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The Role of Context in Volitional Control of Feature-Based Attention

Artem V. Belopolsky
VU University Amsterdam

Edward Awh
University of Oregon

Visual selection can be biased toward nonspatial feature values such as color, but there is continued debate about whether this bias is subject to volitional control or whether it is an automatic bias toward recently seen target features (*selection history*). Although some studies have tried to separate these 2 sources of selection bias, mixed findings have not offered a clear resolution. The present work offers a possible explanation of conflicting findings by showing that the context in which a trial is presented can determine whether volitional control is observed. We used a cueing task that enabled independent assessments of the effects of color repetitions and current selection goals. When the target was presented among distractors with multiple colors (*heterogeneous* blocks), Experiment 1 revealed clear goal-driven selection effects, but these effects were eliminated when the target was a color singleton (*pop-out* blocks). When heterogeneous and pop-out displays were mixed within a block (Experiment 2), however, goal-driven selection was observed with both types of displays. In Experiment 3, this pattern was replicated using an encoding-limited task that included brief displays and an A' measure of performance. Thus, goal-driven selection of nonspatial features is potentiated in contexts where there is strong competition with distractors. Selection history has powerful effects, but we find clear evidence that observers can exert volitional control over feature-based attention.

Keywords: feature-based attention, goal-driven control, top-down control, biased competition

Since the typical visual scene contains far more information than an observer has the capacity to process at once, selective attention is crucial for directing limited processing resources toward the most relevant aspects of the environment. Thus, a central research question in psychology has been to understand how selective attention is controlled. The most prominent models of attentional control propose that attention can be allocated in a voluntary fashion (consistent with the observer's current goals) or in an automatic fashion that is determined by the physical properties of the stimulus display (i.e., "top-down vs. bottom-up" control; Corbetta & Shulman, 2002; Egeth & Yantis, 1997; Jonides, 1981; Posner, Snyder, & Davidson, 1980; Theeuwes, Olivers, & Belopolsky, 2010; cf. Awh, Belopolsky, & Theeuwes, 2012). In line with this framework, a consensus has emerged that observers can direct spatial attention to specific locations at will (e.g., Eriksen & Hoffman, 1973; Moran & Desimone, 1985; Posner et al., 1980) or that spatial attention can be "captured" at specific locations regardless of the observer's will by salient events such as an abrupt onset (Jonides, 1981; Yantis & Jonides, 1990). In either case, target discrimination at attended locations is faster and more accurate than at unattended locations (Eriksen & Hoffman, 1973; Jonides, 1981; Posner et al., 1980; Yantis & Jonides, 1990).

In line with the findings from the spatial attention literature, many influential theories of visual selection also describe control processes that direct attention toward nonspatial features such as color, orientation, or motion. For example, guided search (Wolfe, Cave, & Franzel, 1989) suggests that observers can prepare to search for a target with a certain feature (e.g., red) or dimension (e.g., color) by placing a "higher weight on the output of one channel than on others" (Wolfe, 2007, p. 105). Similarly, according to the dimensional weighting account (Found & Müller, 1996), "preattentive saliency computations may be biased by top-down signals reflecting expectations of particular stimulus attributes" (Müller et al., 2010, p. 118). This in turn biases the processing in favor of the elements sharing the target feature or dimension in a subsequently presented display. In support of this idea, it has been demonstrated that observers are more efficient in finding the target among distractors when they possess advance knowledge of the target feature (Müller, Reimann, & Krummenacher, 2003) and that they have difficulty ignoring distractors that share features with the target (Folk, Remington, & Johnston, 1992). Similarly, neuroimaging studies have demonstrated that attending to color or motion results in an increase in baseline activity in the corresponding areas of early visual cortex (Chawla, Rees, & Friston, 1999; Saenz, Buracas, & Boynton, 2002), spreading across the whole visual field, including the empty areas (Serences & Boynton, 2007). In addition, recent work (Zhang & Luck, 2008) has shown that a distractor that shares a color with the target elicits a larger visually evoked neural response even when it is presented at an unattended location.

Artem V. Belopolsky, Department of Cognitive Psychology, VU University Amsterdam; Edward Awh, Department of Psychology, University of Oregon.

Edward Awh is now at the Department of Psychology, Institute for Mind and Biology, University of Chicago.

Correspondence concerning this article should be addressed to Artem V. Belopolsky, Department of Cognitive Psychology, VU University Amsterdam, Van der Boechorststraat 1, 1081 BT Amsterdam, the Netherlands. E-mail: a.belopolsky@psy.vu.nl

Nevertheless, despite the diverse array of evidence showing that selection can be biased toward nonspatial features, the extant data do not yet make a strong case for *goal-driven* control over these visual biases. Many past studies are ambiguous because they relied on blocked designs in which the relevant nonspatial feature (e.g., the target-defining color) was held constant across multiple trials (e.g., Folk et al., 1992; Wolfe, Butcher, Lee, & Hyle, 2003). This design allows for intertrial priming effects in which the repetition of a target feature yields long-lasting benefits in both the speed and accuracy of responses. Moreover, these selection history effects have been shown to occur automatically, regardless of whether the observer is aware of the repetition or whether his or her current goals have shifted to a different feature value (e.g., Maljkovic & Nakayama, 1994). Thus, when selection history is confounded with the putative effects of goal-driven selection, there is no clear evidence that goal-driven selection has had an effect (Awh et al., 2012; Belopolsky, Schreij, & Theeuwes, 2010; Theeuwes, 2013).

This point was clearly illustrated in a study by Theeuwes and Van der Burg (2007) that directly compared the effect of spatial and nonspatial precues in a visual search task. To allow separation of goal-driven selection and selection history, Theeuwes and Van der Burg (2007) varied the specific location or color that was cued on a trial-by-trial basis. In addition, to prevent priming from the physical presentation of the cues, the locations and color precues were communicated with words that did not require the physical presence of the cued feature value. Finally, all targets in this study were color singletons, because they reasoned that such "pop-out" targets (combined with brief, masked displays and a behavioral measure of perceptual sensitivity) would provide a cleaner index of early stages of visual processing that occur during the first feedforward sweep of visual activity (Nothdurft, Gallant, & van Essen, 1999; Treisman, 1988). The results showed a striking contrast between the efficacy of the spatial and nonspatial cues. Clear evidence for goal-driven selection—independent of selection history effects—was observed with the spatial precues, but no such effect was observed with the color precues. Thus, Theeuwes and Van der Burg (2007) concluded that while observers could exert goal-driven control over spatial attention, only automatic priming of specific feature values was possible with nonspatial cues. Indeed, when the color word cues were replaced with physical cues that contained the cued feature value, Theeuwes and Van der Burg (2007) observed reliable benefits of the color cues; critically, this effect was observed regardless of whether the cue was predictive or not, suggesting that it was not connected with the volitional selection goals of the observer.

