Inter-trial inhibition of attention to features is modulated by task relevance

Brian R. Levinthal

Alejandro Lleras

The Distractor Previewing Effect (DPE) is an inter-trial effect that arises in efficient visual searches where participants are asked to find a feature oddball in the display. Specifically, the DPE is the finding that an observer’s ability to focus on an oddball target is impaired if, on the immediately preceding trial, no target was present and all distractors shared a visual feature with the current target (e.g., all objects were red on trial \(N\), and the target was a red oddball on trial \(N+1\)). Though recent evidence suggests that the DPE emerges from an attentional bias against focusing on a recently examined feature common to all stimuli in a target-absent trial, it is unclear whether this inhibition is formed for all features in target-absent trials, or is instead limited to the search-relevant feature. In two experiments we manipulated task instructions while keeping displays identical, alternating which feature (shape or color) was relevant for the search task and which was not. Our results showed that attentional inhibition is applied only to the search-relevant feature. Additionally we found that although search-irrelevant features affect search times, these effects are independent of any relationship to the previous trial.

Keywords: inter-trial inhibition, attention, top-down modulation, visual search, attentional set


Introduction

As we search through our environment for an item of interest (e.g., keys), we are typically required to reject distracting objects around us (e.g., journals, computer equipment). Upon locating the desired item, we often must focus our attention on it to perform some additional task (“these aren’t my keys!”). Understanding the mechanisms that allow observers to quickly find and act upon such visual targets is an important theoretical issue that has received much attention in vision research. Research on visual search has identified two primary factors that influence an observer’s search behavior: top-down factors, such as an observer’s instructions, goals, or knowledge about a target (Folk, Remington, & Johnston, 1992; Wolfe, 1994; Yantis, 1998), and bottom-up factors, such as the salience of an object in a display, or the configuration, contents, and clutter of the display as a whole (Bundesen, 1990; Treisman & Gelade, 1980; Wolfe, 1994).

In addition to the well-studied influence of bottom-up factors and top-down factors in visual search, there is a growing body of research centered on how recent visual experience affects the deployment of selective attention on future visual searches (e.g., Chun & Jiang, 1998; Goolsby, Grabowecki, & Suzuki, 2005; Goolsby & Suzuki, 2001; Kristjánsson, Mackeben, & Nakayama, 2001; Lleras, Kawahara, Wan, & Ariga, 2008; Maljkovic & Nakayama, 1994). A now classic example of such “history effects” on visual search is priming of pop-out (Maljkovic & Nakayama, 1994, also 1996, 2000), which is observed in efficient, so-called “pop-out” visual searches where the target is defined by a unique feature (e.g., the target may be the only red item among several green distractors, or vice versa). Priming of pop-out (PoP) refers to the finding that observers get better at finding these pop-out targets when the search context is repeated across consecutive trials. For example, finding a red target among green distractors is faster when the previous trial also contained a red target among green distractors compared to when the previous trial contained a green target among red distractors. PoP is a robust inter-trial effect that has been interpreted as facilitation to deploy focused attention toward the target in repeated search contexts compared to novel or reversed search contexts (Kristjánsson & Nakayama, 2003; Kristjánsson et al., 2001; Maljkovic & Nakayama, 1994). PoP has mostly been characterized as a target-centered phenomenon. For example, the majority of the RT benefit in PoP comes from the repetition of the target, whereas distractor repetition produces more modest decreases in RT (Maljkovic & Nakayama, 1994). Furthermore, theories of PoP focus on accounting for this behavioral benefit in terms of target-related processing.
For instance, Huang, Holcombe, and Pashler (2004) propose PoP arises because an active episodic memory representation of the target facilitates attentional deployment toward the target on subsequent trials (see Desimone & Duncan, 1995), and Wolfe, Butcher, Lee, and Hyle (2003) propose that perceptual gains are modulated after each trial to uniquely increase the salience of the recently selected target features (a similar gain modulation account was proposed by Navalpakkam & Itti, 2007). In this paper, we will focus our efforts on another robust intertrial effect on focused attention: the distractor previewing effect (DPE; Ariga & Kawahara, 2004; Goolsby et al., 2005; Lleras et al., 2008), which centers not on the behavioral consequences of repeatedly selecting the same target, but rather on the consequences of failing to find a target in a search scene.

Distractor previewing effect

The DPE reflects a special case in oddball feature searches in which the failure to find a target on a target-absent display produces a lingering inhibition of the “rejected” or “failed” feature that defined distractors in that display. For example, if participants were asked to look for a color oddball and an initial display contained three red items (i.e., no color oddball), the future selection of a red target on a subsequent target-present trial is inhibited, while the rejection of future red distractors is facilitated. This pattern of results, an overall biasing of attention away from a previously rejected feature, marks every study of the DPE (Ariga & Kawahara, 2004; Goolsby et al., 2005; Lleras et al., 2008; Shin, Wan, Fabiani, Gratton, & Lleras, 2008).

