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Probing early attention following negative and positive templates

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Abstract
In visual search tasks, cues indicating the upcoming distractor color can benefit search performance compared with uninformative cues. However, benefits from these negative cues are consistently smaller than benefits from positive cues (cuing target color), even when both cues are equally informative. This suggests that using a negative template is less effective than using a positive template. Here, we contrast the early attentional effects of negative and positive templates using the letter probe technique. On most trials, participants searched for a shape-defined target after receiving a positive, negative, or neutral color cue. On occasional probe trials, letters briefly appeared on the search items, and participants reported as many letters as possible. Examining the proportion of letters reported on potential targets versus distractors provided a snapshot of attentional allocation at the time of the probe. Across probes at 100, 250, and 400 ms, participants recalled more letters on target-colored objects than letters on distractor-colored objects following both negative and positive cues. These cuing benefits on probe report trials were larger at later probe times than early probe times, indicating both types of cues became more effective across time. Importantly, negative cue probe benefits were consistently smaller than positive cue benefits. Finally, following an extremely short probe (25 ms), we found no RT benefit following negative cues as well as no evidence that negatively cued items capture attention. These results help explain the previously reported differences in RT benefit following positive and negative cues, and support the idea of early active attentional suppression.

Keywords Cognitive and attentional control · Visual search · Working memory

Traditionally, research on visual search has emphasized enhancement of search items from an internal representation of a search goal, the target template. That is, search items that match the known features of the upcoming target tend to be prioritized during visual search (Egeth, Virzi, & Garbart, 1984; Wolfe, 1994). For example, if you are searching a shelf for a red book, you might constrain visual search to only red objects. However, there is now growing evidence that foreknowledge of *distractor* features also aids in visual search (Arita, Carlisle, & Woodman, 2012; Carlisle & Nitka, 2019; Cunningham & Egeth, 2016; Reeder, Olivers, & Pollmann, 2017). For example, Arita et al. (2012) designed a series of search experiments in which participants searched displays of Landolt Cs for a target of a specific orientation. Importantly, each search display was preceded by a cue that could be noninformative (*neutral cues*), indicate the upcoming target color (*positive cues*), or indicate the upcoming distractor color (*negative cues*). Note that the specific color cued changed randomly across trials, so there is no possibility participants learned to associate a particular cue with targets or distractors. Participants were explicitly told to use cues to help them find the target (see Fig. 1a). Importantly, both positive cues and negative cues led to faster RTs compared with neutral cues, demonstrating that cueing to-be-ignored information also helped search. From these findings, the researchers suggested that a negative template could benefit search by allowing participants to actively suppress a known distractor, which is also known as the *active attentional suppression* hypothesis (Arita et al., 2012).

Although both positive and negative templates can lead to search benefits, behavioral and neuroimaging research have suggested different mechanisms may be at play. In behavioral research, RT benefits following positive cues were consistently larger than RT benefits following negative cues, despite both cues being equally informative (Arita et al., 2012; Beck & Hollingworth, 2015, Experiment 1; Carlisle & Nitka, 2019; Reeder et al., 2017). This difference implied that negative templates may guide attention differently than positive

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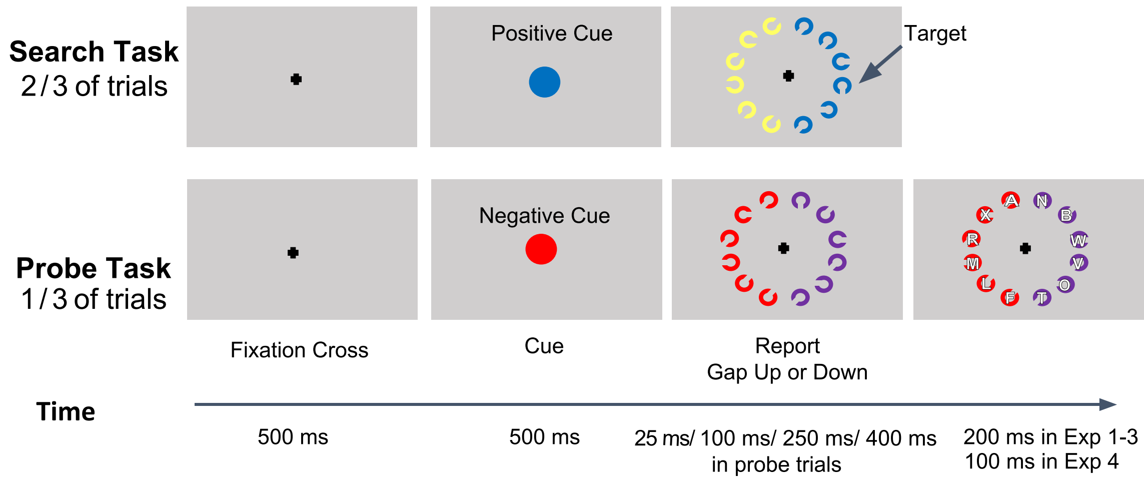

Fig. 1 Task and stimuli used in all experiments. On search trials, participants searched for a target shape (e.g., Landolt C with a gap at the top/bottom) in the display. On probe trials, probe letters were superimposed on the search items briefly. Participants then reported as many letters as they could recall (stimuli are not to scale)

templates. Neuroimaging research provides stronger support for distinct mechanisms of positive and negative templates (Reeder, Olivers, Hanke, & Pollmann, 2018; Reeder et al., 2017). Specifically, fMRI revealed differential preparatory responses between positive and negative templates. Negative cues led to lower activation in large parts of visual cortex compared with neutral cues, whereas positive cues led to much higher activation in the largely overlapping areas (Reeder et al., 2017). Critically, positive templates, but not negative templates, were distinctly represented in the early visual cortex compared with neutral feature representations (Reeder et al., 2018). These differential neural mechanisms support the idea that active suppression may be mechanistically distinct from enhancement, and that negative cues should have a different impact on attention than positive cues.