To summarize, despite clear evidence for goal-driven selection in the spatial domain, the role of volitional control in the selection of nonspatial features is less certain. Clear evidence for goal-driven selection of nonspatial features requires an experimental design that can disentangle the automatic biases that are caused by selection history and the biases in visual selection that are subject to volitional control. This motivates an experimental design that includes trial-by-trial variations in the cued feature value (so that it is possible to test whether current goals bias visual selection in the absence of repetition priming) and that employs abstract cues rather than physical presentations of the cued feature value. To date, a handful of studies have fulfilled these criteria (Leonard & Egeth, 2008; e.g., Mortier, Theeuwes, & Starreveld, 2005; Müller & Krummenacher, 2006; Müller et al., 2003; Theeuwes, Reimann, & Mortier, 2006; Theeuwes & Van der Burg, 2007; Zehetleitner, Krummenacher, Geyer, Hegenloh, & Müller, 2011), but the findings have been mixed. While some studies have seen evidence of goal-driven selection that cannot be explained by selection history (Müller & Krummenacher, 2006; Müller et al., 2003; Zehetleitner et al., 2011), the size of the effects (about 10 ms faster for valid than for neutral trials) has often been modest. In a recent study, large cueing effects were observed, but only for the smaller display sizes (Leonard & Egeth, 2008). One concern with this result is that with only a few elements in the display, there is a large uncertainty about the target feature, which could imply the decisional and not attentional origin of the cueing effects (Meeter & Olivers, 2006). Moreover, various studies that used almost identical experimental designs did not find reliable benefits of the nonspatial cues (Mortier et al., 2005; Theeuwes et al., 2006; Theeuwes & Van der Burg, 2007). Thus, our goal in the present work was to examine the boundary conditions of goal-driven selection with nonspatial cues, with an eye toward reconciling some of the conflicting findings in the literature.

One characteristic of all of the prior work noted above is that the target stimuli were color singletons within an array of homogenous distractors. Because pop-out stimuli are highly salient even when they are not relevant to the current task (e.g., Maljkovic & Nakayama, 1994), one might question whether or not observers in these studies were strongly motivated to use the color cues. Both Theeuwes et al. (2006) and Müller and Krummenacher (2006) attempted to address this concern by including filler trials on which participants had to report the cue or compliance with the cue; participants were extremely accurate in reporting the cue or indicated high compliance. Nevertheless, we hypothesized that increased competition between the target stimulus and the surrounding distractors might help to elicit more robust evidence of goal-driven selection. Such an interaction between the effects of visual selection and the degree of distractor interference is predicted by the biased competition theory of selective attention (Desimone & Duncan, 1995). According to this framework, attention enhances the signal-to-noise ratio for relevant stimuli by biasing competitive interactions between targets and distractors. In line with this claim, many studies have shown that the effects of visual selection are indeed enhanced when there is substantial distractor interference in a target display (Awh, Matsukura, & Serences, 2003; Awh, Sgarlata, & Kliestik, 2005; Dosher & Lu, 2000; Kastner, De Weerd, Desimone, & Ungerleider, 1998; Shiu & Pashler, 1994).

All of these considerations led us to employ a task similar to that used by Theeuwes and Van der Burg (2007), except that we also included an active manipulation of the strength of distractor interference in the target display. Observers searched for either a blue or an orange target. Before the search display, participants received a word cue indicating the likely target color. We included two types of search trials. In the pop-out condition, the target was a singleton presented among homogeneously colored distractors. In the heterogeneous condition, the target was presented among an array of distractors that each had a unique color, thereby amplifying the amount of distractor interference. Motivated by the biased competition perspective, we reasoned that the latter condition would provide a clear incentive to engage in goal-driven selection based on the cue and would magnify the performance benefit observed for validly cued stimuli. To anticipate our findings, in

Experiment 1 in which the pop-out and heterogeneous conditions were blocked, cueing effects were either absent or minimized in the pop-out condition depending on the analytic approach. By contrast, when the pop-out and heterogeneous conditions were intermixed within blocks in Experiment 2, we found more robust evidence of goal-driven selection in the pop-out condition. These findings suggest that the pop-out target displays used in past studies may not have been conducive to robust goal-driven selection effects. Finally, Experiment 3 replicated these empirical patterns using masked displays and with accuracy as a dependent measure. This suggests that the benefits of goal-driven selection influenced the perceptual encoding of the target stimuli rather than just the efficiency of postperceptual decision or response processes.

Experiment 1

Participants received a word cue indicating the upcoming target color (orange or blue) with 80% validity. The word cue did not share any features with the upcoming target; thus, this cue eliminated the possibility of low-level priming from the physical presentation of the relevant hue. Participants received ample time to use the cue and bias their visual selection. The pop-out and heterogeneous conditions were blocked. This design allowed us to examine whether there were goal-driven selection effects that were not contingent on selection history.

Method

Participants. Twenty naïve participants (seven females, mean age of 24, age range of 20–32 years) from VU University Amsterdam with normal or corrected-to-normal vision participated in the experiment.

Apparatus and stimuli. The experiment was programmed in E-Prime (Schneider, Eschman, & Zuccolotto, 2002). Stimuli were presented on a 22-in. Samsung Syncmaster 2233RZ monitor at 120 Hz.

A trial started with the presentation of a white instructional cue (*ORANGE* or *BLUE* in 18-point Courier New font) at the center of a black display for 2,000 ms (see Figure 1). It was followed by a display with a fixation dot (0.5°) that, after 300 ms, was replaced by a search display. The search display consisted of six outline circles (2.8° in diameter) positioned on an imaginary circle with a radius of 6.7° (Clock Positions 1, 3, 5, 7, 9, and 11). One of the circles was the target and could be either orange (Commission de Internationale de l'Eclairage [CIE]: .475, .467; 16.5 cd/m^2) or blue (CIE: .153, .106; 6.3 cd/m^2). In the pop-out condition, the target circle was unique and all distractor circles were green (CIE: .196, .701; 15.9 cd/m^2). In the heterogeneous condition, the target was not unique since the distractor circles were all different colors (red [CIE: .574, .390; 14.0 cd/m^2], green [CIE: .196, .701; 15.9 cd/m^2], purple [CIE: .302, .219; 9.0 cd/m^2], yellow [CIE: .39, .54; 96.0 cd/m^2], and pink [CIE: .409, .393; 43.6 cd/m^2]). Inside each circle, there was a light gray line segment (CIE: .256, .440; 30.8 cd/m^2). In the distractor circles, the line segments were tilted 22.5° to either side of the horizontal or vertical plane. The target circle always contained either a horizontal or vertical line segment. The search display was presented until a response was made or until 2,000 ms had elapsed. The intertrial interval was 1,500 ms.