Recent studies have indicated that the DPE reflects an overall biasing of selective attention during visual search (Lleras et al., 2008; Shin et al., 2008). Lleras et al. (2008) presented a series of experiments demonstrating several important properties of the DPE. The DPE emerges only during tasks that require focused attention: a strong DPE was observed when participants performed a target-discrimination task, but the effect was eliminated when observers were required only to detect the presence of a target without any further discrimination, despite viewing otherwise identical stimuli (Lleras et al., 2008, Experiment 1). The effect is not influenced by a presence or absence of a response on target-absent trials (Lleras et al., 2008, Experiments 2 and 3), suggesting that the DPE does not reflect a response bias formed by withholding a response when a target is absent. Finally, the time course of the DPE strongly indicates an affect of attention rather than a response bias. When the colors present in a color-oddball search were swapped shortly after the onset of the trial (e.g., red items become green items and vice versa), the DPE was modulated by switches occurring as early as 100 ms (Lleras et al., 2008, Experiment 5). The evidence in favor of an attentional locus of the DPE was corroborated by a recent electrophysiological study by Shin et al. (2008). In that study, the DPE produced a modulation only for ERP components commonly associated with shifts of attention (N2pc), but not for ERP components associated with perceptual fluency and color-based attention (e.g., P1/N1) nor with those associated with response selection processes (Lateralized Readiness Potentials; Gratton, Coles, Sirevaag, Erikson, & Donchin, 1988).

Thus, converging evidence from behavioral and electrophysiological studies indicates that the DPE results from a biasing of attention. In the context of these findings, Lleras et al. (2008) proposed that the DPE emerges because of the failure to find a target during pop-out visual search and ultimately reflects a bias against the selection of the “failed” feature in the future (i.e., to avoid repeating a recent failure). In a sense, this interpretation is analogous to that of inhibition of return (IOR; Posner & Cohen, 1984), which can be viewed as a bias against reorienting attention toward a recently inspected location where a target was expected but failed to appear.

While there are some obvious parallels between PoP and DPE (e.g., both are inter-trial effects that involve pop-out visual search), the two phenomena can be quite clearly dissociated. On theoretical grounds, PoP is viewed as the consequence of successfully finding and selecting a target, whereas the DPE is viewed as the consequence of failing to find and select a target. As a result, PoP is viewed as a positive bias of attention toward a recently attended feature, whereas the DPE is viewed as a negative bias of attention aimed at preventing attention from focusing on a recently rejected feature (though see Lamy, Antebi, Aviani, and Carmel (2008), who demonstrate a clear contribution of both target activation and distractor inhibition in PoP). On empirical grounds, these two effects have been dissociated in a number of experiments. For instance, in two separate experiments Ariga and Kawahara (2004) found a DPE without finding a corresponding PoP when faces and coherent motion were used as stimuli. In other words, when a target-absent trial was followed by a target-present trial, a DPE was observed, yet when a target-present was followed by a second target-present trial, no PoP was found. In addition, Goolsby et al. (2005) also showed a dissociation between these two effects by showing that PoP arises from attention-based segmentation of the search displays (i.e., even in the absence of a color oddball, a PoP effect can be observed when participants repeatedly attend to the same target color in the presence of the same distractor color), whereas the DPE arises only from uniformly colored displays. In sum, a DPE can be observed in the absence of PoP and vice versa.

The DPE reflects attentional inhibition against a feature recently previewed in a target-absent display and is in some respects similar to inter-trial priming observed in oddball conjunction searches (i.e., when a target is defined as a unique combination of features along two or more dimensions; Geyer, Müller, & Krummenacher, 2006;
Kristjánsson & Driver, 2008; Wang, Kristjánsson, & Nakayama, 2005). During conjunction searches, an observer is unlikely to be solely guided by bottom-up properties of the display as the target shares features with multiple distractor items and cannot guide search via top-down knowledge since the target’s characteristics vary randomly across trials. Performance in these search tasks shows evidence of inter-trial priming (Wang et al., 2005). Further studies of inter-trial priming with conjunction searches have demonstrated that the effect originates predominantly from a repetition of distractor features (Geyer et al., 2006), with particularly strong (negative) inter-trial priming observed when the target and distractor features swap roles from trial to trial (Kristjánsson & Driver, 2008). The pattern of results typically associated with the DPE follows an analogous pattern (i.e., repetition of a distractor feature produces a response-time benefit, while a “switch” of a distractor feature to a target feature produces a response-time cost), though it is important to note again that the DPE has only been demonstrated for oddball discrimination tasks, and thus far has only been shown in the context of efficient search tasks (Arieta & Kawahara, 2004; Goolsby et al., 2005; Lleras et al., 2008).

Despite evidence that the DPE reflects a bias against selecting features that were present in a target-absent display (e.g., Lleras et al., 2008), it is unclear whether this inter-trial inhibition is formed automatically for all features present in a failed search, or is instead modulated by an observer’s intent. Our study aims to address these possibilities by dissociating features of a search-relevant dimension (e.g., color) from features of a search-irrelevant dimension (e.g., shape). The logic of our study is as follows: if the DPE emerges exclusively from the inhibition of a failed feature (i.e., one that defines distractors in a target-absent search), then we should expect to find inhibition of search-relevant features, but not of search-irrelevant features. If, however, some component of the DPE is formed automatically for all features in a target-absent display, then we should reasonably expect to find inhibition both for search-relevant features and search-irrelevant features when both categories of features are presented in the same general configuration (i.e., when the target-absent display is homogeneous for both features).

From a different perspective, our study may be interpreted as an examination of the relative influences of top-down and bottom-up processes on the DPE. While it is clear that the bottom-up characteristics of a display are critical to the DPE (e.g., an observer must be able to characterize a display as target-present or target-absent before deploying focused attention; Lleras et al., 2008), we will argue that the bottom-up characteristics of the display alone are insufficient to produce the DPE. Specifically, we will argue that the DPE emerges only for features that are part of an observer’s top-down attentional set (e.g., it does not extend to all viewed features; Leber & Eggeth, 2006).

