Relative contributions of task-relevant and task-irrelevant dimensions in priming of pop-out

Audrey L. Michal Department of Psychology, Northwestern University, Evanston, IL, USA

Alejandro Lleras Beckman Institute Department of Psychology, University of Illinois, Urbana-Champaign, IL, USA

Diane M. Beck Beckman Institute Department of Psychology, University of Illinois, Urbana-Champaign, IL, USA

Intertrial effects such as *priming of pop-out* (PoP) often occur for task-irrelevant dimensions as well as task-relevant dimensions, though to a weaker extent. Here we test the hypothesis that increased priming for task-relevant dimensions is due to greater passive build-up of priming for the task-relevant dimension rather than to an active filtering of task-irrelevant dimensions; if this is the case, then we should observe a positive correlation between the magnitude of task-relevant and task-irrelevant priming. We tested this hypothesis using a pop-out search task in which the task-relevant dimension was orientation and the task-irrelevant dimension was color. We found a strong, positive association between task-relevant and task-irrelevant priming across a large group of participants ($N = 100$); additionally, we observed increased priming over consecutive repetitions for the task-relevant dimension, whereas task-irrelevant priming was constant across multiple repetitions. As further evidence against an active filtering account, task-irrelevant priming showed no systematic relationship with visual short-term memory capacity, which has been shown to correlate with filtering ability. Together, our results suggest that task-irrelevant dimensions are co-selected rather than filtered out during target search. Further, increased task-relevant priming may reflect an enhanced representation of the task-relevant dimension that is reinforced over consecutive repetitions.

Introduction

Searching for a unique item is typically a straightforward process; in general, when one thing is not like the others around it, it "pops" out and is easy to locate. However, searching for a pop-out stimulus is not completely driven by display parameters; search performance is also influenced by target repetitions (e.g., Maljkovic & Nakayama, 1994, 1996, 2000; for a review, see Kristjánsson & Campana, 2010). For instance, observers are faster to locate a red target among green distractors following a red target trial than following a green target trial (e.g., Maljkovic & Nakayama, 1994). This effect, known as *priming of pop-out (PoP)*, suggests that repetitive pop-out search is susceptible to bias from the previous trial, even when specific target values vary randomly from trial to trial.

One might think that this bias reflects a purely perceptual priming, in which the second target is speeded simply because it matches the previous target. Although a simple visual match may explain some of the priming, priming is also influenced by the subject's task; that is, the priming reflects in part the subject's intention to find the pop-out stimulus. In support of this idea, priming is generally greater for repetitions of task-relevant than task-irrelevant dimensions of pop-out items (e.g., Fecteau, 2007; Huang, Holcombe, & Pashler, 2004; Kristjánsson, 2006; Levinthal & Lleras, 2008). For instance, when participants searched for multidimensional targets (i.e., colored, oriented gabors of various spatial frequencies), repeating the target-defining dimension (i.e., the dimension on which the item was a singleton) consistently led to greater priming effects relative to repeating the task-irrelevant dimension (Kristjánsson, 2006). Additionally, in an experiment with two possible targets (e.g., a shape and a color singleton), one of which is designated the target at the

Citation: Michal, A. L., Lleras, A., & Beck, D. M. (2014). Relative contributions of task-relevant and task-irrelevant dimensions in priming of pop-out. *Journal of Vision*, *14*(12):14, 1–12, http://www.journalofvision.org/content/14/12/14, doi:10.1167/14.12.14.

doi: 10.1167/14.12.14 Received February 26, 2014; published October 13, 2014 ISSN 1534-7362 © 2014 ARVO

beginning of the trial, priming only occurred for repetitions of the current target (i.e., the specific singleton was defined as task-relevant on consecutive trials; Fecteau, 2007). Similarly, observers are slower to locate a singleton that shares features with items from an immediately preceding target-absent trial (i.e., *distractor preview effect*), but this effect only occurs for the task-defining dimension (e.g., repeating the color of colored shapes only affected search performance when color was task-relevant; Levinthal & Lleras, 2008). Taken together, these data indicate that intertrial effects are more sensitive to repetitions of task-relevant than task-irrelevant dimensions.

Although previous studies have established that task-relevant dimensions carry more weight than task-irrelevant dimensions in intertrial effects, it is still unclear *why* this bias occurs. Are participants actively filtering the task-irrelevant dimension, or is priming of the task-relevant dimension simply enhanced due to repeated selection of that dimension? To address this question, we took a two-pronged approach.

First, across a large number of participants, we asked whether priming on the task-relevant dimension was correlated with priming on the task-irrelevant dimension. If participants are actively filtering task-irrelevant dimensions, then we would predict one of two relationships *between* task-relevant and task-irrelevant priming: either a negative relationship (i.e., a tradeoff between the dimensions, such that the more observers concentrate on the task-relevant dimension, the less they are influenced by the task-irrelevant dimension); or, if filtering does not bear a tight relationship with enhancement, no relationship between task-relevant and task-irrelevant priming (i.e., filtering of the task-irrelevant dimension regardless of how well people attend to the task-relevant dimension). A positive relationship between task-relevant and task-irrelevant priming, however, would be incompatible with a filtering hypothesis and instead would suggest that the enhanced priming for task-relevant features is a passive result of selecting the target feature (i.e., without filtering the task-irrelevant feature). Such a view would be in line with object-based attention theories in which attending to a multidimensional target should lead to co-selection of all target dimensions regardless of task-relevance (e.g., Duncan, 1984; O'Craven, Downing, & Kanwisher, 1999); however, in this case the task-relevant feature would be further enhanced due to being previously selected.

Second, to further assess whether participants are engaging in filtering of the task-irrelevant dimension, we included an assessment of each individual's visual short-term memory (VSTM) capacity. Since individuals with higher VSTM capacity show greater ability to filter task-irrelevant items (e.g., Vogel, McCollough, & Machizawa, 2005), we reasoned that if participants are actively excluding the task-irrelevant dimension from their attentional set, then VSTM capacity should negatively correlate with the amount of task-irrelevant priming; in other words, individuals with the lowest VSTM capacity (i.e., poor filterers) should show more priming for the task-irrelevant dimension than individuals with high VSTM capacity.