Design and procedure. Each observer was seated 70 cm from a computer screen with their head positioned on a chin rest. Participants were instructed to search for either an orange or a blue circle among distractor circles and to determine the orientation of a line segment inside of it. On every trial, the color of the target was equally likely to be either orange or blue, while its position on the imaginary circle and the line orientation inside of it were chosen randomly. Participants were asked to respond quickly and accurately by pressing the *z* key when the line segment inside the target circle was oriented vertically and the *m* key when it was oriented horizontally. Participants were informed that the word cue preceding the search display indicated the target color with 80% validity. The pop-out and heterogeneous conditions were presented in separate blocks, while the target color and the presentation of valid (80% of trials) or invalid (20% of trials) color cue were mixed randomly within blocks. Half of the participants started with the pop-out condition (10 blocks of 40 trials), and the other half started with the heterogeneous condition (10 blocks of 40 trials). Each search condition was preceded by two respective practice blocks (40 trials each). In practice blocks, participants received feedback about the correctness of their response after each trial (the word *correct* or *incorrect* in the middle of the screen). After each block, participants received feedback about their average reaction time (RT) and accuracy.

Results and Discussion

Error rates. Overall, participants made very few errors (3%). The analysis on error rates showed no significant effects or interaction.

Reaction times. Trials in which participants responded faster than 150 ms or slower than 1,500 ms were excluded from further analysis. This led to a loss of 1.8% of the trials.

A within-subject analysis of variance (ANOVA) with search condition (pop-out vs. heterogeneous) and cue validity (valid vs. invalid) revealed a main effect of search condition, $F(1, 19) = 129.33$, $p < .001$, indicating that, as expected, it took longer to find the target in the heterogeneous condition (787 ms) than in the pop-out condition (610 ms). The cue validity was also significant, $F(1, 19) = 33.76$, $p < .001$, indicating that participants were faster in finding the target when the word cue indicated the upcoming target correctly. The Search Condition × Cue Validity interaction was significant, $F(1, 19) = 34.02$, $p < .001$, indicating that the cueing effect was larger in the heterogeneous condition (142 ms) than in the pop-out condition (14 ms). Importantly, planned comparisons revealed that a significant cueing effect was present in both conditions—heterogeneous condition: $t(1, 19) = 5.90$, $p < .001$; pop-out condition: $t(1, 19) = 3.04$, $p < .01$. These cueing effects, however, do not yet demonstrate goal-driven selection of the cued color, because the analysis did not correct for the expected effects of selection history. Instead, these effects could have been caused by the automatic benefits of responding to a target color that is the same as the target color in the preceding trial. To examine this possibility, we performed an intertrial analysis.

Intertrial effects. There are two ways to examine the intertrial effects in this task. On the one hand, trials can be grouped based on whether or not the color cued in a trial is the same as the color of the most recently presented target. This approach allows us to examine whether having an immediate experience with selecting a

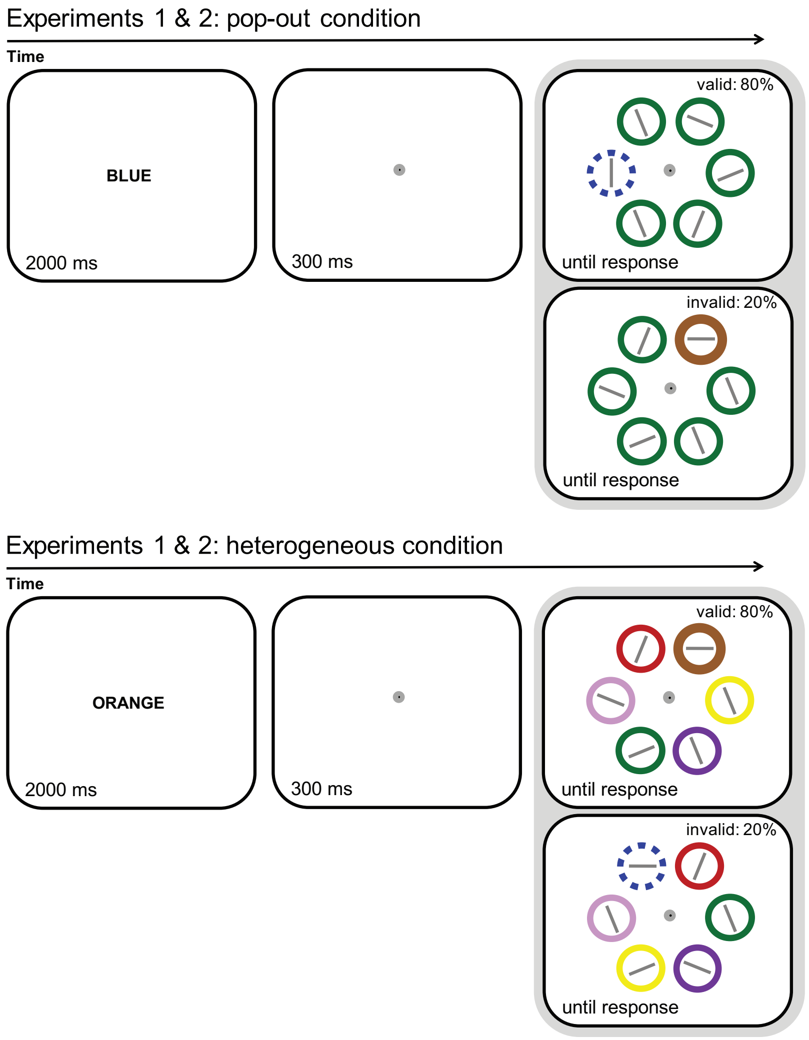

Figure 1. Time course of a typical trial in Experiments 1 and 2. Participants had to search for either an orange (thick line) or a blue (dashed line) circle and determine the orientation of the line inside it. Before the search display, they were provided with a word cue, which indicated the likely color of the target with 80% validity. Top: an example of a trial in the pop-out condition. Bottom: an example of a trial in the heterogeneous condition. In Experiment 1, pop-out and heterogeneous conditions were blocked, while in Experiment 2 they were mixed. See the online article for the color version of this figure.

specific color facilitates the voluntary selection of the same color on the next trial. In other words, selecting the color *blue* on one trial should facilitate the usage of the cue word *BLUE* in guiding attention on the next trial. This is similar to the logic that was previously used to parse out the intertrial and goal-driven influences in control of visual attention (Belopolsky et al., 2010; Folk & Remington, 2008). On the other hand, trials could be grouped based on whether the color of the current target matches the color of the most recent target, regardless of the cued color. This approach enables a focus on the stimulus-driven consequences of repeating a target color. Throughout this paper, we report the results of both analytic approaches and discuss their distinct strengths and weaknesses.