Other studies have examined the role of task relevance in inter-trial effects, though primarily within the context of priming of pop-out (Fecteau, 2007; Huang et al., 2004; Kristjánsson, 2006). Kristjánsson (2006) presented participants with an array of Gabor patches that varied in spatial frequency, orientation, and color. In a series of experiments, these feature dimensions were alternately assigned to the role of a search feature, response feature, and task-irrelevant feature. The results indicated that task-relevance modulated priming, though in some circumstances priming was also observed for a task-irrelevant feature (specifically, color always produced a priming effect). In a similar fashion, Huang et al. (2004) examined priming across multiple dimensions and found evidence of relative independence between dimensions. In their experiments, a target was defined as a size oddball among randomly colored and oriented bars. Though the magnitude of priming observed (i.e., the response-time difference between a repetition or switch of a feature across trials) was greatest for the defining feature, the authors observed a significant cross-over interaction driven by priming along the irrelevant feature. Finally, Fecteau (2007) examined priming of pop-out for features in a display that were made either task-relevant or task-irrelevant via instructions between trials. Participants performed a search for a feature singleton based upon prior instructions (a specific feature dimension, color or shape, was defined as the target dimension by a cue prior to the search display). When the search feature was repeated, Fecteau observed the standard PoP. In the critical “switch” trials, however, no PoP was observed. In other words, whereas the studies by Huang et al. (2004) and Kristjánsson (2006) found evidence of a contribution to inter-trial priming by the repetition of a task-irrelevant feature, Fecteau (2007) failed to find any such irrelevant-feature driven effects. These somewhat disparate findings will be further addressed in the General discussion section.

In sum, these previous studies suggest that the extent to which past trials will influence future trials can be modulated by the current goals of an observer. Here, we will examine this issue in the context of the DPE by investigating whether a DPE can be observed for features that are irrelevant to the search task, and thus not part of the observer’s search goals.

Current study

In two experiments, we dissociated search-relevant and search-irrelevant features in oddball-feature searches in an attempt to determine whether inter-trial inhibition was formed for all features presented in a target-absent display, or rather only for those features that defined the target. In Experiment 1, participants viewed three-item displays consisting of colored shapes. They were asked to find a uniquely colored object (i.e., color was the search dimension) and report its shape (i.e., shape was a search-irrelevant
dimension). In critical trials, target-present displays were preceded by displays that were homogenous along both search and response features, and thus would be expected to produce inter-trial inhibition (Goolsby et al., 2005; Lleras et al., 2008). To preview our results, we found the expected DPE along the search dimension, but not along the search-irrelevant dimension (i.e., a color DPE but no shape DPE). Experiment 2 was analogous to Experiment 1, with the roles of color and shape swapped such that color was search-irrelevant and shape was the search-relevant dimension. Though the search displays were essentially the same as in Experiment 1, shape (the new search-relevant dimension) now produced a DPE, while color no longer produced an inter-trial effect.

Experiment 1

In Experiment 1, we attempted to isolate the influences of search-relevant and search-irrelevant features on the DPE. In light of evidence that the DPE reflects a biasing of selective attention (Lleras et al., 2008) and the finding that inter-trial effects can be at least partially modulated by a top-down attentional set (Fecteau, 2007; Kristjánsson, 2006), our hypothesis was that the DPE would occur only for features that could be used to successfully guide attention (i.e., only for the search-relevant feature). Since the DPE generally emerges during relatively efficient pop-out visual searches, we selected two feature dimensions that could independently allow for pop-out visual search: color and shape (Theeuwes, 1992; also see Wan & Lleras, 2008). In Experiment 1, color was search-relevant (an oddball color defined a target) while shape was search-irrelevant (participants indicated the shape of the odd-colored item).

Methods

Participants

Sixteen students from the University of Illinois participated in a one-hour experiment. Participants were compensated for their time via course credit in an introductory psychology class. All participants had normal or corrected-to-normal vision, and none were colorblind.

Apparatus

The experiment was programmed using Matlab and the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997) and was run on a 3.4-GHz Pentium 4 PC running Windows XP. Stimuli were presented on a 17-inch CRT monitor at a resolution of 1024 × 768, at 60 Hz. Participants were seated comfortably at a distance of approximately two feet and responded via keyboard.

Stimuli

Each search array consisted of three equidistant objects, arranged along an iso-acuity ellipse that extended from the center of the screen with a horizontal axis of approximately 10° and a vertical axis of approximately 8°. Objects appeared against a black background in one of three colors, red, green, or blue, and as one of two shapes, circle or equilateral triangle. The target object in a display was defined as a color oddball (e.g., a green target among two red distractors), and all target-present displays also contained a shape pop-out. In a target-absent display, all objects were homogenous for color but would frequently contain a shape pop-out (approximately 50% of trials). Target-present displays were presented indefinitely until the participant made a response, while target-absent displays were presented for approximately 600 ms before being replaced by a blank screen. All displays were preceded by a variable 800–2300 ms blank screen.

Search displays were organized as trial pairs: in the majority (82%) of trial pairs, participants were presented with a target-absent display followed by a target-present display. In the remaining trial pairs, participants were presented with either two consecutive target-present displays (9%), or two consecutive target-absent displays (9%).