Other studies have examined how positive and negative cues affect the effectiveness of visual search by examining eye movements. For example, Beck, Luck, and Hollingworth (2018) found that following negative cues the first eye movements were more likely to be directed to the cued distractors than was predicted by baseline. However, later eye movements showed suppression of attention to the negatively cued color. In contrast, positive cues were consistently effective in guiding eye movement toward potential targets during the search. This pattern of initial capture and later suppression of cued distractors was also found in another study (Kugler, ‘t Hart, Kohlbecher, Einhäuser, & Schneider, 2015, Experiment 1 only).

Overall, these eye-tracking findings suggest that negative templates may initially be detrimental to search. Attention will first be captured by the negatively cued distractors. After this initial capture, the negatively cued distractors are suppressed, leading to attention guidance toward potential targets. This pattern of results is broadly consistent with the *search-and-destroy* hypothesis suggested by Moher and Egeth (2012), where negative cues first lead participants to attend to the to-be-ignored features. At face value, search-and-destroy models are directly inconsistent with active suppression models. While the search-and-destroy mechanism could explain the smaller RT benefits following negative cues compared with positive cues, it seems difficult to reconcile with the fMRI data suggesting different preparation for negative and positive templates. If negative cues initially lead to capture, as predicted by search and destroy, we would expect to see a similar preparation following both negative and positive cues, as both cues would initially guide attention toward cue-matching stimuli. Therefore, the current literature contains conflicting results that do not resolve the debate between the mechanisms underlying negative cue benefits.

To reconcile these conflicting results, we examined early attentional deployments during visual search using a letter probe paradigm (Gaspelin, Leonard, & Luck, 2015). In this paradigm, frequent search trials are randomly intermixed with infrequent probe trials. On search trials, participants perform a visual search task with positive, negative, or neutral cues preceding search arrays. On probe trials, shortly after the onset of search arrays, letters are superimposed on search items, half of which were potential targets and half of which were distractors (see Fig. 1). Participants report as many letters as they can after the letters disappeared. If attention is allocated to a given search item, participants should be more likely to report the letter at that location. If a given search item is suppressed, participants should be less likely to report the letter at that location. This technique allows us to obtain a “snapshot” of attention allocation at an early window after the search display appeared. Using the probe technique gives us flexibility in the time at which we examine attention, allowing us to examine multiple time points during early visual search.

We used the probe data to contrast two hypotheses about negative templates from the previous literature. The first is that negative templates will lead to attention capture early in the search while becoming beneficial to search later, as predicted by the search-and-destroy hypothesis (Moher & Egeth, 2012), and supported by eye-tracking results (Beck et al., 2018; Kugler et al., 2015). Under this hypothesis, on probe trials following a negative cue, participants should be more likely to report letters on potential distractors early during the search period and be more likely to report letters on potential targets later in the search. We used the timing of the first saccades in Beck et al. (2018) as a guide for when we should expect to see attention guided toward distractors matching the negative cue. In their work, attention was directed toward negatively cued distractors on the first saccades, which were initiated between 345 and 390 ms. Moher and Egeth (2012) suggested a different time course, with search occurring at 117 ms and ignoring occurring at 167 ms. Therefore, the exact timing of capture versus suppression is unclear based on previous research. To deal with this uncertainty in exact timings, we used a number of probe timings. The search-and-destroy hypothesis predicts we will see evidence of capture at early probes in our work, with more probe letters reported on distractors than potential targets following negative cues. The second hypothesis is the active attentional suppression hypothesis (Arita et al., 2012; Carlisle, 2019), which predicts that negative templates will be effective at directing attention toward potential targets throughout the search, although perhaps driven by a different mechanism than positive templates (Reeder et al., 2018; Reeder et al., 2017). Under this hypothesis, we expect to see more letters reported on potential targets following negative cues, regardless of when letters appear.

Experiment 1

In Experiment 1, we presented the probes 100 ms into the search interval to test early attentional allocation to the potential targets and potential distractors. It is important to keep in mind that this time interval is earlier than when attention was captured by the negatively cued items on the first saccade in previous eye-tracking studies (Beck et al., 2018; Kugler et al., 2015) and when attention was directed to probes on negatively cued items (Moher & Egeth, 2012). By examining a time earlier than when capture was reported in previous studies, we should clearly show evidence that the cued distractor feature is being selected more than the cued target feature according to the search-and-destroy hypothesis. In contrast, the active suppression account suggests that there should be no capture, and that the cued distractor feature should already be suppressed in the early portions of visual search leading to more probe letters reported on potential targets than distractors.

Method

Participants

Twenty-four undergraduates from Lehigh University participated for course credit. This sample size was chosen to match prior research on negative templates (Arita et al., 2012) and prior research using the letter probe technique (Gaspelin et al., 2015). All participants reported normal or corrected-to-normal vision and normal color perception.