Previous target–current cue analysis. The results of this intertrial analysis are presented in Figure 2. A within-subject ANOVA with search condition (pop-out vs. heterogeneous), cue matching the previous target (match vs. mismatch), and cue validity (valid vs. invalid) revealed that the cueing effect was much larger on the trials on which the word cue matched the previous target feature, Cue Match × Cue Validity interaction, $F(1, 19) = 49.33$, $p < .001$. This effect was much larger for the heterogeneous trials than for the pop-out trials, three-way interaction, $F(1, 19) = 25.99$, $p < .001$. There was no main effect of cue match or Cue Match × Search Condition interaction (both *F*s < 1). Planned comparisons showed that the cueing effect was significant in all conditions, except when the cue did not match the previous target feature on the pop-out trials. For the heterogeneous condition, the cueing effect was 215 ms when the cue matched the previous target feature, $t(19) = 8.94$, $p < .001$, and 68 ms when it mismatched, $t(19) = 2.33$, $p < .05$. For the pop-out condition, the

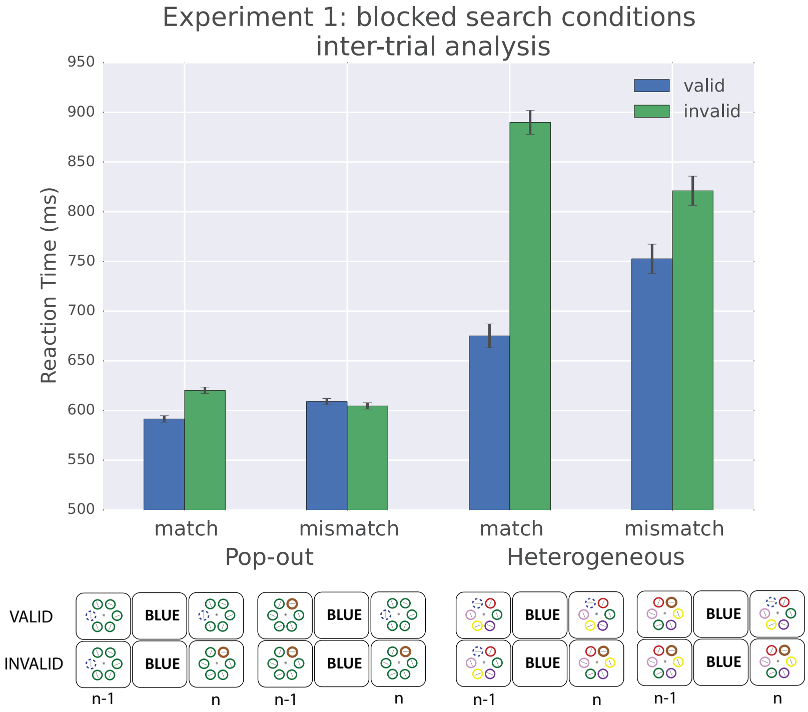

Figure 2. Mean reaction times in the pop-out and heterogeneous conditions as a function of cue validity and whether the word cue matched the color of the target on the previous trial in Experiment 1. The error bars represent standard error of the mean for within-subject designs normalized for the cue validity factor (Loftus & Masson, 1994). The inset illustrates the conditions plotted on the graph; the search target was either orange (thick line) or blue (dashed line). See the online article for the color version of this figure.

cueing effect was 29 ms when the cue matched the previous target feature, $t(19) = 4.42$, $p < .001$, and −4 ms when it mismatched, $t(19) = 0.67$, $p = .5$.

The intertrial analysis suggests that intertrial priming has a profound effect on biasing feature selection in both heterogeneous and pop-out conditions. The apparent cueing effect diminished from 215 to 68 ms in the heterogeneous condition and from 29 to −4 ms in the pop-out condition. Thus, this analysis suggests that only the heterogeneous condition produced reliable evidence of goal-driven selection in Experiment 1.

One possible concern with this analysis is that the magnitude of the cueing effects covaried with overall response speed. For example, Zehetleitner et al. (2011) found larger cueing effects for targets of relatively low salience. They argued that since the evidence accumulation rate is higher for salient targets, then the effect of top-down dimension cueing on further rate increase is limited (e.g., a ceiling effect). To partial out the large differences in response speed between the two search conditions, we performed the intertrial analysis on normalized data. The data were normalized per search condition relative to the respective mean and standard deviation (*z*-score). All main effects and interactions were preserved. The cueing effect was much larger on the trials on which the word cue matched the previous target feature, Cue Match × Cue Validity interaction, $F(1, 19) = 48.46$, $p < .001$, and this effect was much larger for the heterogeneous trials than for the pop-out trials, three-way interaction, $F(1, 19) = 17.76$, $p < .001$. There was no main effect of cue match or Cue Match × Search Condition interaction (both Fs < 1). Note that the normalization procedure does not change the planned comparisons for each condition. This analysis suggests that the overall response speed did not determine the pattern of results.

To reiterate, the preceding analysis grouped trials based on whether the current cue word matched or mismatched the color of the most recent target. One concern for this analysis is that repetition priming effects were imbalanced in the valid and invalid conditions. For example, in the mismatch condition (see the inset in Figure 2), the target color repeats for the invalid cues but not for the valid cues. Therefore, target repetition priming would have enhanced performance in the invalid condition (but not the valid condition), yielding a smaller validity effect. Thus, we next present an analysis that grouped trials based on whether the target color repeated or not.

Previous target–current target analysis. Here, the data were analyzed by grouping trials based on whether the color of the prior target matched the color of the current target (regardless of the currently cued color). This analysis can assess whether repetitions of the target color interact with the cue validity (e.g., Leonard & Egeth, 2008; Weidner & Müller, 2013). A within-subject ANOVA with search condition (pop-out vs. heterogeneous), target repetition (same target vs. different target), and cue validity (valid vs. invalid) revealed a significant main effect of target repetition, $F(1, 19) = 49.33$, $p < .001$, as well as a significant Search Condition × Target Repetition interaction, $F(1, 19) = 25.99$, $p < .001$, and Search Condition × Cue Validity interaction, $F(1, 19) = 32.35$,

$p < .001$. Importantly, there was no interaction between target repetition and cue validity and no three-way interaction between search condition, target repetition, and cue validity (all Fs < 1). This analysis suggests that both target repetition priming and goal-driven control have independent effects on visual selection. One caveat for this conclusion, however, is that the previous target–current target analysis suffers from a confound between cue validity and the match between current cue and past target colors. For example, in the different-target condition, the currently cued color differs from the color of the most recent target in the valid trials but not the invalid trials. Selection of the cued color may be stronger in the invalid condition, such that more time is needed to find targets in an uncued color. Such an effect would slow RT in the invalid condition, thereby leading to an overestimate of cueing effects in the different-target condition.