Figure 1 depicts the trial pairs of interest in this experiment. The critical target-absent/target-present trial pairs were divided evenly among three experimental conditions: target-color previewed, distractor-color previewed, and neither-color previewed. In the target-color previewed condition, the color of items in the target-absent display (e.g., three green items) defined the target in the subsequent display (e.g., a green target among red distractors). In the distractor-color previewed condition, the color of items in the target-absent display was the same as the color of distractors in the target-present display. Finally, in the neither-color previewed condition, the color of items in the target-absent display did not appear in the target-present display. Half of all target-absent displays contained a shape pop-out, and the other half were homogenous in shape. While all target-present displays contained a shape pop-out, on half of the trials the shape pop-out co-occurred with the color pop-out (i.e., the same item was unique along the color and shape dimensions, which we termed the redundant singleton condition), and on the other half of trials the shape pop-out and color pop-out occurred on different items (i.e., the two pop-outs were in different locations, which we termed the competing singleton condition).

Procedure and data analysis

Participants were instructed to search each display for a color pop-out. If a color pop-out was present, they were then instructed to indicate whether the target was a circle or a triangle, and made their response via keyboard (i.e.,
the left-arrow key was used for ‘circle,’ and the right-arrow key for ‘triangle’). Participants were told to respond as quickly as possible when a target was present (while maintaining a high level of accuracy), and to make no response when a target-absent display was presented.

Accuracy and response times were collected and all trial parameters were recorded during the experiment. For the analyses presented below, we included all trials, regardless of whether the target-absent preview was heterogeneous or homogeneous along the search-irrelevant feature. Panel B shows trial pairs used to isolate inter-trial inhibition of the search-irrelevant feature, using trials from the neither-color previewed condition. For the analysis, only target-absent trials that were homogeneous for shape were used. In Experiment 2, the strategy for producing preview trials was identical, but the respective roles of color and shape were reversed.

![Figure 1](https://jov.arvojournals.org/pdfaccess.ashx?url=/data/journals/jov/933527/) A description of critical trial pairs in which a target-absent trial was followed by a target-present trial. Panel A depicts the trial pairs selected to determine whether inter-trial inhibition was present for the search-relevant feature. For our analysis of this effect, we included all trials, regardless of whether the target-absent preview was heterogeneous or homogeneous along the search-irrelevant feature. Panel B shows trial pairs used to isolate inter-trial inhibition of the search-irrelevant feature, using trials from the neither-color previewed condition. For the analysis, only target-absent trials that were homogeneous for shape were used. In Experiment 2, the strategy for producing preview trials was identical, but the respective roles of color and shape were reversed.

...
Further, we analyzed only those neither-color previewed trials in which the target-absent display had been homogenous for shape. Within this context, we defined a shape-preview condition in the following way: when a target was the same shape as all distractors in the preceding target-absent display (e.g., participants must respond “circle” when they recently viewed a target-absent display with all circle shapes), the trial was labeled “target-shape previewed”. Analogously, the “distractor-shape previewed” condition was defined as those trials in which the distractors on the target-present trials had the same shape as the items in the preceding target-absent trial. Again, because in these trials, the color-dimension carried no inhibitory bias from target-absent to target-present trial, any observed bias must come from the shape dimension.

Huang et al. (2004) found an interaction of a task-irrelevant feature dimension on inter-trial priming for the target-defining feature dimension. In keeping with that finding, we performed an additional ANOVA including preview condition (distractor vs. target-color previewed), pop-out (competing vs. redundant singletons in the target-present displays), and the shape-preview condition described above. This analysis was restricted to those trials in which the target-absent presentation was homogenous for shape.

Figure 2. Results of Experiments 1 and 2, for their respective search-relevant features. For both experiments, we found a significant DPE for the competing singleton condition (Experiment 1: 89 ms; Experiment 2: 49 ms), but no DPE in the redundant singleton condition. In both experiments, the redundant singleton condition elicited reliably faster responses compared to the competing singleton condition.
Results

Our primary interest is in the comparison of inter-trial effects for the search-relevant and search-irrelevant feature dimensions. To determine whether the search-relevant feature dimension, color, produced the expected inter-trial effect, we performed a repeated-measures ANOVA on participants’ RTs, including the preview and pop-out conditions as factors (see Figure 2A for details). The analysis revealed a significant main effect of preview condition, $F(1,15) = 9.77, p < 0.005$, and a significant main effect of pop-out condition, $F(1,15) = 10.77, p < 0.005$. The interaction was also significant, $F(1,15) = 8.83, p < 0.010$. Post-hoc comparisons revealed that the DPE emerged most strongly (89 ms) when a competing singleton was present in the target-present display, $t(15) = 3.70, p < 0.002$, and was eliminated when the search-irrelevant pop-out was redundant with the target in the display, $t(15) = 1.16, p < 0.266$ (i.e., when the target was a pop-out both in the color and shape dimensions). Within competing pop-out trials, response times in the distractor-color previewed condition were 42 ms faster (and target-color previewed response times 35 ms slower) than in the neither-color previewed condition, indicating a roughly equal contribution of inhibition and facilitation in the observed DPE. However, pairwise comparisons between

![Bar chart](A)

**A**  
Search-irrelevant feature: Shape

![Bar chart](B)

**B**  
Search-irrelevant feature: Color

---

Figure 3. Results of Experiments 1 and 2, examining inter-trial effects of search-irrelevant features. Here, both the competing and redundant singleton conditions failed to produce any reliable inter-trial effect.
the distractor (and target) previewed conditions and the neither-color previewed condition failed to reach significance (ps > 0.14).