Stimuli

Stimuli were presented using Psychtoolbox (Brainard, 1997) for MATLAB and were displayed on an Asus LCD monitor with a gray background, placed at a viewing distance of approximately 60 cm. The cue was a filled colored circle (1.3°) presented at the center of the screen. Search items were outlined circles (1.3° in diameter with a 0.2° line thickness) with a gap (0.5° long) that were presented 6.3° from fixation. Colors of the stimuli were selected randomly from a set of six colors (red, green, blue, magenta, orange, and cyan) on each trial. In search arrays, six items appeared in each hemifield, and items within a hemifield were the same color. On probe trials, letters (0.5° tall) in light gray appeared on top of the search array items.

Procedure

All participants completed three blocks that varied by cue meaning. In the positive cue block, the color of the cue always matched the target color. In the negative cue block, the cue color always matched the distractor color. In the neutral cue block, the cue color did not appear in the search array. The order of the three block types was randomized across participants. Critically, the specific colors appearing during the search array were randomly selected on each trial, meaning that there was no learning of which colors to ignore or attend.

Two types of trials were randomly intermixed in each block. Search trials (two-thirds of trials) began with a fixation point presented for 500 ms. Next, a color cue was presented for 100 ms, followed by a 500-ms presentation of fixation point. Finally, the search items were presented until participants responded. If participants did not make a response within 3,500 ms, the trial was terminated. On search trials, participants were instructed to find the single item with a gap at the top or bottom and respond as quickly and accurately as possible by pressing either the up or down arrow on the keyboard.

Probe trials (one-third of trials) started like search trials, but the search array appeared for only 100 ms. Then, probe letters were superimposed on the search items for 200 ms, and all items disappeared. After the probe items and search items disappeared, participants entered all the letters they recalled.

Letters on each trial were selected randomly, without replacement, from the 26 letters in English alphabet.

At the beginning of each block, participants received instructions regarding the meaning of the cue color and tasks they needed to do on both search and probe trials. Before the first experimental block, they practiced the search task alone for 10 trials and combined search and probe tasks for 10 trials. Before blocks two and three, the practice only included the search task alone. After practice, they completed 96 experimental trials. Participants had a 10-s rest break after completing 24 trials. During the break, they received feedback on their mean RT and accuracy since the last break.

Results

Search trials

Trials with an RT less than 300 ms or greater than 2.5 deviations above the individual mean (1.1% of trials) were excluded from all analyses. Additionally, trials with an incorrect response (5.7%) were excluded from RT analysis.

Accuracy was highest following positive cues (97%), then negative cues (95%), and then neutral cues (91%). A repeated-measures ANOVA with the factor of cue type (positive, negative, neutral) revealed a main effect of cue type, $F(2, 46) = 23.58$, $p < .001$, $\eta_p^2 = .51$. Follow-up t tests showed higher accuracy following positive cues, $t(23) = 7.85$, $p < .001$ $d = 1.58$, and negative cues, $t(23) = 3.59$, $p = .005$, $d = .79$, compared with neutral cues. Additionally, positive cues also led to higher accuracy than did negative cues, $t(23) = 2.79$, $p = .031$, $d = .63$.

As depicted in Fig. 2, mean RT was fastest following positive cues (1.28 s), then negative cues (1.56 s), and neutral cues (1.76 s). A repeated-measures ANOVA with the factor of cue type (positive, negative, neutral) revealed a main effect of cue, $F(2, 46) = 84.72$, $p < .001$, $\eta_p^2 = .79$. Follow-up t tests showed that reaction times were faster following both positive cues, $t(23) = 15.77$, $p < .001$, $d = 3.19$, and negative cues, $t(23) = 5.02$, $p < .001$, $d = 1.05$, compared with neutral cues. Additionally, RTs following positive cues were faster than RTs following negative cues, $t(23) = 6.94$, $p < .001$, $d = 1.45$.

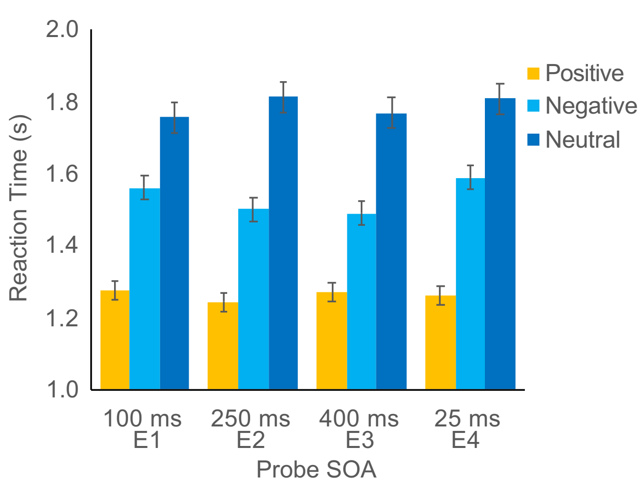

Fig. 2 Mean RT on search trials for all experiments. Error bars indicate the standard error of the mean