We collected PoP data and individual VSTM capacity scores from a large population ($N = 100$) to compare task-relevant and task-irrelevant priming at the level of the individual. In order to promote the possibility of independent selection of each dimension, we designed our targets so that the task-relevant and task-irrelevant dimensions would have minimal overlap in their underlying neural substrates (e.g., Kristjánsson, 2006). In particular, we chose orientation and color because they are processed in largely separate areas of the visual system (e.g., Livingstone & Hubel, 1987). To maximize the potential for filtering of the task-irrelevant dimension, color was always task-irrelevant due to its higher salience than orientation (e.g., Theeuwes, 1991). Additionally, since we were interested in distinguishing between task-relevant and task-irrelevant priming effects, we included trials where a single target dimension repeated (i.e., only orientation or only color) in addition to trials where both dimensions and neither dimension repeated.

Based on previous work, we anticipated greater task-relevant (orientation) priming than task-irrelevant (color) priming overall; however, our main objective was to investigate relationships between task-relevant and task-irrelevant priming and between priming effects and VSTM capacity, as outlined above. A better understanding of why the task-irrelevant dimension produces less priming than the task-relevant dimension would help clarify what exactly is being primed in intertrial experiments.

Methods

Observers

One hundred eleven students at the University of Illinois Urbana-Champaign participated in the experiment for course credit. Data from 11 participants were discarded due to poor performance on the PoP task: that is, a mean accuracy score or response time (RT) more than 3 standard deviations below (for accuracy) or above (for RT) the average accuracy or RT across all participants. The 100 remaining participants (50 males) ranged in age between 18 and 24 (average age, 19.5), had normal or corrected-to-normal visual acuity, and gave informed consent (approved by the institu-

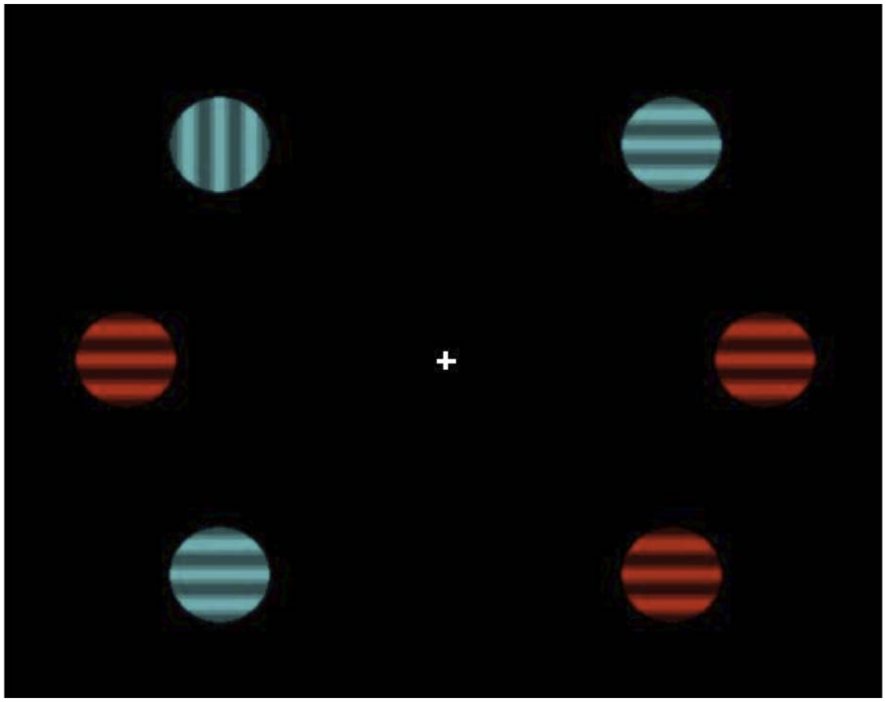

Figure 1. Example stimulus display for the PoP experiment. Targets were singletons in the orientation dimension only (e.g., vertical target among horizontal distractors).

tional review board of the University of Illinois, Urbana-Champaign).

Experimental tasks

Our goal for the current study was to measure priming of task-relevant and task-irrelevant dimensions independently of one another; thus, we designed a PoP task in which targets varied randomly on both orientation (task-relevant dimension) and color (task-irrelevant dimension). One each trial, participants viewed six circular gratings (radius = 1.14° of visual angle) arranged in a circle around a central fixation cross (radius = 0.32°; sample display in Figure 1), and they were instructed to report the visual field (left or right) of the grating that differed in orientation from the other five gratings as quickly and as accurately as possible. On each trial, the target grating appeared randomly in one of the six possible locations, and the target orientation could either be vertical (orientation = 0°) surrounded by all horizontal distractors (orientation = 90°), or vice versa. Additionally, the target could either be red or cyan among equal numbers of red and cyan distractors; thus, the target was only a singleton in the orientation dimension. Both the orientation and color of the target varied randomly and independently from trial to trial, creating four possible target repetition conditions: *orientation only*, *color only*, *both* orientation and color, or *neither* dimension repeated. Thus, although repetitions of target orientation and color were equally likely, orientation was the task-defining singleton dimension, and color was always task-irrelevant. Each run consisted of 49 trials (4 repetition conditions × 6 target locations × 2 trial repetitions = 48 repetition trials, plus one start trial), and there were eight runs, each starting with a unique target orientation, color, and location.

To measure each participant's VSTM capacity, after completing the PoP task, participants performed a change detection task modeled after Luck & Vogel (1997). On each trial, six different colored squares (possible colors included white, black, red, blue, green, yellow, and purple) were simultaneously presented on a gray background in random locations for 100 ms, removed for 900 ms, and presented again until response. On half of the trials, one of the squares changed its color, and participants were instructed to report whether a color change had occurred or not. Participants completed 100 trials in a single run.