Having found a significant and substantial inter-trial inhibition for the search-relevant feature, color, we performed a similar analysis of the search-irrelevant feature, shape (see Figure 3A). We performed a two-way repeated-measures ANOVA on the response times from these trials, with shape-preview and pop-out conditions included as factors. The analysis revealed a significant main effect for the pop-out condition, \( F(1,15) = 4.99, p < 0.041 \), but no main effect for the shape-preview condition, \( F(1,15) = 2.98, p < 0.105 \), and no interaction, \( F(1,15) = 0.36, p < 0.556 \). A pairwise comparison of the shape-preview condition within the competing singleton condition failed to reach significance, \( t(15) = 0.41, p < 0.691 \), as did a pairwise comparison within the redundant singleton condition, \( t(15) = 1.55, p < 0.105 \). In sum, the search-irrelevant dimension (shape) did not produce an inter-trial inhibitory effect of attention (whereas the search-relevant dimension, color, did). However, the oddball status on the search-irrelevant dimension did affect overall RTs, with RTs being faster in the redundant singleton condition and slower in the competing singleton condition. In other words, the search-irrelevant dimension did significantly affect the deployment of attention on target-present trials but did so in an amnesic manner, independent of its relative repetition (or alternation) across consecutive trials.

Finally, we turned our attention to a potential interaction of the search-irrelevant feature, shape, on the DPE observed for color. We performed a repeated-measures ANOVA including pop-out, color-preview, and shape-preview as factors. The analysis revealed a main effect of pop-out, \( F(1,15) = 11.878, p < 0.004 \), a main effect of color preview, \( F(1,15) = 4.935, p < 0.042 \), and an interaction of pop-out and color preview, \( F(1,15) = 7.526, p < 0.015 \). Importantly, the analysis failed to find any main effect of the shape-preview, nor any interaction with this factor (all \( F < 2.7, all ps > 0.12 \)). In other words, there was no evidence of any inter-trial bias arising from the search-irrelevant feature.

**Error analysis**

To ensure that our above results were not the result of a speed-accuracy trade-off, we repeated our analyses on error rates instead of response times. Across all analyses, differences in error rates failed to approach significance (all \( ps > 0.1 \)).

**Discussion**

In Experiment 1, we sought to determine whether focused attention to a search-irrelevant feature would be inhibited in a manner analogous to the inhibition found for search-defining features in the DPE. Would a target-absent trial containing all identical shapes produce a bias against focusing on that shape on a subsequent target-present trial, when shapes are irrelevant to the search task? Our results clearly indicate that this is not the case. Instead, the results of Experiment 1 suggest that the inter-trial suppression of a feature in a display is entirely modulated by its relevance to the search task: color, the search-relevant dimension in each display, produced a strong DPE while shape, the search-irrelevant dimension, produced no inter-trial effect. This result is consistent with the finding by Fecteau (2007) that search-irrelevant features do not produce inter-trial priming effects (but see Huang et al. (2004) and Kristjánsson (2006), which are further addressed in the General discussion section). Together, our findings together suggest that participants do not process search-irrelevant features in the same manner as they process search-relevant features, insofar as the repetition of search-irrelevant features fails to produce either facilitatory (in priming of pop-out) or inhibitory effects on attention (no DPE).

The finding that search-irrelevant features fail to induce inter-trial effects does not mean that these features do not affect search processes. Clearly they do, as evidenced here by the finding that the color-based DPE was modulated by the shape oddball: we found a strong color-based DPE when the two feature oddballs occurred on different items on the display, yet we found no color-based DPE when the color-oddball target was also a shape-oddball target (an elimination of an 89 ms effect). This is consistent with a large literature on attentional capture showing that search-irrelevant features affect the deployment of attention (e.g., Theeuwes, 1992).

A straightforward pattern of results emerged from Experiment 1: search-relevant features produced an inter-trial inhibitory effect on focused attention (i.e., a DPE), whereas search-irrelevant features did not. In other words, failing to find a color-oddball target on a homogeneously colored display produced a bias against focusing attention on that color on subsequent trials. However, failing to find a color-oddball target on a homogeneously shaped display failed to produce a bias against focusing attention on that shape on subsequent trials. Presumably, this is because the bias was put in place as a way to improve performance in the task (finding a color oddball), for which shape was irrelevant. Our results did show that search-irrelevant features can influence behavior, but this effect was amnesic: the effect occurred within a trial and was not modulated by previous events. However, it is reasonable to argue that our current results might be dependent on the features that we tested. Color may be more likely to produce an inter-trial effect than shape in general, given evidence that color pop-outs capture attention more strongly than shape pop-outs (Theeuwes, 1992). To address this concern, in Experiment 2 we replicated the findings...
of Experiment 1, but with a reversal of the roles of shape and color as search-relevant and search-irrelevant dimensions.

**Experiment 2**

In Experiment 2, we swapped the roles of color and shape: participants were now instructed to find an oddball shape in a display, and report that oddball shape’s color. The findings of Experiment 2 replicated those of Experiment 1: a significant DPE for shape (the new search-relevant dimension) and no inter-trial effect for color (the search-irrelevant dimension) although, once again, search-irrelevant pop-outs influenced participants’ responses on a within-trial basis.

**Methods**

All methods for Experiment 2 were identical to that of Experiment 1, except where noted.

