and the high-discriminability colors were yellow and blue. As the main interest was in sequences involving two consecutive trials within the same condition of discriminability, this design minimized priming effects in sequences that involved different discriminability conditions. The experiment began with 60 practice trials followed by 760 experimental trials divided into 12 blocks.

4.2. Results

In all RT analyses, error trials (4.3% of all trials) and trials preceded by an error trial were removed from analysis, and so were outlier trials (less than 1% of all trials). In all analyses, trials that were preceded by a trial in a different condition of color discriminability were excluded. Thus, only low–low and high–high discriminability trial sequences were analyzed.

We conducted an ANOVA with color repetition (repeated target and distractors colors vs. switched target and distractors colors), response repetition (same vs. different response) and target–distractor discriminability (high vs. low) as factors. Mean RTs and accuracy rates are presented in Fig. 6.

4.2.1. Reaction times

Responses were faster when color contrast was strong than when it was weak, $F(1,12) = 39.24$, $p < 0.0001$, and when the target and distractors colors repeated than when then switched, $F(1,12) = 55.33$, $p < 0.0001$. There was no main effect of response repetition, $F < 1$. The interaction between color repetition and color contrast was significant: as expected, color repetition effects were larger when color contrast was weak than when it was strong, 115 ms vs. 48 ms, $F(1,12) = 18.89$, $p < 0.001$. Color repetition interacted with response repetition: as expected, color repetition effects were larger when the response repeated from the previous trial than when it changed, 98 ms vs. 65 ms, $F(1,12) = 5.49$, $p < 0.04$. However, the 3-way interaction was no longer significant, $F < 1$, indicated that this effect was of equal magnitude whether target–distractor discriminability was low or high.

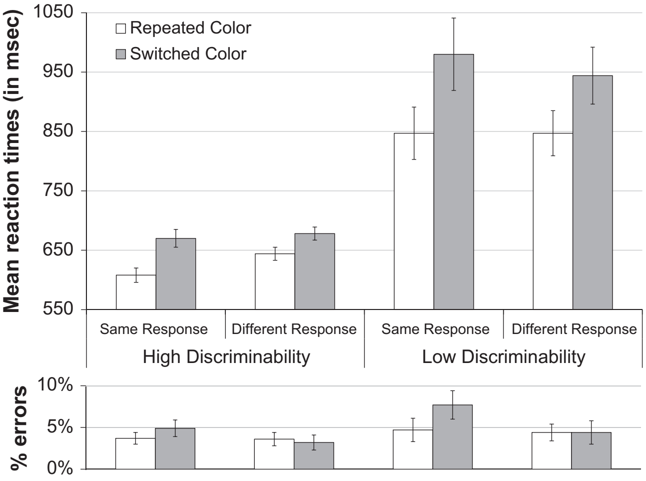

Fig. 6. Mean RTs (upper panel) and percentage of errors (lower panel) for repeated and switched-color trials, by condition of response repetition (same response vs. different response) for each condition of target–distractor color discriminability in Experiment 3. In this experiment, conditions of discriminability were randomly mixed within blocks of trials. Error bars indicate the standard errors.

4.2.2. Accuracy

Only the interaction between color repetition and response repetition reached significance, $F(1,12) = 8.52$, $p < 0.02$. The color repetition advantage was larger when response also repeated than when it did not (2.1% vs. 0.2%, respectively), thus mirroring the RT data. Again, the 3-way interaction was non-significant, $F < 1$.

4.3. Discussion

The results show that when conditions of search difficulty are unpredictable, color repetition and response repetition interact to the same extent whether the search is easy or difficult. Thus, we can reject the notion that the response-based component of feature priming relies upon a mandatory mechanism that is more likely to complete when the searching process takes more time. We suggest that under certain circumstances, namely, when the search task is demanding, subjects use the heuristic processing strategy of retrieving the response produced on the previous trial when the current and previous search contexts are similar.

It is noteworthy that in the present as in the previous experiments, the magnitude of feature priming was considerably larger in the difficult than in the easy search condition. In Experiments 1 and 2, this difference could possibly stem from the addition of the response-based component in the low-discriminability condition, but not in the high-discriminability condition. Thus, it was not possible to determine whether target–distractor discriminability might also modulate the selection-based component of inter-trial feature repetition priming. By contrast, in the present experiment, there was no longer such an ambiguity: the larger feature priming effect observed in the low-discriminability condition could only result from a larger selection-based effect because the response-based component was of equal magnitude in the two conditions of search difficulty.