Results

Priming of pop-out

Figure 2 shows average priming effects for repetitions of target orientation only, target color only, and both target orientation and target color. Only trials

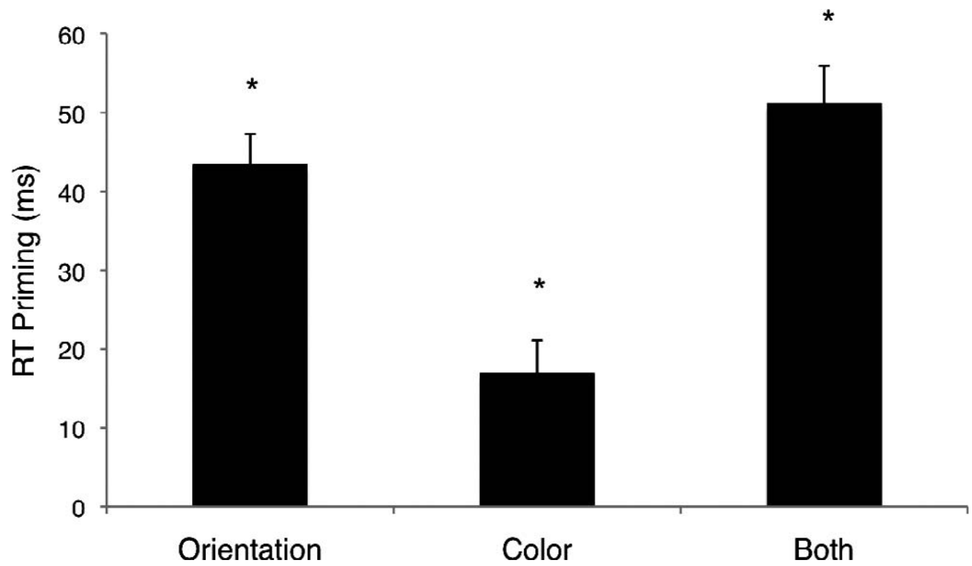

Figure 2. Average priming effects for orientation only, color only, and both orientation and color target repetitions. Priming was calculated by subtracting average RTs for each condition from average RTs for trials in which neither dimension repeated. Error bars are based on within-subject standard error (Cousineau, 2005).

with correct responses were included in the RT analyses. Additionally, trials with RTs 2 standard deviations above the mean for each participant were excluded, resulting in a total of 4.1% of correct trials that were discarded as outliers. Priming effects for individual participants were calculated by subtracting average RT for each repetition condition from average RT for trials in which neither dimension repeated; these data were submitted to a one-way, repeated-measures ANOVA with repetition condition (orientation, color, or both) as the factor of interest. There was a significant main effect of repetition condition, $F(2, 198) = 11.9$, $p < 0.0001$, and post hoc pairwise comparisons revealed that priming effects were significantly greater than zero for all conditions (orientation, $p < 0.0001$; color, $p < 0.02$; both, $p < 0.001$). Additionally, orientation priming was significantly greater than color priming ($p < 0.001$), and priming for both dimensions was significantly greater than color priming ($p < 0.001$). These results are consistent with previous PoP studies that found priming for both task-relevant and task-irrelevant dimensions, but greater priming for repetitions of the task-relevant dimension (for review, see Kristjánsson & Campana, 2010).

To test for interactions between repetition status of target dimensions and response (i.e., left or right hemifield), we also ran a three-way, repeated-measures ANOVA on average RTs with orientation status (repeated/switched), color status (repeated/switched), and response status (repeated/switched) as factors (Figure 3). This analysis revealed significant main effects of each factor [orientation: $F(1, 99) = 49.69$, $p < 0.0001$; color: $F(1, 99) = 5.36$, $p < 0.02$; response: $F(1, 99) = 16.92$, $p < 0.0001$]. Mean RTs were faster when the target orientation was repeated versus switched (*M* orientation repeated = 1134 ms, *M* orientation switched = 1172 ms) and when the target color was repeated versus switched (*M* color repeated = 1147 ms, *M* color switched = 1159 ms); however, mean RTs were slower when the response was repeated versus switched (*M* response repeated = 1168 ms, *M* response switched = 1138 ms). Importantly, there were no interactions between any factors (all *F*s < 1.4), confirming that priming occurred independently for target orientation, color, and left/right response.

Correlation between task-relevant and task-irrelevant priming

Having demonstrated distinct priming for orientation and color, we next compared these priming effects at the level of the individual. As Figure 4 shows, priming effects were wide-ranging, with orientation-only priming effects ranging from −124 to 293 ms and color-only priming effects ranging from −170 to 188 ms. Importantly, there was a significantly positive association between orientation and color priming ($R^2 = 0.33$, $p < 0.0001$), suggesting that participants did not experience a tradeoff between the two dimensions. Rather, this result indicates that the more participants were influenced by repetitions of orientation alone, the more they were influenced by repetitions of color alone. However, the slope of the correlation (0.58) suggests a greater influence of task-relevant priming; in other words, the strength of the orientation priming effect was a little more than twice that of the color priming effect for each individual. Thus, although priming

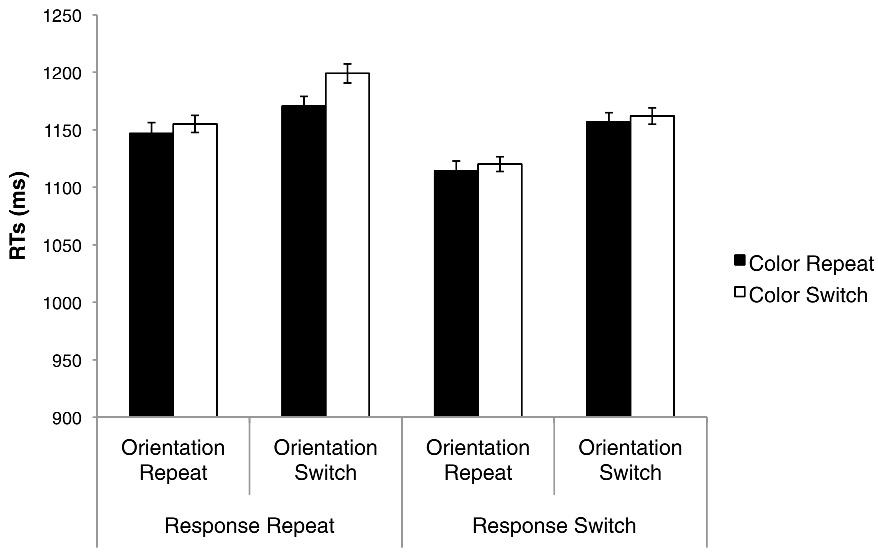

Figure 3. Mean RTs as a function of target orientation repetition status (repeated/switched), color repetition status (repeated/switched), and response repetition status (repeated/switched).

occurred for both task-relevant and task-irrelevant dimensions, task-relevant priming was modulated to a greater extent. More importantly, this positive relationship between task-relevant and task-irrelevant priming is incompatible with a model in which participants actively filter the task-irrelevant dimension. Instead it suggests that both dimensions are selected, but the task-relevant dimension receives some further benefit.