**Participants**

17 students from the University of Illinois participated in a one-hour experiment. Participants were compensated for their time via course credit in an introductory psychology class. All participants had normal or corrected-to-normal vision, and none were colorblind.

**Stimuli**

Objects were one of three possible shapes (circle, triangle, or square) and appeared in one of two possible colors (red or green). The target object in a display was now defined as the shape oddball (e.g., a circle target among two square distractors), and all target-present displays contained a color pop-out. As in Experiment 1, in a target-absent display all objects were homogenous for the search-relevant feature (shape) but contained a search-irrelevant pop-out (a color oddball) 50% of the time.

**Procedure and data analysis**

Participants were instructed to search each display for a shape pop-out, which was their target. If a shape-pop-out was present, they were then instructed to indicate whether the target was green or red, and made their response via keyboard (using the left-arrow key for green, and right-arrow key for red). When a target was present, they were instructed to respond as quickly as possible while maintaining high accuracy. When a target-absent display was presented, they made no response. The maximum response time was increased from 3000 ms to 3500 ms for Experiment 2, to reflect larger overall RTs in the shape-oddball search task. Accuracy was high (~93%), and as in Experiment 1, approximately 96% of accurate responses fell within the allowable time range.

Following the strategy of analysis described in Experiment 1, we examined inter-trial inhibition for the search-relevant feature via repeated-measures ANOVA that included preview (distractor-shape previewed vs. target-shape previewed) and pop-out conditions. As in Experiment 1, we performed pairwise comparisons between the distractor (and target)-shape previewed conditions and the neither-shape previewed condition.

To evaluate the effects driven by the search-irrelevant dimension, we again looked at target-present trials in the neither-shape previewed condition (e.g., which carried no inhibition along the search-relevant dimension from the preceding target-absent trial), and that were preceded by target-absent trials homogenous in color: A target-color previewed trial was one in which the color of the target in a target-present display was the same as the homogeneous distractors in the preceding target-absent display. A distractor-color previewed trial was one in which the color of the target in a target-present display did not match that of the homogeneous distractors in the previous target-absent display. Note, once again, that here color was the search-irrelevant dimension.

We were interested in whether a search-irrelevant dimension would produce an interaction on the DPE of the search-relevant feature (following Huang et al., 2004), and we performed a repeated-measures ANOVA including as factors the pop-out condition, preview condition, and search-irrelevant preview condition (as described above). Again, this analysis was restricted to trials for which the target-absent display had been homogeneous for the search-irrelevant feature (color).

**Results**

As in Experiment 1, our primary interest was the potential inter-trial inhibition associated with the search-relevant feature (shape) compared to the search-irrelevant feature (color). A summary of the findings of this experiment is shown in Figure 2B. To isolate inter-trial inhibition associated with the search-relevant feature, we performed a repeated-measures ANOVA on participants’ response times and included the preview and pop-out conditions as factors. Unlike Experiment 1, the analysis failed to reveal a significant main effect for the preview condition, $F(1,16) = 2.58, p < 0.128$. Consistent with the previous experiment, however, there was a significant main effect of pop-out condition, $F(1,16) = 44.55, p < 0.001$, and a significant interaction, $F(1,16) = 6.48, p < 0.022$. Pairwise comparisons revealed a significant DPE for shape in the competing singleton condition (49 ms), $t(16) = 3.07, p < 0.007$, but no DPE for shape
in the redundant singleton condition (−0.8 ms), \(t(16) = 0.04, p < 0.967\). Though overall mean RTs show that the 49 ms DPE was divided equally between a response time benefit (the distractor-shape previewed condition was 24.8 ms faster than the neither-shape previewed condition) and a response time cost (the target-shape previewed condition was 24.2 ms slower than the neither-shape previewed condition), pairwise comparisons were not significant (both \(p > 0.25\)).

To determine whether the search-irrelevant feature produced an inter-trial effect, response times were examined for trials in the ‘neither-shape previewed’ condition in which the target-absent display was homogenous for color (see Figure 3B). We performed a repeated-measures ANOVA that included the color-preview and pop-out conditions. The analysis revealed a significant main effect for the pop-out condition, \(F(1,16) = 9.08, p < 0.008\), but no significant main effect for the color-preview, \(F(1,16) = 0.31, p < 0.588\), and no interaction, \(F(1,16) = 0.36, p < 0.555\). Pairwise comparisons indicated that the search-irrelevant feature failed to elicit a DPE in either the competing singleton or redundant singleton condition, \(t(16) = 0.19, p < 0.852\) and \(t(16) = 0.78, p < 0.446\), respectively.

With regard to a possible DPE driven by the search-irrelevant feature, we once again performed a repeated-measures ANOVA that included shape-preview and pop-out conditions. The analysis revealed a significant main effect for the pop-out condition, \(F(1,16) = 9.08, p < 0.008\), but no significant main effect for the color-preview, \(F(1,16) = 0.31, p < 0.588\), and no interaction, \(F(1,16) = 0.36, p < 0.555\). Pairwise comparisons indicated that the search-irrelevant feature failed to elicit a DPE in either the competing singleton or redundant singleton condition, \(t(16) = 0.19, p < 0.852\) and \(t(16) = 0.78, p < 0.446\), respectively.