To summarize, both trial-by-trial analyses indicate that selection history has a strong influence on performance in this task, although the precise consequences for cueing effects depend upon whether history effects are defined based on the current target or the currently cued color. These differences notwithstanding, both analytic approaches support two clear conclusions. First, cueing effects are larger in the heterogeneous condition than in the pop-out condition, dovetailing with past studies showing that visual selection effects are amplified in the displays that contain strong distractor interference (Awh et al., 2003, 2005; Dosher & Lu, 2000; Kastner et al., 1998; Shiu & Pashler, 1994). Second, this study provides clear evidence of goal-driven selection of color that cannot be explained by selection history.

Experiment 2

Depending on the analytic approach, Experiment 1 showed that cueing effects were either absent or much smaller in the pop-out condition than in the heterogeneous condition. The goal of Experiment 2 was to examine whether this was due to an experimental context in which target localization could be efficiently guided without color selection. Although previous studies showed that participants actively process color cues like the ones in the present study (Müller & Krummenacher, 2006; Theeuwes et al., 2006), this does not establish that they actively use these cues to guide their attention. To examine this issue, we intermixed the pop-out and heterogeneous trials within each block. Because observers did not know which type of target array would be presented, we reasoned that they would be more likely to engage in goal-driven selection, even during pop-out trials.

Method

Participants. Twenty-eight naïve participants (eight females, mean age of 23, age range of 19–30 years) from VU University Amsterdam with normal or corrected-to-normal vision participated in the experiment. One participant's data were discarded from analysis because of an extremely high error rate (23%).

Stimuli, design, and procedure. The experiment was exactly the same as Experiment 1, except that the pop-out and heterogeneous conditions were now randomly mixed within blocks. That is, participants were equally likely to get a pop-out or a heterogeneous trial. Participants completed 20 blocks (40 trials each) of experimental trials preceded by two blocks of practice (also 40 trials each).

Results and Discussion

Error rates. Overall, participants made very few errors (4%). The analysis on error rates showed no significant effects or interaction. Only the cue validity approached significance, $F(1, 26) = 3.94$, $p = .06$, with slightly fewer errors being made when the cue was valid (3.8% vs. 4.7% for the valid and invalid conditions, respectively).

Reaction times. Trials in which participants responded faster than 150 ms or slower than 1,500 ms were excluded from further analysis. This led to a loss of 1.6% of the trials.

A within-subject ANOVA with search condition (pop-out vs. heterogeneous) and cue validity (valid vs. invalid) revealed a main effect of search condition, $F(1, 26) = 341.81$, $p < .001$, indicating that, as expected, it took much longer to find the target in the heterogeneous condition (763 ms) than in the pop-out condition (604 ms). The cue validity was also significant, $F(1, 26) = 97.0$, $p < .001$, indicating that participants were faster in finding the target when the word cue indicated the upcoming target correctly. The Search Condition × Cue Validity interaction was also significant, $F(1, 26) = 75.01$, $p < .001$, indicating that the cueing effect was larger in the heterogeneous condition (142 ms) than in the pop-out condition (31 ms). Importantly, planned comparisons revealed that a significant cueing effect was present in both the heterogeneous condition, $t(1, 26) = 9.79$, $p < .001$, and the pop-out condition, $t(1, 26) = 6.08$, $p < .01$. Just as in Experiment 1, however, these cueing effects cannot be clearly interpreted until the effects of selection history are examined. Thus, we again performed analysis conditional on the trial-by-trial match between the prior target and either the current cue or the current target.

Intertrial effects. The intertrial effects were analyzed using the two analytical approaches described above.

Previous target–current cue analysis. The results are presented in Figure 3. A within-subject ANOVA with search condition (pop-out vs. heterogeneous), cue matching the previous target (match vs. mismatch), and cue validity (valid vs. invalid) revealed that the cueing effect was much larger on the trials on which the word cue matched the previous target feature, Cue Match × Cue Validity interaction, $F(1, 26) = 96.38$, $p < .001$, and this effect was larger for the heterogeneous trials than for the pop-out trials, three-way interaction, $F(1, 26) = 53.52$, $p < .001$. Unlike Experiment 1, there was a main effect of cue match, $F(1, 26) = 5.37$, $p < .05$, indicating that RTs were faster when the word cue matched (648 ms) the target feature on the previous trial relative to when it mismatched it (667 ms). The Cue Match × Search Condition interaction was not significant ($F < 1$). Planned comparisons showed that the cueing effect was significant in all conditions. For the heterogeneous condition, the cueing effect was 217 ms when the cue matched the previous target feature, $t(26) = 14.07$, $p < .001$, and 63 ms when it mismatched, $t(26) = 3.63$, $p < .005$. For the pop-out condition, the cueing effect was 47 ms when the cue matched the previous target feature, $t(26) = 7.36$, $p < .001$, and 13 ms when it mismatched, $t(26) = 2.25$, $p < .05$. Thus, although there were strong intertrial priming effects, Experiment 2 also provided reliable evidence of goal-driven selection in both the heterogeneous and pop-out conditions. That is, goal-driven selection was clearly present when we controlled for target cue priming. These findings suggest that a higher probability of distractor interference elicited more robust goal-driven selection effects with

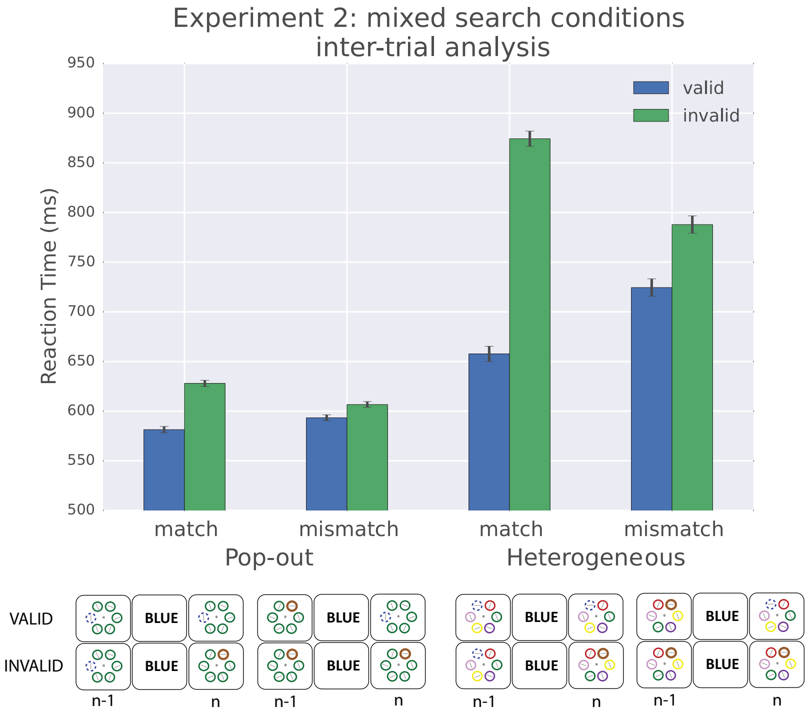

Figure 3. Mean reaction times in the pop-out and heterogeneous conditions as a function of cue validity and whether the word cue matched the color of the target on the previous trial in Experiment 2. The error bars represent standard error of the mean for within-subject designs normalized for the cue validity factor (Loftus & Masson, 1994). The inset illustrates the conditions plotted on the graph; the search target was either orange (thick line) or blue (dashed line). See the online article for the color version of this figure.

the pop-out displays—a result that falls in line with past work examining the impact of distractor probability on visual selection (Awh et al., 2003, 2005).