One possible explanation for the positive relationship between orientation and color priming is that slow RTs drove the relationship; that is, priming effects may have generally increased on trials in which participants took a longer time to process the target. To test this possibility, we compared priming effects for the fastest and slowest RTs for each participant (defined by the lower and upper third quantiles of RTs, respectively). If priming generally increases with slower responses, there should be greater priming effects for the upper quantile of RTs than the lower quantile. Although the variability in priming effects increased with RT, we observed similar average priming effects for all three repetition conditions (orientation, color, and both) across the fastest and slowest RTs [main effect of quantile: $F(1, 99) = 0.05$, $p = 0.3$; Figure 5]; thus, long RTs alone cannot account for the positive relationship between priming for orientation and color. Instead the data suggest a model by which participants show more or less propensity for priming, and this predisposition is true for both task-relevant and task-irrelevant dimensions.

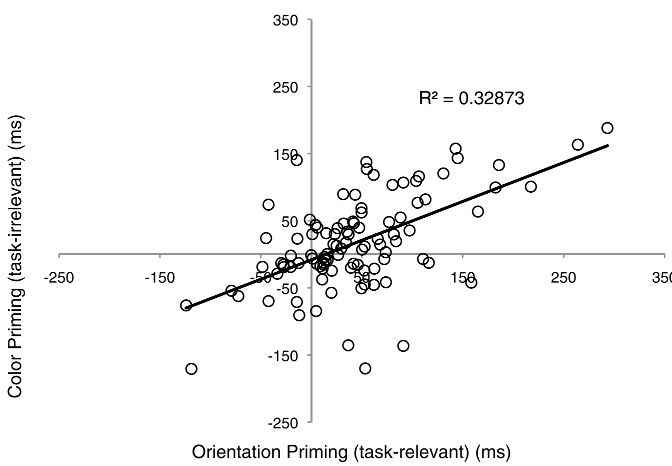

Figure 4. Correlation of priming for color (task-irrelevant) versus orientation (task-relevant). Priming effects are based on trials in which only a single dimension repeated (i.e., color only and orientation only).

Priming over consecutive repetitions

If greater priming for task-relevant than for task-irrelevant dimensions is not due to active filtering of the task-irrelevant dimension, why is priming greater for the task-relevant dimension? One possibility is that the task-relevant dimension simply benefits more from each target repetition. In other words, we might expect task-relevant priming to increase with each consecutive repetition, whereas task-irrelevant priming should be less sensitive to repeated repetitions. Thus, we measured the extent to which priming effects for orientation and color increased across one, two, or three or more repetitions. Since there were few consecutive trials in which only one of the dimensions repeated, we collapsed across trials in which one or both dimensions repeated. For example, a repeated orientation means

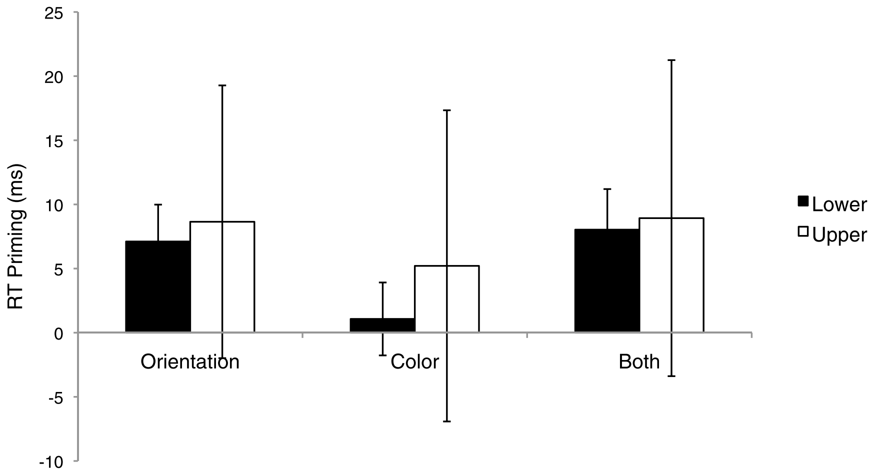

Figure 5. RT quantile analysis. Average priming for each repetition condition is similar for the fastest (lower third quantile) and the slowest (upper third quantile) RTs for each subject.

that orientation repeated while color may or may not have also repeated.

In line with our predictions, as the number of consecutive orientation repetitions increased from one to three or more, orientation priming increased [Figure 6; main effect of number of repetitions: $F(2, 198) = 4.1$, $p < 0.02$]; in contrast, priming for color repetitions was similar across consecutive trials [main effect of number of repetitions: $F(2, 198) = 0.12$, $p < 0.9$]. Post hoc comparisons also revealed a trend for greater orientation priming than for color priming after one repetition, $t(99) = 1.97$, $p = 0.05$, no difference between orientation and color priming after two repetitions, $t(99) = 0.44$, $p = 0.67$, and significantly greater priming for orientation than for color after three or more repetitions, $t(99) = 2.8$, $p < 0.01$. Importantly, the selective increase in task-relevant priming after three or more repeats could explain the overall increased priming for the task-relevant versus task-irrelevant

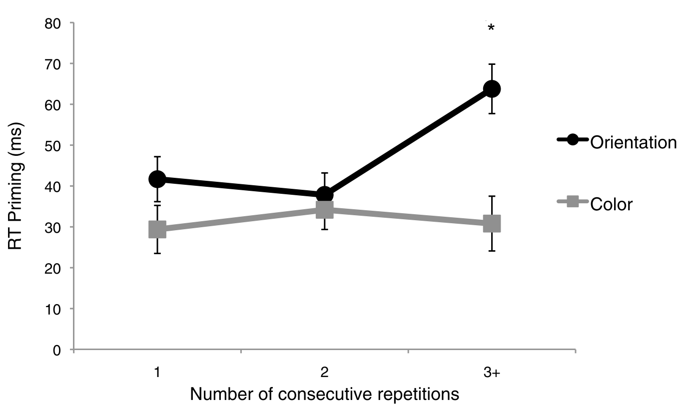

Figure 6. Consecutive priming effects for orientation and color, plotted by number of repetitions (one, two, or three or more). Priming effects are collapsed across repetitions of a single dimension and both dimensions.

dimension. Taken together, both the positive relationship between task-relevant and task-irrelevant priming and the increase in task-relevant priming over consecutive repetitions suggest that participants are not actively filtering the task-irrelevant dimension but instead that priming builds up over time only for the task-relevant dimension.