Discussion

The results of Experiment 2 replicated those of Experiment 1, even though the roles of the color and shape dimensions were reversed: a DPE was found in the search-relevant dimension (shape) and no DPE was found in the search-irrelevant dimension (color). Further, we once again found evidence that the deployment of attention on any given target-present trial was affected by the presence of a search-irrelevant singleton, yet that modulation was amnesic (i.e., independent of any previous events). As a result of this modulation, and consistent with Experiment 1, the DPE was once again eliminated when the shape singleton (the target) happened to be a color singleton as well, yet the DPE was substantial when the shape singleton and the color singleton were different items. Given the analogous pattern of results across experiments, we can now conclude that on target-absent trials not all viewed features are “treated equally” by the attentional system: search-relevant features are marked with a bias that will affect future deployments of attention, whereas search-irrelevant features are not. In other words, the participants’ goals determine how features will be processed on any given trial and which features will be examined (and inhibited) on target-absent trials. Examination of those search-relevant features will produce lasting effects on the attentional system, whereas other perceived features will not.

General discussion

This study addressed a specific question: is the DPE modulated by the observer’s goals? That is, do the observers’ goals determine which visual features drive this inter-trial effect? In order to answer this question, we manipulated through our instructions which visual feature (color or shape) was search relevant and which visual feature was search irrelevant. Consistently, we found that an inter-trial effect was only observed for the search-relevant feature. Even though both features had the potential to produce a DPE when search relevant, both features failed to produce an inter-trial effect when they were irrelevant to the search task. In addition, we consistently found an amnesic effect of the search-irrelevant feature on search trials: the presence, in this irrelevant dimension, of a singleton item modulated
overall RTs as well as the magnitude of the DPE itself. This effect was identical on every search trial, regardless of its relation to the preceding trial.

Our present findings are consistent with previous studies in a number of different literatures. First, we should note that finding a DPE that is constrained to search-relevant features is entirely analogous to recent findings reported by Fecteau (2007) showing that priming of pop-out is driven by the inter-trial repetitions (or alternations) of the search context along the search-relevant feature and is insensitive to repetitions of features along search-irrelevant features. That said, our results, along with Fecteau’s, differ from Kristjánsson (2006) as well as Huang et al. (2004), who demonstrated a partial modulation of inter-trial priming by irrelevant features.

Though these studies appear at odds with each other, Fecteau suggested a way of reconciling these results. In her study, as in ours, the “search-irrelevant” dimension was not entirely irrelevant to the task because on some trials participants had to scrutinize this feature dimension in order to complete the task (and in our experiment, it was the dimension they had to scrutinize to produce a response). This stands in contrast to the design in Huang et al. (2004) and in Kristjánsson (2006), in which the irrelevant feature dimension that modulated inter-trial priming was in fact totally task-irrelevant (i.e., participants never had to scrutinize it at any point during the experiment). Fecteau speculated that attentional gating of inter-trial priming may be more effective on task-relevant dimensions (even if search irrelevant) than on task-irrelevant dimensions, simply because these latter dimensions are never actively monitored by the attentional system during the experiment. In other words, when a given feature dimension is totally irrelevant to the experimental task, repetitions of features along this dimension may modulate inter-trial priming in some automatic, presumably bottom-up manner. However, when a feature dimension is part of the task set, the attentional system actively and effectively gates whether or not biases along this dimension are allowed to influence behavior (or whether they are formed at all). Certainly, our results fall in line with Fecteau’s account. In our paradigm the search-irrelevant feature was always part of the task set (i.e., it was the response feature in all trials) but was never search relevant. Thus, we may be observing an example of very effective attentional gating: because our search-irrelevant dimension is constantly being monitored by the attentional system (to produce responses), any priming effects arising from this “response-relevant” dimension are effectively blocked as they could not improve performance during target selection.

At a more general level, the observed dissociation regarding how the visual system processes search-relevant and search-irrelevant feature dimensions is quite interesting in and of itself and goes to show that not all seen features are “processed equal”, nor are all seen feature dimensions. This finding is consistent with research showing preferential treatment of feature dimensions that are within an “attentional set” (Folk et al., 1992), and the notion that features within a task set can be used to guide search (e.g., Wolfe, 1994). Our current findings extend those ideas to inter-trial effects: “attended” features are capable of making a lasting impression on the visual system by creating a bias that influences attentional deployment on future occurrences of similar scenes (i.e., a modulation of top-down guidance in search), whereas features outside of this attentional set may be incapable of producing such biases, at least within the context of the DPE.

The dissociation between the lasting effects of relevant and irrelevant features on search is also consistent with recent empirical work from our lab on interrupted visual search (Lleras, Rensink, & Enns, 2007). In an interrupted visual search trial, search displays are presented briefly (100 ms) and alternate with longer blank displays (900 ms). Observers are quite good at finding and reporting the identity of the target, typically within 3 or 4 looks at the display (Lleras, Rensink, & Enns, 2005). More to the point, in two experiments, Lleras et al. (2007) investigated what would happen to response times if changes to the target stimuli were made during the interruptions. Specifically, there was a 50% chance that on a given re-presentation of the search display, the current target would be different from the target on the previous search display (though in the same search trial), and a 50% chance that the target would be the same as on the previous display. Though participants did not report being aware of changes to the target, their response times were severely disrupted when the target had changed on the last two presentations along a task-relevant feature dimension but were unaffected when the target had changed along a task-irrelevant feature dimension. These results provide further converging evidence for the existence of a processing hierarchy of visual features determined by task relevance. It is worth mentioning that a similar hierarchy in feature processing has been proposed by Grossberg in the context of his computational work on pattern recognition in human vision (Grossberg, 1976a, 1976b; also, Carpenter & Grossberg, 1987, 2003). In this model (ART), sensory inputs activate high-level codes in memory and these codes are then tested as top-down expectations back against sensory inputs. A pattern is recognized when a match (or near-match) between the top-down expectation and the sensory input occurs. Interestingly, visual patterns can still be positively recognized when the two signals (input and expectation) are quite different, as long as the differences occur along features that are outside of the “attentional focus” of the task. On the other hand, when the two signals differ along features within this attentional focus, the visual pattern is not recognized and the sensory input must be tested anew against a new set of top-down expectations.