Previous target–current target analysis. A within-subject ANOVA with search condition (pop-out vs. heterogeneous), target repetition (same target vs. different target), and cue validity (valid vs. invalid) revealed a significant main effect of target repetition, $F(1, 26) = 96.38$, $p < .001$, as well as a significant Search Condition × Target Repetition interaction, $F(1, 26) = 53.52$, $p < .001$, and Search Condition × Cue Validity interaction, $F(1, 26) = 75.87$, $p < .001$. Importantly, there was a significant interaction between target repetition and cue validity, $F(1, 26) = 5.37$, $p < .05$. The three-way interaction between search condition, target repetition, and cue validity was not significant ($F < 1$). This analysis suggests that the influences of target repetition priming and goal-driven control on visual selection are not independent. Specifically, for both search conditions, the cueing effects were larger when the target did not repeat (25 vs. 35 ms and 130 vs. 150 ms, respectively, for the pop-out and heterogeneous search conditions). This seems to be primarily driven by the trials on which the target feature did not repeat and the word cue was invalid. Note that in this case, the word cue matched the target on the previous trial (see the inset of Figure 3). Thus, when participants were cued to attend to the same color as the target that had just been processed in the prior trial, strong selection of the cued color may have extended the time required to find a target in the uncued color. Qualitatively similar effects consistent with this account were observed in both the pop-out and heterogeneous search conditions.

To summarize, both analytic approaches provide clear evidence for goal-driven selection of colors that was stronger in the heterogeneous condition than in the pop-out condition. Moreover, in the pop-out condition, these selection effects were enhanced relative to those observed in Experiment 1, suggesting that a higher probability of distractor interference potentiated this form of nonspatial selection.

Experiment 3

Experiment 2 demonstrated that goal-driven selection effects can be reliably observed, even with pop-out targets, when there is a strong need to resolve interference between targets and distractors. The stage of processing affected by goal-driven selection, however, is somewhat ambiguous. Faster RTs in the valid condition could reflect either changes in the initial perceptual encoding of the stimulus or changes in the efficiency of postperceptual response or decision processes. To further examine whether goal-driven selection of colors affected the initial perception of the target, Experiment 3 employed brief stimulus displays and backward masks. A' was the primary dependent variable in this unspeeded task, and discrimination difficulty was staircased within subjects. As in Experiment 2, the pop-out and heterogeneous trials were intermixed.

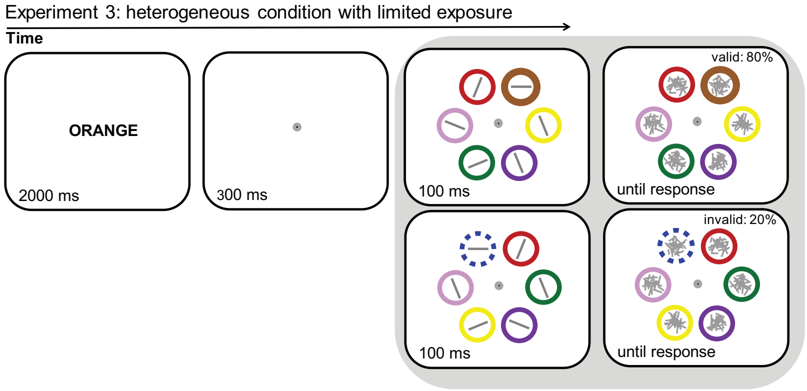

Figure 4. Time course of a typical heterogeneous trial in Experiment 3. Participants had to search for either an orange (thick line) or a blue (dashed line) circle and determine the orientation of the line inside it. The search displays were presented for 100 ms and quickly masked. The pop-out trials looked exactly the same except that the distractor circles were all green. The staircase was used to keep performance around 75%. See the online article for the color version of this figure.

Method

Participants. Twenty-six participants (seven females, mean age of 23, age range of 19–30 years) from VU University Amsterdam with normal or corrected-to-normal vision participated in the experiment. Two participants' data were discarded from analysis because in more than 20% of the trials they did not produce any response. Due to a network malfunction, the experiment ended early for two participants. They had only a slightly fewer number of trials (553 and 580 out of 600).

Stimuli, design, and procedure. The experiment was very similar to Experiment 1, except that it was modified for measuring A'. The search display was presented for 100 ms and backward masked (see Figure 4). The mask consisted of 20 randomly generated gray line segments randomly positioned within each circle. The mask display was presented for 1,500 ms. The intertrial interval was 500 ms. Participants completed 15 blocks of 40 trials each preceded by two practice blocks (also 40 trials each). As in Experiment 2, participants were equally likely to receive a pop-out or a heterogeneous trial. The orientation of the line segment within the target circle was also equally likely to be either horizontal or vertical. All conditions were mixed randomly within each block. Half of the participants responded by pressing the *z* key when the line segment inside the target circle was oriented vertically and the *m* key when it was oriented horizontally. The response mapping was reversed for the other half of the participants. It was stressed that participants should be as accurate as possible. The difficulty of the task was adjusted online by using a procedure similar to that of Theeuwes and van der Burg (2007). Specifically, the length of the target line was adjusted to ensure that the performance was kept around 75% correct. Every 10 trials, we calculated the accuracy and increased the length of the line by 0.05° if the accuracy dropped below 75% and decreased the length of the line by 0.05° if the accuracy exceeded 75%.