Priming and VSTM capacity

As further evidence of increased task-relevant priming being driven by task-relevant enhancement as opposed to task-irrelevant filtering, we correlated priming with individuals' VSTM capacity. As argued above, we reasoned that if reduced task-irrelevant priming was due to filtering of the task-irrelevant dimension, then general filtering ability might be negatively associated with task-irrelevant priming. If, however, as the above analyses suggest, reduced priming for the task-irrelevant dimension does not depend on filtering, then we should see no relationship between VSTM capacity and priming on either dimension. To measure general filtering ability, we calculated each individual's VSTM capacity (see Methods for task details) based on their throughput (K value) of a color change detection task using Pashler's (1988) formula: $K = N \times (H - F)/(1 - F)$, where N is the number of items (6), H is the hit rate, and F is the false alarm rate. We did not observe any significant correlations between VSTM capacity and priming for any condition (Figure 7; orientation, $R^2 = 0.003$, $p = 0.6$; color, $R^2 = 0.04$, $p = 0.7$; both, $R^2 = 0.01$, $p = 0.9$; composite [average of orientation, color, and both conditions], $R^2 = 0.07$, $p = 0.5$). Given the positive relationship between orientation and color priming, the lack of an association between color priming and

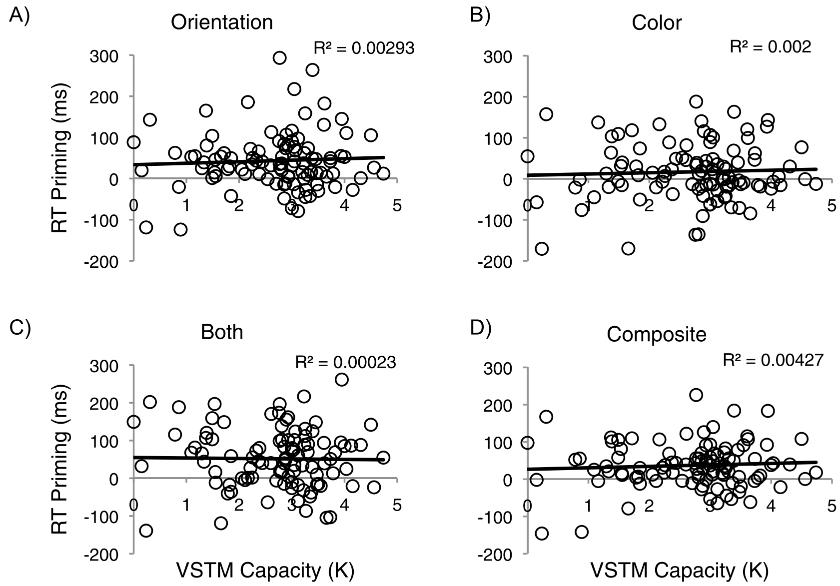

Figure 7. Correlations between priming and VSTM capacity for (A) orientation, (B) color, (C) both dimensions, and (D) composite priming.

VSTM capacity is perhaps not surprising; it again suggests that filtering of task-irrelevant information may not be the underlying cause of diminished task-irrelevant priming effects.

However, an alternative reason for the lack of correlation between priming and VSTM capacity is that the measures were not stable enough to correlate in a meaningful way. Thus, we first measured the reliability of the *K* value using the split-half method; specifically, for each participant, we randomized trials from the VSTM experiment and split the data into two halves, calculated a separate *K* value for each half, and correlated the two *K* values from the two halves. Across participants, the *K* values from the two halves were highly correlated ($R^2 = 0.77$, $p < 0.0001$); thus, the VSTM capacity measure was sufficiently reliable. We then attempted to measure the reliability of the orientation-only and color-only priming effects for each participant. However, given that priming effects are largely influenced by the context of local trials (i.e., heterogeneity of repetition types, consecutive repetitions), we did not have sufficient power to correlate subsets of trials within each repetition condition. Nonetheless, given the observed strong correlation between orientation and color priming, there must be some source of stability driving priming along one dimension that simultaneously drove priming along the other dimension. Moreover, given the high reliability of the *K* value, it is clear that the factors driving priming were unrelated to VSTM capacity, since the two measures did not correlate. Thus, we interpret the lack of correlation between VSTM capacity and priming as a true lack of relationship rather than a reflection of large within-subject variability in the two measures.

We next tested whether the relationship between orientation and color priming differed for low versus high VSTM participants. Although we observed a positive relationship between orientation and color priming overall, we wanted to test whether low VSTM capacity participants were more likely to show a positive orientation-color priming relationship than those with high VSTM capacity, which would provide some evidence for active filtering (at least among high VSTM capacity participants). Thus, we took a median split of VSTM capacity scores (median = 2.89) and ran Fisher's *z* test (Fisher, 1915) to compare the correlation coefficients for color versus orientation priming of low VSTM capacity participants ($R^2 = 0.34$) and high VSTM capacity participants ($R^2 = 0.34$). These correlations were not statistically different, Fisher's z ($r_{\text{low VSTM}} - r_{\text{high VSTM}}) = 0.02$, $p = 0.98$. As Figure 8 shows, both low and high VSTM capacity participants showed a similar positive relationship between orientation and color priming; thus, even high VSTM capacity participants showed little evidence of active filtering of the task-irrelevant dimension.