Probe trials

Percentages of letters reported on potential targets were calculated by the following formula: $Reported\ Percentage_{target} = \frac{Reported\ Number_{target}}{6}$. The percentages of letters reported on potential distractors were calculated similarly. The pattern of letters reported on potential targets and potential distractors varied based on the cue type (see Fig. 3b). As can be seen, in the negative cuing and positive cuing conditions, participants were less likely to report letters in distractor-colored shapes than letters in target-colored shapes. To formally assess this, we conducted a repeated-measures ANOVA with the factors cue type (positive, negative, neutral) and letter location (potential target, potential distractors). We found a main effect of cue type, $F(2, 46) = 9.64$, $p < .001$, $\eta_p^2 = .30$, and a main effect of letter location, $F(1, 23) = 172.86$, $p < .001$, $\eta_p^2 = .88$. Critically, we found an interaction between two factors, $F(2, 46) = 120.20$, $p < .001$, $\eta_p^2 = .84$. Follow-up t tests showed that participants reported a higher percentage of letters on potential targets than potential distractors when given negative cues, $t(23) = 2.40$, p = .025, $d = 0.42$, or positive cues, $t(23) = 19.28$, $p < .001$, $d = 3.74$. But when given neutral cues, participants reported a nearly equal percentage of letters on potential targets and distractors ($p = .53$; see Table 1).

Discussion

The results from search trials in Experiment 1 replicate previous studies demonstrating search benefits of negative cues (Arita et al., 2012; Carlisle & Nitka, 2019; Reeder et al., 2017). The results of the probe trials provided new information demonstrating that attention was directed toward the target side following the negative cues at just 100 ms into search. The attentional effect toward the potential targets was also pronounced following positive cues. These results are in contrast to the predictions of the search-and-destroy model supported by previous eye-tracking results (Beck et al., 2018; Kugler et al., 2015, Experiment 1). Given that we are at an earlier time point than when initial saccades suggested participants were attending the negatively cued distractors in these studies and when search was demonstrated in Moher and Egeth's (2012) work, participants should be in "search" mode leading to attentional capture by the negatively cued distractor color when our probes were presented. Instead, we found a weak, but significant, attentional benefit demonstrating that attention was directed more to the target side than the distractor side after the negative cues. Importantly, this effect

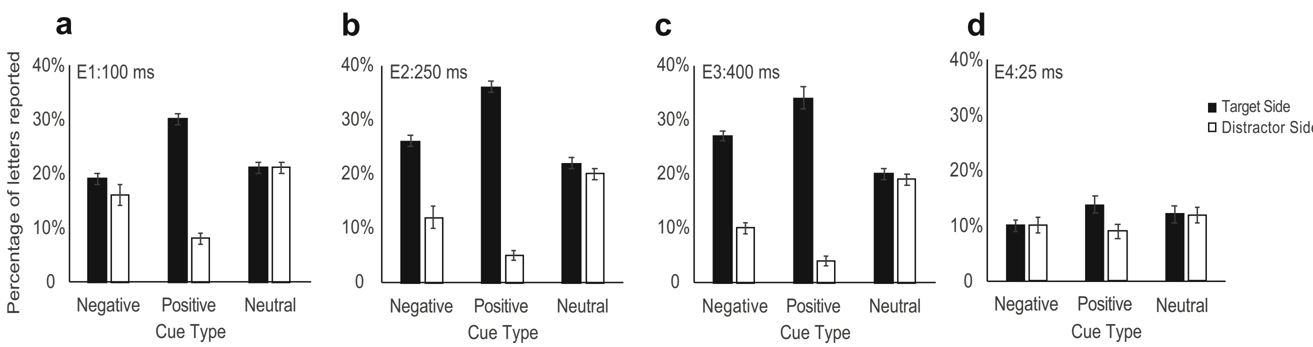

Fig. 3 Mean percentage of letters reported on probe trials for all experiments. **a** Experiment 1: 100 ms. **b** Experiment 2: 250 ms. **c** Experiment 3: 400 ms. **d** Experiment 4: 25ms. Error bars represent the standard error of the mean

did not occur in the neutral cue condition, demonstrating that the benefit was driven by the negative cue.

Experiment 2

Experiment 1 provided a snapshot of attention 100 ms into the visual search period. The prioritization of potential targets over distractors was much smaller following negative than following positive cues. We wanted to explore whether the attentional prioritization would increase as search continued. To this end, in Experiment 2 we shifted the timing of the probe stimuli to 250 ms after the search array onset. To be clear, we are still at a time point earlier than when negatively cued distractors were being attended during the first saccade in the previous eye-tracking studies (Beck et al., 2018; Kugler et al., 2015), so these studies would still predict that attention should be directed toward the negatively cued items at 250 ms into the search. In contrast, the active suppression account predicts evidence of suppression of the negatively cued distractor color.

Method

Twenty-four undergraduates from Lehigh University participated for course credit. The methods were identical to those of Experiment 1, except that probe letter onset was changed to 250 ms after the onset of the search array.

Results

Search trials

Trials with an RT less than 300 ms or greater than 2.5 deviations above the individual mean (1.3% of trials) were excluded from all analyses. Additionally, trials with an incorrect response (6.3%) were excluded from RT analysis.

Accuracy in trials following positive cues (98%) was highest, then negative cues (94%), and neutral cues (89%). A repeated-measures ANOVA revealed a main effect of cue type on accuracy, $F(2, 46) = 25.65$, $p < .001$, $\eta_p^2 = .53$. We found higher accuracy following both positive cues, $t(23) = 7.09$, $p < .001$, $d = 1.40$, and negative cues, $t(23) = 3.06$, $p = .017$, $d = .67$ compared with neutral cues. Positive cues were more effective, as participants also achieved higher accuracy following positive cues compared with negative cues, $t(23) = 4.79$, $p < .001$, $d = .89$.