Finally, our within-trial attentional effects are entirely consistent with findings in the attentional capture literature...
but rather as an automatic reduction in salience of recently viewed search items. In other words, they proposed that the saliency of recently viewed search items is automatically and pre-attentively decreased on future viewings of the same items. Goolsby et al. restricted their study to the perception of color (i.e., they refer to the DPE as a Color Saliency Aftereffect) and did not test for other visual features. However, in our Experiment 2, we clearly demonstrated that the saliency of color is not automatically and pre-attentively reduced by merely viewing red search items over consecutive trials. On the contrary, we found no evidence that simply viewing color produced any type of inter-trial effect in that experiment (when color was search irrelevant). Clearly, it is not the mere viewing of a feature during a search trial that reduces its salience on a future search trial. How a feature relates to the definition of the search, that is, whether it is relevant to the search task or not, determines whether the feature will give rise to an inter-trial effect, both in the case of priming of pop-out and the DPE.

Another interesting finding of our study is that, under the right circumstances, the inter-trial suppression of a feature (e.g., DPE) can be circumvented. When the search-irrelevant pop-out was one and the same with the search-relevant pop-out, we observed a total elimination of the DPE in both experiments. In nearly all prior studies of the DPE (Ariga & Kawahara, 2004; Goolsby et al., 2005; Lleras et al., 2008; for an exception see Wan & Lleras, 2008), participants’ responses were restricted to visual features that could not be detected without focused attention (e.g., a missing side of a diamond, orientation of a small diagonal line, or the relative location of a dot in an image). In other words, presence of a singleton along the search-relevant dimension could always be detected in a very efficient manner, whereas focused attention would have been required to notice an oddball along search-irrelevant dimensions. In our study, however, singletons along both the search-relevant and search-irrelevant dimensions could be detected without focused attention. Given their overall effect on participants’ response times (i.e., main effects of the pop-out condition in Experiments 1 and 2), it is likely that singletons in the search-irrelevant dimension captured participants’ attention on our experiments (Yantis & Egeth, 1999). At this point, however, it is unclear how or why such attentional capture along a search-irrelevant dimension should lead to the total elimination of the inter-trial bias along the search-relevant dimension. We see one possible explanation for these results.

The elimination of the DPE on redundant singleton trials may be due to the increased salience of the target on these trials: indeed, the target is a singleton along two feature dimensions and is most different from distractors than on any other trial. If the DPE really reflects a modulation of attentional deployment after the target has been detected (Lleras et al., 2008), the DPE should be reduced when the target is easier to select (i.e., it is more salient). Consistent with this interpretation is the finding on both experiments that RTs were significantly faster on
Conclusion

The ability to perform even simple visual searches can be dramatically influenced by our immediately preceding experiences. Our results contribute to the literature on inter-trial effects in visual search by providing further evidence that only the “relevant” aspects of our past experience influence our future behavior. More specifically, we show that when we are faced with a search failure (due to the absence of a target), our attentional system creates a bias to prevent re-examinations of these “failed” visual features on future trials. This bias is constrained to the search-relevant feature dimension (the dimension that was examined for the presence of a target) and does not extend to search-irrelevant feature dimensions (which, although perceived, were unrelated to the presence of the target). These results suggest that there is a visual processing hierarchy of feature dimensions: whereas search-relevant feature dimensions are examined on every trial and automatically remembered across trials (insofar as they automatically produce inter-trial biases of attention), search-irrelevant feature dimensions are examined on every trial (insofar as they can capture attention) yet they are not automatically remembered. This processing hierarchy reflects the current goals of the observer and can be set via simple instructional manipulations. In the case of the Distractor Previewing Effect, our visual system remembers the feature that “failed” us (by trying to prevent us from attending to it on future trials), yet remains amnesic to the other equally salient features that it processed during that failed search.

Acknowledgments

This research was partially supported by a grant from the National Science Foundation to A.L., BCS 07-46586 CAR.

References


Footnote

1We included a proportion of trials in which the target-absent display was heterogeneous for the search-irrelevant feature for several reasons. First, target-absent displays are typically heterogeneous along the response feature in prior studies of the DPE (e.g., Goolsby et al., 2005; Lleras et al., 2008). Second, if an analogous inter-trial effect were found along the search-irrelevant dimension, these trials would provide an opportunity to observe a DPE for the search-relevant dimension uncontaminated by search-irrelevant priming. As we ultimately failed to observe any inter-trial effect along the search-irrelevant dimension, our analysis of the DPE for the search-relevant dimension was collapsed across all target-absent trials, and this distinction was not examined any further.

Commercial relationships: none.
Corresponding author: Brian R. Levinthal.
Email: levintha@uiuc.edu.
Address: Department of Psychology, University of Illinois at Urbana-Champaign, 603 East Daniel St., Champaign IL, 61820, USA.