Discussion

Our aim for the current experiment was to explain why priming tends to be greater for the task-relevant than for the task-irrelevant dimension during pop-out search. Participants showed significant priming both for repetitions of orientation alone (task-relevant) and color alone (task-irrelevant), but priming was significantly larger for orientation than for color. Addition-

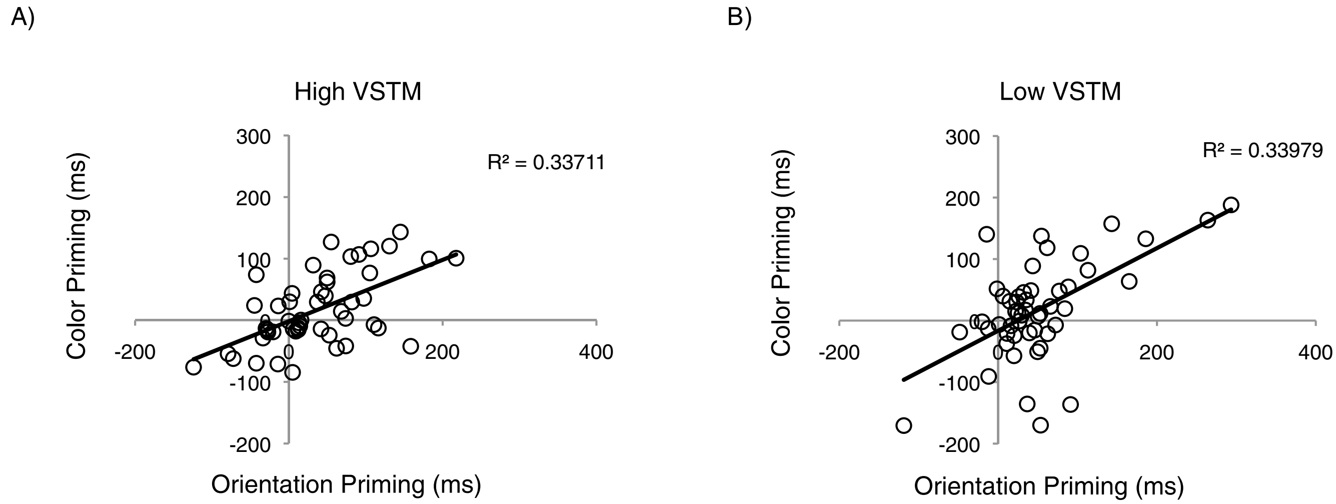

Figure 8. Correlations between orientation and color priming effects for high VSTM capacity (A) and low VSTM capacity participants (B). Participants were grouped into low and high capacity based on a median split analysis.

ally, we found no interactions between priming for orientation, color, or response, suggesting that these priming effects were present regardless of whether the other dimension or response repeated or switched. Nonetheless, there was a relationship between the size of an individual's orientation-only and color-only priming effects. Specifically, we observed a significantly positive association between orientation and color priming, suggesting that if a participant was particularly susceptible to a repetition on one dimension, he or she was also susceptible to a repetition on the other. However, orientation repetitions were approximately twice as influential as color repetitions in guiding selection.

Why was the task-relevant dimension so much more influential than the task-irrelevant dimension? We see two possibilities: (a) participants actively filtered the task-irrelevant dimension or (b) they maintained a stronger or more persistent representation of the task-relevant dimension. Our results support the latter; first, the relationship between task-relevant and task-irrelevant priming was positive, suggesting that observers did not rely on the task-relevant dimension at the expense of the task-irrelevant dimension. Second, we found evidence that the task-relevant dimension was represented more robustly than the task-irrelevant dimension; priming effects for consecutive repetitions increased with target orientation repetitions, but not with target color repetitions. Specifically, participants showed similar color priming effects after one, two, or three or more repetitions, whereas orientation priming increased further after three or more repetitions. Additionally, the increase in orientation priming relative to color priming was largest for three or more repetitions, suggesting that observers may show similar sensitivities to task-relevant and task-irrelevant dimensions after one or two repetitions, but a building sensitivity after three or more repetitions occurs only for the task-relevant dimension. Finally, VSTM capacity was not predictive of priming for either dimension, suggesting that general filtering ability may not play a strong role in guiding target search. Together, these results are inconsistent with the notion that the task-irrelevant dimension is actively filtered during PoP search; rather, it suggests that participants select the object as a whole and process both dimensions to some degree with the task-relevant dimension receiving more weight as the target-defining dimension.

It is worth noting that there are several inconsistencies between our findings and results from previous PoP studies; for instance, past work has shown interactions between priming for task-relevant and task-irrelevant dimensions (Huang et al., 2004) and between target priming and response priming (e.g., Huang et al., 2004; Yashar & Lamy, 2011). However, there are several differences in task parameters between these studies and the current study, particularly for the target dimensions tested and task demands. For instance, Huang et al. (2004) found that repetition status of a task-irrelevant dimension (color) interacted with repetition status of a task-relevant dimension (size); specifically, responses were speeded when either both dimensions repeated or both dimensions switched, but responses were slowed when only one dimension repeated and the other dimension switched. This pattern of results suggests that the task-relevant and task-irrelevant dimensions interacted to a greater extent in the Huang et al. (2004) study than in the current study, possibly because there is something atypical about size as the target-defining feature (e.g., object size is more naturally coded in relative rather than absolute units; Becker, 2008), or perhaps size and color are more likely to interact than orientation and color. Thus, our results may only generalize to tasks in which the task-relevant and task-irrelevant dimensions can be primed independently of one another. Additionally, our task differed from previous PoP studies by requiring participants to localize the target in space as a whole, whereas the tasks from Huang et al. (2004) and Yashar and Lamy (2011) required participants to judge specific target features (target orientation and direction of the target's chipped corner, respectively). Because we were primarily interested in dissociating task-relevant and task-irrelevant priming stemming from target-related processing, we specifically chose a response-defining feature (i.e., hemifield location) that would *not* involve analysis of target features and potentially interact with target-related priming (e.g., Kristjánsson, 2006). Thus, the fact that we did not observe any interactions between target priming and response priming is consistent with our goals for the study.

However, by using a task that did not require participants to judge target features, in theory our task could be performed without focused attention, which has been shown to be critical for observing priming effects stemming from early perceptual processing (e.g., Lleras, Kawahara, Wan, & Ariga, 2008), particularly for tasks with limited viewing time (e.g., Yashar & Lamy, 2010). Importantly, priming effects arising from tasks that do not require a fine-grained discrimination may be driven by response-related processing, not target-related processing (Yashar & Lamy, 2010). Although it may be possible to perform our task without focused attention, the fact that we found significant priming for both dimensions (neither of which was response-relevant) suggests that participants did in fact use focused attention in this case.