Mean RT on search trials for each cue condition in Experiment 2 is depicted in Fig. 2. As can be seen, mean RT was fastest for positive cues (1.25 s), followed by negative cues (1.50 s), and neutral cues (1.81 s). A repeated-measures ANOVA revealed a main effect of cue type on RT, $F(2, 46) = 149.41$, $p < .001$, $\eta_p^2 = .87$. Replicating Experiment 1, positive cues led to faster responses compared with negative cues, $t(23) = 8.37$, $p < .001$, $d = 3.59$, and neutral cues, $t(23) = 17.46$, $p < .001$, $d = 1.80$. Negative cues also led to faster responses than neutral cues, $t(23) = 8.80$, $p < .001$, $d = 1.75$.

Table 1 Mean percentage of probe letters reported in Experiments 1–4

	Positive cue		Negative cue		Neutral cue	
	Potential targets	Distractors	Potential targets	Distractors	Potential targets	Distractors
Exp. 1 (100 ms)	30%	8%	19%	16%	21%	21%
Exp. 2 (250 ms)	36%	5%	26%	12%	22%	20%
Exp. 3 (400 ms)	34%	4%	27%	10%	20%	20%
Exp. 4 (25 ms)	14%	9%	10%	10%	12%	12%

Probe trials

The percentage of probe letters reported for each search item type and cue condition is depicted in Fig. 3c. As can be seen, participants were more likely to report letters in the target color for both the negative and positive cue conditions. A repeated-measures ANOVA with the factors cue type and letter location revealed a marginally significant main effect of cue type, $F(1.60, 36.81) = 3.37$, $p = .055$, $\eta_p^2 = .13$, and a main effect of letter location, $F(1, 23) = 236.69$, $p < .001$, $\eta_p^2 = .91$. More importantly, a significant interaction effect was found, $F(2, 46) = 167.80$, $p < .001$, $\eta_p^2 = .88$. Follow-up *t* tests showed that higher percentage of letters were reported on potential targets than potential distractors when negative cues, $t(23) = 7.91$, $p < .001$, $d = 1.59$, or positive, $t(23) = 23.06$, $p < .001$, $d = 4.60$, were given, but not neutral cues ($p = .105$).

Discussion

In Experiment 2, we replicated the RT and accuracy results from Experiment 1. Importantly, we also replicated the pattern of results on probe trials, with negative cues leading to significant benefits, which were numerically smaller than the benefits for positive cues. Once again, we found no evidence that attention was directed to the distractors on negative cue trials, supporting the active suppression account.

Experiment 3

As the prior experiments demonstrated that the probe benefits for negative cues were smaller than for positive cues, we wondered how these benefits would continue to evolve over time. In Experiment 3, we extended the probe timing to 400 ms after search array onset.

Method

Twenty-four undergraduates from Lehigh University participated for course credit. The methods were identical to those of Experiment 2, except that the time when letters appeared on probe trials was changed to 400 ms after the onset of the search array.

Results

Search trials

Trials with an RT less than 300 ms or greater than 2.5 deviations above the individual mean (1.1% of trials) were excluded from all analyses. Additionally, trials with an incorrect response (5.7%) were excluded from RT analysis.

Accuracy was highest following positive cues (98%), then negative cues (96%), and neutral cues (89%). Consistent with Experiments 1 and 2, a repeated-measures ANOVA revealed a main effect of cue type, $F(2, 46) = 41.47$, $p < .001$, $\eta_p^2 = .63$. Accuracy was higher following positive, $t(23) = 7.32$, $p < .001$, $d = 1.54$, and negative cues, $t(23) = 6.06$, $p < .001$, $d = 1.31$, compared with neutral cues. Positive cues also led to higher accuracy compared with negative cues, $t(23) = 3.35$, $p = .003$, $d = .66$.

Figure 2 shows that the mean RT was fastest following positive cues (1.27 s), then negative cues (1.49 s), and neutral cues (1.77 s). A repeated-measures ANOVA also revealed a main effect of cue type, $F(2, 46) = 67.79$, $p < .001$, $\eta_p^2 = .74$. Specifically, mean RT following positive cues was significantly faster than following negative cues, $t(23) = -11.75$, $p < .001$, $d = 2.40$, or neutral cues, $t(23) = -7.26$, $p < .001$, $d = 1.08$. Critically, mean RT following negative cues was also significantly faster than mean RT following neutral cues ($t(23) = -5.26$, $p < .001$, $d = 1.46$).

Probe trials

Figure 3d shows that more letters were reported on targets than on distractors following the positive and negative cues. A repeated-measures ANOVA with the factors cue type and letter location was conducted, showing a significant main effect of cue type, $F(2, 46) = 5.02$, $p = .011$, $\eta_p^2 = .18$, and a main effect of letter location,($F(1, 23) = 289.33$, $p < .001$, $\eta_p^2 = .93$. More importantly, a significant interaction between cue type and letter location was also found, $F(2, 46) = 99.32$, $p < .001$, $\eta_p^2 = .81$. Follow-up *t* tests showed that higher percentage of letters were reported on potential targets than on potential distractors for negative cues, $t(23) = 9.77$, $p < .001$, $d = 2.91$, and positive cues, $t(23) = 21.28$, $p < .001$, $d = 5.03$. However, there was still no difference following neutral cues ($p > .5$).