5. General discussion

5.1. Summary of the main findings

The present findings are compatible with the dual-stage model suggested by Lamy et al. (2010), as they show that, rather than being a unitary phenomenon, inter-trial feature repetition priming (aka, PoP) is best viewed as a composite effect that reflects several different mechanisms occurring at different stages of processing. In the present study, we focused on the response-based component of feature priming, the marker of which is an interaction between repetition of the search relevant feature and response repetition. We moved one important step towards clarifying why this interaction emerges in some studies and not in others by showing that it occurs when selection is difficult and not when selection is easy. However, we also found that the critical factor is not how difficult the search is on a given trial but how difficult the search is overall: the interaction was observed on easy-search trials when these were randomly intermixed with difficult-search trials but not when they were run in a separate block of trials. Taken together, these findings suggest that the response-based component of feature priming is not mandatory or automatic but may be described as a heuristic that subjects sometimes use, in particular when overall search difficulty during the experiment is high.

Second, we showed response repetition speeded search when both the target and distractor colors repeated and slowed search when these colors switched. However, when either the target or the distractor colors changed to a new color, it did not matter whether or not the response repeated.[2] These findings suggest that the information that is important for the retrieval of the previous response does not pertain to the features of the target alone (e.g., Huang et al., 2004) but to the search context, defined as the search-relevant characteristics of the whole display – here, the conjunction of the target and distractors colors.

Finally, the results showed that increasing search difficulty – here, by lowering target–distractor discriminability on the search-relevant dimension – enhances the selection-based component of intertrial feature priming, independently of the response-based component.

5.2. The role of search difficulty in feature priming

We found that PoP is larger when the search is difficult than when it is easy. This result is consistent with Oliver and Meeters' (2006) suggestion that the amount of ambiguity in a task determines the magnitude of intertrial feature priming. However, these authors also suggested that the locus of the ambiguity determines whether feature priming affects search at a perceptual or at a post-perceptual stage of processing. Our findings do not fully support this hypothesis. The locus of ambiguity in our task was at the stage of selecting the target: indeed, we manipulated the color contrast of the display items but not response-related demands. Although we did not manipulate display size, there is ample evidence from previous studies (e.g., Duncan & Humphreys, 1989) that reducing target–distractor discriminability impairs search efficiency, that is, makes search more difficult. We found the increased difficulty at the selection stage to affect not only the magnitude of the selection-based component of feature priming (Experiment 3), but also its response-based component, in contrast with Meeter and Olivers' (2006) claim.

In addition, the mechanisms underlying the effects of task difficulty on each component of feature priming are fundamentally different. The effect on the selection-based component is likely to reflect the fact that when target–distractor discriminability is high, attentional engagement in the target is fast and is therefore less susceptible to speeding by feature repetition priming than when discriminability is low. By contrast, the effect on the response-based component reflects a heuristic processing strategy that participants are more likely to use when they perceive the search as being difficult overall.

5.3. The dual-stage model of intertrial feature priming

We suggest that when the search display appears, the different stages of visual search unfold: in singleton search, the candidate target is detected at the location of highest contrast. Then, when the task entails attention focusing on the target (e.g., when fine discrimination is required at the target location), attention is shifted to the target location. It is then engaged at this location such that the response feature can be extracted. Processes related to feature-to-motor response mapping follow and the appropriate motor response is prepared and executed. Previous findings from our lab (Yashar & Lamy, 2010, 2011) suggest that in this sequence of events, intertrial feature priming does not affect processes related to local contrast representation but later stages of visual search such as attentional shifting and engagement: this effect constitutes the selection-based component of feature priming.

In parallel, when the search is difficult, participants sometimes resort to the strategy of retrieving the previous trial episode and comparing it to the current episode. If the search context (which we found to include the conjunction of both the target and distractors colors in the present study) is different in the two trials (that is, if either one or both colors changed relative to the previous trial), the comparison process is aborted: therefore, it does not affect search. This was the case in Experiment 2, where response repetition did not influence search speed when one color from the previous trial repeated but not both. If the search context is similar, the comparison proceeds further. In this case, if color assignment to the target and distractors is the same as in the previous trial (i.e., on repeated-color trials), the response associated with the previous trial is activated in the current trial. If color assignment is the opposite (i.e., on switched-color trials) then the alternative response is activated.

5.4. What stage(s) of processing does retrieval of the previous trial episode modulate?

It is important to underscore that the response-based component of feature priming stipulated by the dual-stage account does not refer to the same mechanism as the episodic retrieval account put forward by Huang and colleagues (Huang & Pashler, 2005; Huang et al., 2004). In other words, our model does not simply propose that a selection-based component should be added to Huang et al.'s model.

Huang et al. (2004) suggested that "When a candidate target has been located, the system…seeks to verify that this element is indeed the target. Here, episodic retrieval plays a role… When all the feature dimensions cohere … (all favoring the same judgment or all favoring a different judgment), the judgment is easy. On the other hand, inconsistency across dimensions will have a cost. When it arises, the system may need extra time to double check the status of the target". Thus, they suggested that the episodic retrieval mechanism that gives rise to inter-trial feature priming hinges on the similarity of the various features of the target (defining, response and irrelevant features) on the previous and current trial and speeds the decision as to whether the selected candidate should be treated as the target. By contrast, we propose an episodic retrieval mechanism that affects a later stage, namely, that biases which motor response will be selected.