Since one of our goals was to correlate task-relevant and -irrelevant priming, we wanted to maximize the chance of obtaining priming for the task-irrelevant dimension. In addition to differences in overall salience between color and orientation (e.g., Theeuwes, 1991), past work has demonstrated differing priming effects for color versus orientation as the target-defining feature (e.g., Hillstrom, 2000; Kristjánsson, 2006; Lamy, Yashar, & Ruderman, 2013); for instance, priming tends to be larger when targets are defined by color than by orientation, and cumulative priming effects have been observed for color but not orientation as the target-defining feature (Hillstrom, 2000). Additionally, by comparing performance when the target/distractor orientations were repeated versus new (i.e., a different orientation than the target and distractor orientations from the previous trial) or switched versus new, Lamy et al. (2013) demonstrated that PoP effects for color-defined targets are driven by both target activation and distractor inhibition, but PoP effects for orientation-defined targets are only driven by distractor inhibition. Together, these results suggest that priming for orientation is less robust than for color. Therefore, in order to maximize our chances of obtaining task-irrelevant priming, we only tested PoP with color as the task-irrelevant dimension. However, based on the evidence for differing PoP effects for targets defined by orientation versus color, it is possible that our results may not replicate with color as the task-relevant dimension and orientation as the task-irrelevant dimension.

However, we have several reasons to believe that orientation priming could be strong enough to survive the reduction observed when it is made task-irrelevant. First, using a similar design as the current study, Kristjánsson (2006) did measure PoP with color as the task-relevant dimension and orientation as a completely task-irrelevant dimension (not the reported dimension as in Hillstrom, 2000) and found significant priming for both color and orientation, with larger priming effects for color than for orientation; thus, this aspect of the reversed results has already been shown. More importantly, we have reason to believe that the previous difficulty in obtaining orientation priming may be remedied by different task parameters and larger numbers of subjects. First, we have already shown that, in contrast to Hillstrom's (2000) results, cumulative priming effects can be observed for targets defined by orientation. There are a number of differences between the two studies that could explain the greater cumulative priming effects we observed for orientation. For instance, Hillstrom (2000) had many fewer participants in Experiment 2 ($N = 12$) compared to our study ($N = 100$) and in fact, although not significant, did show a trend for cumulative orientation priming, raising the possibility that the cumulative priming effect was present in Hillstrom (2000) but was obscured by noise. Second, there are differences in how cumulative priming was measured between the two studies; Hillstrom (2000) compared average RTs from 0 to 3 consecutive repetitions, whereas we compared the *size* of consecutive priming effects from 1 to 3 *or more* consecutive repetitions. It may be that the inclusion of more than 3 consecutive repetitions increased the cumulative priming effects for orientation. Finally, the target-distractor orientation contrast was higher in our study (i.e., horizontal among vertical) than in Hillstrom's (2000; i.e., tilted among vertical); thus, cumulative priming effects may have been stronger in our experiment due to build-up from more highly contrasting items. One might also argue that we observed greater priming for orientation than for color because orientation is more difficult than color as a target-defining feature, and previous work has shown that more difficult visual search tasks lead to greater priming effects (e.g., Lamy, Zivony, & Yashar, 2011; Meeter & Olivers, 2006). However, as mentioned above, several studies have shown greater priming for color versus orientation as the target-defining feature, despite the fact that search times are slower overall for targets defined by orientation than by color (e.g., Hillstrom, 2000; Kristjánsson, 2006; Lamy et al., 2013). In short, it seems plausible that given our task parameters and an equivalent number of subjects, orientation priming might be observed even if it were task-irrelevant; however, further work is necessary to confirm this possibility.

Since previous studies have shown a strong relationship between VSTM capacity and attentional filtering (e.g., Vogel et al., 2005), we used VSTM capacity as an indirect measure of general filtering ability. Although we failed to find a relationship between VSTM capacity and task-irrelevant priming, it is possible that our measure of VSTM capacity was too narrow of an index of filtering ability to observe any potential associations. For instance, active filtering may be more important for VSTM than PoP search because of memory demand differences. In the VSTM task we used, participants had to explicitly encode several items into VSTM, whereas they only needed to remember which of two dimensions to respond to during PoP search. Two dimensions fall well below the estimated four-item limit of VSTM capacity (e.g., Cowan, 2001) if one defines the load in terms of the number of features to attend (one) and ignore (one; Tseng, Glaser, Caddigan, & Lleras, in press) rather than as the number of items to select among (six). Alternatively, it is possible that VSTM is only associated with filtering of task-irrelevant *items* and not of task-irrelevant features *within* attended items (e.g., Woodman & Vogel, 2008), suggesting that perhaps another task would be better suited for measuring the ability to filter task-irrelevant dimension within objects. At first glance, the Garner interference task (e.g., Garner & Felfoldy, 1970) appears reminiscent of this form of filtering. We note, however, that although our notion of filtering has some commonality with the Garner interference task, it differs in an important way. Garner finds that speeded classification performance is impaired by variation in a task-irrelevant dimension, but importantly that task-irrelevant interference only occurs when the two dimensions are integral (e.g., height and width of an object). We, on the other hand, used the separable dimensions of orientation and color. Moreover, unlike in the Garner interference task, we find significant priming effects of the task-irrelevant dimension despite it being separable. Thus, it would seem that the two forms of filtering, of that observed in the Garner interference task and of that observed here, are not the same. However, Santee and Egeth (1980) did find evidence of task-irrelevant dimension interference in a sequential same/difference task using separable dimensions; thus, it is possible that performance on this type of task might correlate with priming for task-irrelevant dimensions. Further research is necessary to determine whether some measure other than VSTM might predict task-irrelevant priming in PoP tasks.

Given the lack of evidence that filtering of the task-irrelevant dimension is driving increased task-relevant priming, what can explain this increased priming? One possibility is that the act of selecting the target gives it greater weight or a more sustained representation, resulting in greater cumulative priming. However, the enhanced priming could also result from repetition of the target-distractor relationship. For instance, because the targets in our displays were only singletons in the orientation dimension, consecutive repetitions of target orientation resulted in multiple displays containing the same target and distractor orientations (e.g., consecutive horizontal targets resulted in consecutive vertical distractors), whereas consecutive repetitions of target color did not share the same target-distractor color relationships; the distractors appeared equally often in both colors, including the target color. Thus, it is also likely that consecutive target orientation repetitions were more apparent than consecutive target color repetitions due to the repeated context of the distractors (e.g., Lamy, Antebi, Aviani, & Carmel, 2008).