Discussion

In Experiment 3, we replicate the pattern of RT and accuracy results seen in Experiments 1 and 2, as well as the pattern of results on the critical probe trials. Once again, on probe trials, the negative cues led to more letters being reported on the target side than on the distractor side. As this prioritization of target features was not present in the neutral cue trials, this effect must be driven by the negative cue.

Experiment 4

Although Experiments 1–3 consistently found prioritizing of potential targets following negative cues, these results could potentially also be explained by the search-and-destroy hypothesis. According to this alternative account, participants first attended the negatively cued distractors, but rapidly rejected them as a potential target before the onset of the probe letters before our earliest probe time (100 ms). This may have resulted in a probe suppression effect, even though the negatively cued distractors captured attention prior to 100 ms (see also Theeuwes et al., 2000). To test this possibility, we conducted Experiment 4, which used a very brief probe display to prevent rapid disengagement from the negatively cued distractor items (based upon Gaspelin et al., 2015, Experiment 4). The search array appeared for 25 ms and was followed by probe letters for 100 ms. Then, the probe letters were immediately masked ("#") to prevent further processing. According to search-and-destroy hypothesis, we should observe clear evidence of attentional capture by cued distractors. That is, more probe letters on the distractor side should be reported rather than probe letters on the target side. However, based on active suppression hypothesis, we should find the opposite pattern: More probe letters on the target side are reported.

Method

Twenty-four undergraduates from Lehigh University participated for course credit. The methods were identical to those of Experiment 3, except that we altered the timing of probe trials. After fixation, the search array appeared for 25 ms and was followed by probe letters for 100 ms. After probe letters disappeared, masks ("#") appeared at locations of letters for 250 ms, to eliminate further processing of the probe letters in iconic memory. Thus, the entire display was only visible for 125 ms.

Results

Search trials

Accuracy in trials following positive cues (93%) was highest, then negative cues (85%), and neutral cues (83%). A repeated-measures ANOVA revealed a main effect of cue type on accuracy, $F(2, 46) = 5.75$, $p = .006$, $\eta_p^2 = .20$. We found higher accuracy following positive cues compared with neutral cues, $t(23) = 2.78$, $p = .031$, $d = 0.57$, and negative cues, $t(23) = 3.29$, $p = .009$, $d = 0.67$.

Mean RT on search trials for each cue condition is depicted in Fig. 2. As can be seen, mean RT was fastest for positive cues (1.26 s), followed by negative cues (1.59 s), and neutral cues (1.81 s). A repeated-measures ANOVA revealed a main effect of cue type, $F(2, 46) = 68.16$, $p < .001$, $\eta_p^2 = .75$. Replicating previous experiments, positive cues led to faster responses compared with negative cues, $t(23) = 7.88$, $p < .001$, $d = 1.61$, and neutral cues, $t(23) = 12.16$, $p < .001$, $d = 2.48$. Negative cues also led to faster responses than neutral cues did, $t(23) = 4.08$, $p = .001$, $d = 0.83$.

Probe trials

The percentage of probe letters reported for each cue condition is depicted in Fig. 3a. A repeated-measures ANOVA with factors of cue type and letter location revealed a significant main effect of cue type, $F(2, 46) = 3.73$, $p = .032$, $\eta_p^2 = .14$, and a main effect of letter location, $F(1, 23) = 10.35$, $p = .004$, $\eta_p^2 = .31$). More importantly, a significant interaction effect was found, $F(2, 46) = 11.62$, $p < .001$, $\eta_p^2 = .34$. Follow-up t tests showed that a higher percentage of letters was reported on potential targets than on potential distractors following positive cues, $t(23) = 5.22$, $p < .001$, $d = 1.07$. No difference between target side and distractor side was found for negative cues, $t(23) = 0.63$, $p = .558$, or neutral cues, $t(23) = 0.13$, $p = .872$.

Discussion

In Experiment 4, we reduced the probe duration to prevent rapid shifts of attention before the onset of the search display. On search trials, we replicated the pattern of RT and accuracy results seen in Experiments 1–3. On probe trials, we did not find any evidence of capture by negatively cued items, which is inconsistent with the prediction by the search-and-destroy hypothesis. However, we also did not find evidence of early suppression predicted by the active suppression hypothesis. It appears that the benefits following negative cues takes longer to emerge than the benefits following positive cues. These results are actually consistent with previous research demonstrating that an N2pc toward the target side was delayed following negative cues compared with positive cues (Carlisle & Nitka, 2019). Such delayed effect of negative cues supports the idea that negative templates are mechanistically different from positive templates (Reeder et al., 2017).

Probe comparison across experiments

To examine how the benefits following the informative positive and negative cues change across the early search period, and to determine if we had neared an asymptote regarding the benefits, we completed an additional analysis comparing the results of the probe trials across the experiments.

As the overall percentages of letters reported in each experiment were not the same, we calculated proportions of letters reported on potential targets to facilitate the comparison across experiments in attentional guidance. Proportion of target letters reported was calculated as follows: $Reported\ Proportion_{target} = \frac{Reported\ Number_{target}}{Reported\ Number_{target} + Reported\ Number_{distractor}}$. A three-way repeated-measures ANOVA with factors of probe time (Experiment 1: 100 ms; Experiment 2: 250 ms; Experiment 3: 400 ms; Experiment 4: 25 ms) and cue type (positive, negative, neutral) was conducted. Because proportions of letters reported on potential targets and distractors were no longer independent, the analyses focused solely on the proportion of targets reported (for the raw data, see Table 1).