An important difference between the two accounts is that the Huang et al. underscore the role of repetition of the *response feature*, whereas we highlight the role of repetition of the *motor response*. However, in all published studies of feature priming, as

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[2] The baseline advantage, that is the faster RTs when both the target and distractors took on new colors, disappeared when only one color changed. However, the difference between these conditions did not approach significance. Therefore, we cannot conclude that partial repetition of the display colors affected the response repetition effect.

well as in the present study, the two were confounded. Here for instance, response repetition referred both to a situation in which the T inside the target had the same orientation on consecutive trials and to a situation in which the participant had to press the same key on consecutive trials. It follows that whether feature repetition interacts with repetition of the response feature (as Huang et al. claimed) or with repetition of the motor response (as we claim) cannot be determined based on these studies.

We therefore addressed this issue in a series of new experiments (Yashar & Lamy, in press). We dissociated repetition of the motor response and repetition of the response feature by using two pairs of response features and two motor responses, with two features in a pair being associated with the same response. This study yielded two main findings: (1) Repetition of the response feature considerably speeded search, both when search was easy and when it was difficult. However, (2) repetition of the response feature did not interact with repetition of the defining feature, which interacted only with motor response, and only when search was difficult (thus replicating the present findings). We concluded that the response-based component of feature priming pertains to repetition of the motor response.

In a recent study, Argeirsson and Kristjansson (in press) investigated the boundary conditions of the other interaction on which Huang et al. (2004) based their episodic retrieval account of feature priming. Whereas we examined the factors that modulate the interaction between repetition of the defining feature and repetition of *response*, they focused their interest on the interaction between repetition of the defining feature and repetition of *an irrelevant feature*. After replicating Huang et al.'s experiment, they reported that the critical interaction was no longer found (1) when reversal trials (in which the target on the previous trial becomes the distractor on the current trial or vice versa) were eliminated by keeping distractor feature constant and (2) when variations on the target-defining dimension were made more salient than variations on the irrelevant dimension. They concluded that "target/distractor discriminability plays a key role in whether repetition effects from different features interact or not perhaps because with increased difficulty priming effects occur at later stages of perceptual processing".

Thus, Asgeirsson and Kristjansson (in press) suggest that the interaction between repetition of the defining feature and repetition of an irrelevant feature of the target is contingent on low target–distractor discriminability and reflects a *perceptual* stage of processing. We suggest that the interaction between repetition of the defining feature and repetition of the response is also contingent on low target–distractor discriminability but reflects a *post-perceptual* stage of processing, namely selection of the motor response.

These conclusions are not necessarily incompatible. On the one hand, inter-trial feature priming may include three rather than only two components: one that is selection based, one that reflects modulation of late stages of perceptual processing (as suggested by Asgeirsson and Kristjansson (in press), see also Kristjánsson, Ingvarsdóttir, & Teitsdóttir, 2008) and yet another one occurring during motor selection. On the other hand, however, it may be the case that when an irrelevant feature of the target is salient enough, it becomes part of the search context and thus the interaction between the target's defining and irrelevant features also reflects response-related rather than perceptual mechanisms. This alternative account yields to two predictions. First, it predicts that, just like the interaction with response repetition, the interaction of repetition of the defining feature with repetition of an irrelevant feature is not contingent on the difficulty of the current search trial but of the overall search difficult (i.e., it also reflects a heuristic processing strategy) – whether this is the case cannot be determined based on previous studies because task difficulty was always blocked (Asgeirsson & Kristjansson, in press). Second, it predicts a 3-way interaction between repetitions of the defining feature, the irrelevant feature and the response. However, Asgeirsson and Kristjansson did not report effects related to repetition of response and Huang et al. (2004) did not report whether the 3-way interaction was significant. Further research is therefore needed to resolve these issues.

5.5. Conclusions

Consistent with previous findings (Lamy et al., 2010; Töllner et al., 2008), the results from the present study show that intertrial priming effects such as feature priming in fact reflect several separate effects subtended by very different mechanisms. These findings suggest that feature priming is a fundamentally selection-based phenomenon. However, it is sometimes augmented by the addition of a response-based effect that reflects an episodic retrieval strategy that subjects use when the task is difficult: they are faster to use the response that was appropriate on the previous trial when the search context repeats from the previous trial. Further research is needed to determine whether the response-based component of dimension priming identified by Töllner et al. (2008) also reflects a heuristic processing strategy and whether other intertrial priming effects such as location priming (Maljkovic & Nakayama, 1996) and singleton priming (Lamy, Bar-Anan et al., 2008) can also be decomposed into separate selection- and response-based effects.

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