Taken together, our results indicate that a benefit emerges for task-relevant priming over several consecutive repetitions. Our data are consistent with a model in which targets are selected at an object-based level, which includes processing of the task-irrelevant dimension (e.g., O'Craven et al., 1999). The build-up for the task-relevant dimension may come from reinforcement across trials that the attended dimension is in fact the target-defining dimension, whereas the lack of build-up for the task-irrelevant dimension may result from the absence of a similar form of reinforcement since it is not the singleton dimension by which the target is chosen. We see no evidence that participants are selecting the task-relevant dimension either at the expense of the task-irrelevant dimension or by failing to represent the task-irrelevant dimension. Further testing is required to determine whether the selective build-up of the task-relevant dimension occurs because participants are repeatedly attending to the target dimension, or because they are being primed by the target-distractor relationship, or a combination of both.

Key words: priming of pop-out, visual short term memory, task-relevance

Acknowledgments

The authors wish to thank Gina Giase, Seema Dave, Jasmeet Brar, and Nirav Chheda for their assistance with data collection.

Commercial relationships: none.
Corresponding author: Audrey Lustig Michal.
Email: audrey.lustig.michal@northwestern.edu.

Address: Department of Psychology, Northwestern University, Evanston, IL.

References

Becker, S. I. (2008). Can intertrial effects of features and dimensions be explained by a single theory? *Journal of Experimental Psychology. Human Perception and Performance, 34*(6), 1417–1440.

Cousineau, D. (2005). Confidence intervals in within-subject designs: A simpler solution to Loftus and Masson's method. *Tutorial in Quantitative Methods for Psychology, 1*(1), 4–45.

Cowan, N. (2001). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral and Brain Sciences, 24*(1), 87–185.

Duncan, J. (1984). Selective attention and the organization of visual information. *Journal of Experimental Psychology: General, 113*(4), 501–517.

Fecteau, J. H. (2007). Priming of pop-out depends upon the current goals of observers. *Journal of Vision, 7*(6):1, 1–11, http://www.journalofvision.org/content/7/6/1, doi:10.1167/7.6.1. [PubMed] [Article]

Fisher, R. A. (1915). Frequency distribution of the values of the correlation coefficient in samples of an indefinitely large population. *Biometrika, 10*(4), 507–521.

Garner, W. R., & Felfoldy, G. L. (1970). Integrality of stimulus dimensions in various types of information processing. *Cognitive Psychology, 1,* 225–241.

Hillstrom, A. P. (2000). Repetition effects in visual search. *Perception & Psychophysics, 62*(4), 800–817.

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

Kristjánsson, Á. (2006). Simultaneous priming along multiple feature dimensions in a visual search task. *Vision Research, 46,* 2554–2570.

Kristjánsson, Á., & Campana, G. (2010). Where perception meets memory: A review of repetition priming in visual search tasks. *Attention, Perception, & Psychophysics, 72*(1), 5–18.

Lamy, D., Antebi, C., Aviani, N., & Carmel, T. (2008). Priming of pop-out provides reliable measures of target activation and distractor inhibition in selective attention. *Vision Research, 48,* 30–41.

Lamy, D., Yashar, A., & Ruderman, L. (2013). Orientation search is mediated by distractor suppression: Evidence from priming of pop-out. *Vision Research, 81,* 29–35.

Lamy, D., Zivony, A., & Yashar, A. (2011). The role of search difficulty in intertrial feature priming. *Vision Research, 51*(19), 2099–2109.

Levinthal, B. R., & Lleras, A. (2008). Inter-trial inhibition of attention to features is modulated by task relevance. *Journal of Vision, 8*(15):12, 1–15, http://www.journalofvision.org/content/8/15/12, doi:10.1167/8.15.12. [PubMed] [Article]

Livingstone, M. S., & Hubel, D. H. (1987). Psychophysical evidence for separate channels for the perception of form, color, movement, and depth. *The Journal of Neuroscience, 7*(11), 3416–3468.

Lleras, A., Kawahara, J., Wan, X. I., & Ariga, A. (2008). Inter-trial inhibition of focused attention in pop-out search. *Perception & Psychophysics 70,* 114–131.

Luck, S. J., & Vogel, E. K. (1997). The capacity of visual working memory for features and conjunctions. *Nature, 390,* 279–281.

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

Maljkovic, V., & Nakayama, K. (1996). Priming of popout: II. Role of position. *Perception & Psychophysics, 58,* 977–991.

Maljkovic, V., & Nakayama, K. (2000). Priming of popout: III. A short-term implicit memory system beneficial for rapid target selection. *Visual Cognition, 7,* 571–595.

Meeter, M., & Olivers, C. N. L. (2006). Intertrial priming stemming from ambiguity: A new account of priming in visual search. *Visual Cognition, 13*(2), 202–222.

O'Craven, K. M., Downing, P. E., & Kanwisher, N. (1999). fMRI evidence for objects as the units of attentional selection. *Nature, 401,* 584–587.

Pashler, H. (1988). Familiarity and visual change detection. *Perception & Psychophysics, 44*(4), 369–378.

Santee, J. L., & Egeth, H. E. (1980). Selective attention in the speeded classification and comparison of multidimensional stimuli. *Perception & Psychophysics, 28*(3), 191–204.

Theeuwes, J. (1991). Cross-dimensional perceptual selectivity. *Perception & Psychophysics, 50,* 184–193.

Tseng, Y. C., Glaser, J. I., Caddigan, E. & Lleras, A. (in press). Modeling the effect of selection history on pop-out visual search. *PLOS ONE.*

Vogel, E. K., McCollough, A. W., & Machizawa, M. G. (2005). Neural measures reveal individual differences in controlling access to working memory. *Nature, 438,* 500–503.

Woodman, G. F., & Vogel, E. K. (2008). Selective storage and maintenance of an object's features in visual working memory. *Psychonomic Bulletin & Review, 15*(1)*,* 223–229.

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

Yashar, A., & Lamy, D. (2011). Refining the dual-stage account of intertrial feature priming: Does motor response or response feature matter? *Attention, Perception & Psychophysics, 73*(7), 2160–2167.