Results and Discussion

Trials on which participants did not make any response were not included in the analysis. This resulted in rejection of 0.9% of all trials. The data were analyzed using A' as a dependent measure. A' is a nonparametric analogue of the d' statistic (Stanislaw & Todorov, 1999). A' ranges from .5, which indicates that a signal cannot be distinguished from noise, to 1, which corresponds to perfect performance. We used A' and not d' because in the intertrial analysis some participants did not make any false alarms (FAs) in some conditions.[1]

A within-subject ANOVA with search condition (pop-out vs. heterogeneous) and cue validity (valid vs. invalid) revealed a main effect of search condition, $F(1, 23) = 92.56$, $p < .001$, indicating that, as expected, participants performed worse in the heterogeneous condition (0.71) than in the pop-out condition (0.80). The cue validity was also significant, $F(1, 23) = 45.62$, $p < .001$, indicating that participants performed better in reporting the target when the word cue indicated the upcoming target correctly. The Search Condition × Cue Validity interaction was also significant, $F(1, 23) = 9.67$, $p < .01$, indicating that the cueing effect was significantly larger in the heterogeneous condition (0.17) than in the pop-out condition (0.09). Importantly, planned comparisons revealed that the cueing effect was significant in both the heterogeneous, $t(1, 23) = 7.45$, $p < .001$, and pop-out conditions, $t(1, 23) = 3.63$, $p < .005$. To test whether these cueing effects included a goal-driven component, we examined the intertrial effects.

Intertrial effects. The intertrial effects were analyzed using the two analytical approaches described above.

Previous target–current cue analysis. The results of this analysis are presented in Table 1 and Figure 5. They show that the cueing effect was much larger on the trials on which the word cue matched the previous target feature, Cue Match × Cue Validity interaction, $F(1, 23) = 7.27$, $p < .05$, and that this effect was larger for the heterogeneous trials than for the pop-out trials, three-way interaction, $F(1, 23) = 7.09$, $p < .05$. The Cue Match × Search

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[1] We also reanalyzed the data using accuracy as the dependent measure, since in the forced-choice tasks it is typically considered to be a measure of sensitivity unaffected by response bias (Stanislaw & Todorov, 1999). The results were statistically identical.

Table 1
Mean Percentage Hits, Mean Percentage False Alarms (FAs), and Mean A′ as a Function of Search Condition, Match Between the Word Cue, and the Previous Target Feature and Cue Validity in Experiment 3

	Pop-out trials				Heterogeneous trials			
	Cue match to previous target		Cue mismatch to previous target		Cue match to previous target		Cue mismatch to previous target	
	Valid	Invalid	Valid	Invalid	Valid	Invalid	Valid	Invalid
Hits (%)	75.4 (16.8)	64.5 (19.0)	72.3 (14.8)	66.7 (17.0)	68.3 (13.9)	47.2 (21.3)	66.9 (13.0)	61.4 (17.2)
FAs (%)	18.0 (9.3)	28.0 (15.9)	20.5 (8.7)	27.1 (16.6)	23.9 (9.9)	42.7 (18.1)	26.6 (8.0)	34.8 (20.1)
A′	.85 (.13)	.75 (.13)	.83 (.10)	.76 (.16)	.80 (.09)	.54 (.16)	.78 (.08)	.69 (.18)

Note. Standard deviations are shown in parentheses.

Condition interaction was also significant, $F(1, 23) = 6.62$, $p < .05$, suggesting that the cue matching the previous target feature resulted in better performance on the pop-out trials but not on the heterogeneous trials. Planned comparisons showed that the cueing effect was significant in all conditions. For the heterogeneous condition, the cueing effect was 0.26 when the cue matched the previous target feature, $t(23) = 8.77$, $p < .001$, and 0.10 when it mismatched, $t(23) = 2.46$, $p < .05$. For the pop-out condition, the cueing effect was 0.10 when the cue matched the previous target feature, $t(23) = 3.70$, $p < .005$, and 0.07 when it mismatched, $t(23) = 2.44$, $p < .05$.

Previous target–current target analysis. A within-subject ANOVA with search condition (pop-out vs. heterogeneous), target repetition (same target vs. different target), and cue validity (valid vs. invalid) revealed a significant main effect of target repetition, $F(1, 23) = 7.27$, $p < .05$, as well as a significant Search Condition × Target Repetition interaction, $F(1, 23) = 7.09$, $p < .05$, and Search Condition × Cue Validity interaction, $F(1, 23) = 12.82$, $p < .005$. There was a marginally significant interaction between target repetition and cue validity, $F(1, 23) = 3.17$, $p = .09$, and a significant three-way interaction between search condition, target repetition, and cue validity, $F(1, 23) = 6.62$, $p < .05$. This analysis suggests that the influences of target repetition priming and goal-driven control on visual selection are not independent. Specifically, for the heterogeneous search condition, the cueing effects were

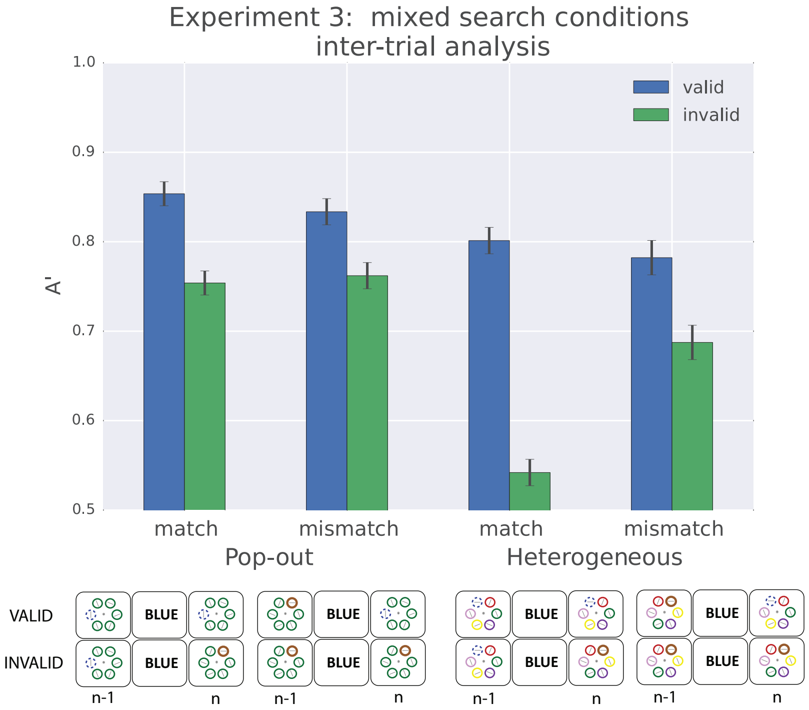

Figure 5. Mean *A*′ in the pop-out and heterogeneous conditions as a function of cue validity and whether the word cue matched the color of the target on the previous trial in Experiment 3. The error bars represent standard error of the mean for within-subject designs normalized for the cue validity factor (Loftus & Masson, 1994). The inset illustrates the conditions plotted on the graph; the search target was either orange (thick line) or blue (dashed line). See the online article for the color version of this figure.

larger when the target did not repeat (0.11 vs. 0.24 for same and different targets, respectively). As in Experiment 2, this seems to be primarily driven by performance in the invalid trials when the cued color matched the color of the prior target. Our hypothesis is that selection of the cued color was potentiated by the match with the recently processed target color, yielding a greater cost when the current target did not match the selected color. Unlike Experiment 2, this was not the case for the pop-out search condition (0.1 vs. 0.07 for same- and different-target conditions, respectively).