Figure 4 shows that the largest proportion of target letters was reported following positive cues (81%), then negative cues (64%), and neutral cues (51%), leading to a significant main effect of cue type, $F(2, 184) = 185.36$, $p < .001$, $\eta_p^2 = .67$. The proportion of target letters was also larger when probes appeared at 400 ms (72%), then 250 ms (71%), 100 ms (63%), and 25 ms (56%), leading to a significant main effect of probe time, $F(3, 92) = 25.69$, $p < .001$, $\eta_p^2 = .46$. Critically, a significant interaction was found, $F(6, 184) = 13.29$, $p < .001$, $\eta_p^2 = .30$. Follow-up *t* tests showed that for negative cues the proportion of target letters reported increased from 100 ms to 250 ms, $t(46) = 3.78$, $p < .001$, $d = 1.06$. However, such increase was absent from 25 ms to 100 ms ($p = .976$), and from 250 ms to 400 ms ($p = .926$). For positive cues, the proportion of target letters reported increased from 25 ms to 100 ms, $t(46) = 6.42$, $p < .001$, $d = 1.47$, and from 100 ms to 250 ms, $t(46) = 2.68$, $p = .056$, $d = 0.84$. However, no further increase was found from 250 ms to 400 ms ($p = 1.000$). Moreover, no differences were found across time for the neutral cues (*p*s > .98). Overall, these results suggest that positive cues led to a prioritization of the target side as early as 25 ms after the onset of search array, and such prioritization was delayed following negative cues, which occurred 100 ms after the onset of search array. Additionally, effects of both cues increased at 250 ms and were likely nearing asymptote by 400 ms, as indicated by no further increases. Over the course of early attentional window (25 ms to 400 ms), cueing effects gradually became stronger and then stabilized (see Fig. 4).

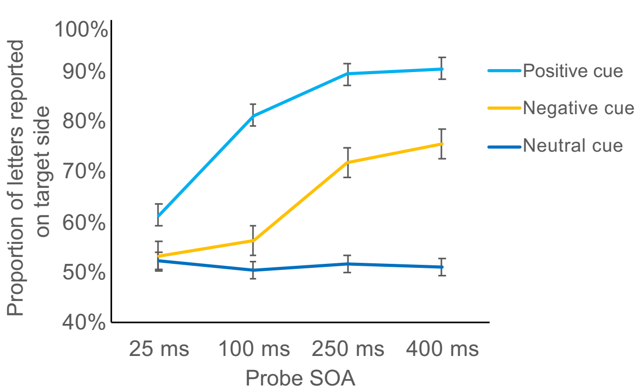

Fig. 4 Mean proportions of total letters reported that fell on potential targets from Experiments 1–4. Error bars indicate standard error of the mean

General discussion

In the current study, we contrasted the search-and-destroy hypothesis (Moher & Egeth, 2012) with the active attentional suppression hypothesis (Arita et al., 2012) by examining how negative templates and positive templates direct attention during the early stages of visual search. In all four experiments, we replicated previous studies of reaction time (Arita et al., 2012; Carlisle & Nitka, 2019; Reeder et al., 2017): Negative cues and positive cues both led to faster detection of the target stimulus than neutral cues did. The key addition of this study was the letter probe trials, which allowed us to directly isolate the early attentional biases from the negative and positive templates. Positive cues led participants to report higher percentages of letters on potential targets than distractors as early as 25 ms after the onset of the search display, whereas effect of negative cues occurred by 100 ms after the onset of the search array. The benefits for both positive and negative cues increased from 100 ms to 250 ms, with no further significant increases at 400 ms, indicating the benefits were likely nearing an asymptote. Importantly, at no time point following negative cues did we find evidence that distractor letters were more likely to be reported than target letters. This directly contradicts search-and-destroy models, which proposes that to-be-ignored distractors automatically capture attention. In summary, our research demonstrated that negative templates guided attention toward the potential targets (and away from distractors), but this benefit had a later onset and was consistently smaller than that of positive cues.

The finding of delayed effect of negative cues is consistent with previous research. For example, in Carlisle and Nitka (2019), the N2pc component contralateral to the target side following negative cues occurred 100 ms later than that following positive cues. In previous eye-tracking research (Beck et al., 2018), the onset of first saccades was also delayed following negative cues compared with positive cues, and benefits did not emerge until later saccades. Such difference in onset of effects may suggest that distinctive mechanisms are involved in active suppression and active enhancement, which may be explained by the difference found in preparatory responses between positive and negative templates (Reeder et al., 2017).

Additional proposed mechanisms for the RT benefits from negative cues are included within the literature on negative templates. Two hypotheses suggest that participants wait until the search array appears and then create a positive template. The *location-based* hypothesis suggests participants see the search array, identify on which side of the screen the distractors items will appear, and search in the other half of the screen (Beck & Hollingworth, 2015). However, a recent study has demonstrated that when participants are placed in a block where ignoring is a good strategy overall, it does not matter whether the colors are separated by hemifield or mixed

(Carlisle & Nitka, 2019). This suggests the Beck and Hollingworth (2015) may have been driven by participant strategy, rather than the inability to suppress features. The *positive recoding* hypothesis suggests that participants identify the color in the array that does not match the negative cue and create a positive template for this color (Becker, Hemsteger, & Peltier, 2015; Beck et al., 2018). Based on this hypothesis, in our results participants must have identified the noncued color and create a positive template within 100 ms. This study was not designed to examine this hypothesis, but future work should address whether this would be mechanistically possible. One limitation of our current approach is that the time course is contrasted across participants. Future research should examine the time course in a within-subjects design, and include additional time points to better characterize the attentional time course and provide a more definitive assessment of when attentional benefits asymptote.

How can we reconcile our results showing early attentional benefits following negative cues with previous findings that showed capture followed by suppression (e.g., Beck et al., 2018)? Although our probe times in Experiments 1, 2, and 4 were earlier than the first saccade, which demonstrated capture in Beck et al.'s (2018) work, we found no evidence of capture at any time points. These differences may be related to differences in the experimental designs. In Beck et al. (2018), using negative cues only helped to rule out two or four items in the search array, leading to search for the target among the 12 or 14 items with varied colors. In our experiments, negative cues were more beneficial—eliminating six items in the search array of 12. Given the difference in potential benefits brought by negative cues between our experiments and Beck et al. (2018), it is possible that participants adopted different strategies. This strategic use of negative cues only when they are more beneficial is in line with the characterization of proactive versus reactive suppression from Geng (2014). Although proactive suppression leads to overall less distractor interference, using this strategy is constrained by practical and cognitive limitations. When proactive suppression is not used, a reactive suppression mechanism can quickly respond to attentional failures and help improve later search. It seems possible that when the negative cues are more beneficial (Arita, et al., 2012; Carlisle & Nitka, 2019) participants may engage in the more effortful proactive suppression mechanism, whereas when negative cues are less beneficial, participants may rely on the reactive suppression mechanism (Beck et al., 2018). Recent work supports the idea that participants may only show an effect for negative cues when the cues are more beneficial. Conci, Deichsel, Müller, and Töllner (2019) found that negative cue RT benefits were absent for a relatively easy search task, but appeared when the search task was made more difficult by increasing target and distractor similarity.

While the current cued suppression benefits are dependent on active attentional control because the color cued changed on each trial, several recent studies have also found *learned* attentional suppression. Specifically, in learned suppression research, researchers found a singleton distractor in the search array could be proactively suppressed after many trials in which the singleton color remained consistent (Gaspelin, Leonard, & Luck, 2017; Gaspelin & Luck, 2018; Vatterott & Vecera, 2012; Vatterott, Mozer, & Vecera, 2018). Mechanisms underlying cued attention suppression and learned attentional suppression may be different. The learned suppression may reflect a gradual tuning of perceptual sensitivity based on a particular feature, which may be modulated by mechanisms related to intertrial priming and selection history (Gaspelin et al., 2019). In contrast, the cued suppression may reflect a rapid tuning of perceptual sensitivity based on a particular feature, modulated by working memory. However, there may be overlap between these mechanisms, as participants may begin to proactively suppress the singleton distractor if they recognize it repeats over trials. It remains to be seen how the underlying mechanisms for learned distractor suppression and cued distractor suppression relate to one another, and future research should address this question.

Importantly, both cued and learned suppression highlight the flexibility of attentional control. Much of the research on attentional templates demonstrates that representations in working memory (Desimone & Duncan, 1995) or long-term memory (Carlisle, Arita, Pardo, & Woodman, 2011; Reinhart, Carlisle, & Woodman, 2014; Woodman & Arita, 2011; Woodman, Carlisle, & Reinhart, 2013) can be used to create positive attentional template to effectively guide visual attention *toward* a known target feature. This view suggests that attentional templates are like a switch that is either on or off (Carlisle, 2019): Templates guide attention toward matching items or there is no attentional control (Olivers, Peters, Houtkamp, & Roelfsema, 2011; Peters, Goebel, & Roelfsema, 2009). Recent research (Carlisle & Woodman, 2011), including findings of cued suppression (Arita et al., 2012; Carlisle & Nitka, 2019; Reeder et al., 2018; Reeder et al., 2017) and learned suppression (Gaspelin et al., 2017; Gaspelin & Luck, 2018; Vatterott & Vecera, 2012; Vatterott et al., 2018), have provided a new perspective for understanding the mechanism of attentional templates. There is now evidence that both attentional enhancement (Carlisle & Woodman, 2011) and attentional suppression (Won, Kosoyan, & Geng, 2019) may be adjusted flexibly based on task demands. Carlisle (2019) has recently proposed a *flexible attentional control hypothesis*, which suggests that attentional control should be conceptualized as a dial where the dial can be turned up to direct attention toward template-matching items or down so template-matching items can be suppressed in the search.

In conclusion, we found negative templates are effective in guiding attention to targets during the early portions of search, although such effect was delayed and was consistently less potent than that of positive templates. These differences in onset of effects and effectiveness between positive and negative templates support the idea that they may be instantiated by different mechanisms (Reeder et al., 2017). Our results support the active attentional suppression hypothesis (Arita et al., 2011) and provide support for flexibility in attentional control (Carlisle, 2019). Future research should continue to explore the relationship between positive and negative templates to help uncover the mechanisms involved in attentional control.

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