To summarize, Experiment 3 replicated and extended the conclusions of Experiment 2. We observed goal-driven selection of colors in both the pop-out and heterogeneous conditions. Because this was an encoding-limited task and we employed an A' measure of performance, these data suggest that goal-driven selection enhanced the initial perception of targets in the cued color.

General Discussion

The present results demonstrate that the context in which visual search is performed has a clear influence on whether evidence of goal-driven control over feature-based visual selection will be observed. When pop-out and heterogeneous conditions were blocked in Experiment 1, volitional control over selection of target features was clear in the heterogeneous condition but either absent or much smaller in the pop-out condition. The findings in the pop-out condition are consistent with the previous findings in the literature that argue against the possibility of goal-driven attention to features (e.g., Theeuwes, 2013). However, when in Experiments 2 and 3 the two search conditions were intermixed within the same blocks, robust evidence for volitional control was observed in the pop-out condition. Thus, a task context where there is a high probability of distractor interference appears to potentiate the goal-driven selection of nonspatial features. Finally, Experiment 3 replicated and extended this empirical pattern with a task that employed data-limited displays and an analysis of perceptual sensitivity, showing that attention affected the initial perceptual encoding of the stimulus rather than the efficiency of postperceptual response or decision processes.

As noted above, many earlier demonstrations of voluntary feature-based selection relied on block designs and thus confounded voluntary orienting with automatic effects of recent selection history (e.g., Folk et al., 1992; Wolfe et al., 2003). The present results indeed show that intertrial priming of previous target features plays an important role in feature-based selection (Kristjánsson, Wang, & Nakayama, 2002), though the nature of this effect depended on how selection history was defined. When we focused on the correspondence between the color of the current cue and the color of the most recent target, we found that cueing effects were approximately 4 times larger when those colors matched than when they did not. This analysis, however, was affected by differential effects of target repetitions in the valid and invalid conditions of the study. When we focused on the correspondence between the color of the previous target and the color of the current target (regardless of what color was cued), we observed larger cueing effects when those colors did not match in two of the three studies (Experiments 2 and 3). This finding echoes the results of a study by Weidner and Müller (2013), who used displays similar to those in our heterogeneous condition. The previous target–current target analysis also had a limitation, however, because cue validity was confounded with whether the voluntarily selected color (i.e., cued color) matched the most recent target color.

Nevertheless, although both analytic approaches have their limitations, three primary conclusions were clearly supported by both approaches. First, cueing effects were much larger in the heterogeneous condition where there was strong distractor interference. This is consistent with many studies that have shown enhanced visual selection with increased competition from distractors (Awh et al., 2003, 2005; Dosher & Lu, 2000; Kastner et al., 1998; Shiu & Pashler, 1994). Second, goal-driven selection effects were clear even when we accounted for selection history effects, in line with models that argue for volitional control over feature-based attention (e.g., Müller et al., 2010). And, finally, the strength of goal-driven orienting effects was augmented in an experimental context where there was a high probability of distractor interference. This context effect dovetails with past studies that have shown enhanced spatial selection when the probability of interference is high (Awh et al., 2003, 2005), and it is consistent with the claim that excluding interference is one of the primary functions of visual selective attention (Desimone & Duncan, 1995; Dosher & Lu, 2000; Kastner et al., 1998; Shiu & Pashler, 1994). Moreover, our findings offer an explanation for why there have been mixed findings in past studies of nonspatial selection that have employed displays that contain relatively low levels of distractor interference (e.g., Leonard & Egeth, 2008; Mortier et al., 2005; Müller & Krummenacher, 2006; Müller et al., 2003; Theeuwes et al., 2006; Theeuwes & Van der Burg, 2007; Zehetleitner et al., 2011). Thus, these findings may help establish the boundary conditions for procedures that will produce consistent evidence for goal-driven selection of nonspatial features.

To summarize, we provide clear evidence that volitional control over feature-based selection can enhance processing during the initial stages of stimulus encoding. We show that the context determines the degree to which the observers use cue information to bias visual selection. This insight regarding the boundary conditions for observing these goal-driven effects may help reconcile the conflicting findings that have been reported in past studies of feature-based selection.

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Special Issue of the *Canadian Journal of Experimental Psychology* on "Everyday Attention"

Guest Editors
Evan F. Risko, University of Waterloo
Alan Kingstone, University of British Columbia
Editor-in-Chief: Penny Pexman

Theme of the Special Issue

Research on "everyday cognition" focuses on cognition in the context of people's day-to-day lives. While most recognizable in the vibrant history of everyday memory research (e.g., Cohen & Conway, 2008; Woll, 2001), interest in examining attention using naturalistic stimuli, tasks, and/or settings is growing (e.g., visual search in baggage screening; Wolfe, Horowitz, & Kenner, 2005; mind wandering in lectures; Szpunar, Kahn, & Schacter, 2013; attentional orienting in social interactions; Laidlaw, Foulsham, Kuhn, & Kingstone, 2011; multi-tasking while driving; Medeiros-Ward, Cooper, & Strayer, 2014). This research both informs our understanding of attention (e.g., the role of salience in the guidance of attention; Tatler, Hayhoe, Land, & Ballard, 2011) and, in many cases, can help address important applied problems (e.g., talking on a cell phone while driving; Strayer & Drews, 2007). This special issue seeks to bring together cutting edge research papers investigating diverse aspects of everyday attention (i.e., investigations of attention using naturalistic stimuli, tasks, and/or settings) that contribute to the basic understanding of attention. With respect to the latter issue - the contribution to the field's understanding of attention - while experimental papers with applied consequences are encouraged, it is important that each submission identifies clearly how the research informs fundamental issues in attention. By bringing together contributions from diverse sectors of attention research we hope to highlight the field's active interest in understanding attention in the context of our day-to-day lives and the important implications of that research.

Call for Papers

Researchers with an interest in issues relevant to everyday attention are invited to submit a full paper to the CJEP Manuscript Central site, indicating in the covering letter that the manuscript should be considered for this special issue. Submitted papers should contain original, unpublished work and can be written in either English or French. Manuscripts should be submitted electronically in accordance with APA guidelines. All submitted papers will go through rigorous review as usual at CJEP, with consideration given to their originality, their theoretical contribution, their methodological soundness, the clarity of the presented results and conclusions, and the relevance of the submission for the special issue. Please send expressions of interest by February 15th, 2016 via email to the Guest Editors (efrisko@uwaterloo.ca, alan.kingstone@ubc.ca). The deadline for submission of papers is June 1st, 2016. Note that, unlike edited books, journal production deadlines make this a firm closing date.