Acta Psychologica 190 (2018) 85–94

Contents lists available at ScienceDirect

Acta Psychologica

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

Negative cues lead to more inefficient search than positive cues even at later stages of visual search

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ARTICLE INFO

PsycINFO classification:
2100 General Psychology
2300 Human Experimental Psychology
2340 Cognitive Processes
2346 Attention*Keywords:*
Attention
Visual search
Distractor inhibition
Cueing distractor

ABSTRACT

Observers can focus their attention on task-relevant items in visual search when they have prior knowledge about the target's properties (i.e., positive cues). However, little is known about how negative cues, which specify the features of task-irrelevant items, can be used to guide attention away from distractors and how their effects differ from those of positive cues. It has been proposed that when a distractor color is cued, people would first select the to-be-ignored items early in search and then inhibit them later. The present study investigated how the effects of positive and negative cues differ throughout the visual search process. The results showed that positive cues sped up the early stage of visual search and that negative cues led to initial selection for inhibition. We further found that visual search with negative cues was more inefficient than that with positive cues even at later stages, suggesting that sustained inhibition is needed throughout the visual search process. Taken together, the results indicate that positive and negative cues have different functions: prior knowledge about target features can weight task-relevant information at early stages of visual search, and negative cues are used more inefficiently even at later stages of visual search.

1. Introduction

Our visual environment is complex to process. As our attentional capacity is limited, we must selectively attend to behaviorally relevant objects and exclude irrelevant items. Most theories propose that maintaining target characteristics in working memory (i.e., having a target template) modulates the competition among objects for selection (Bundesen, 1990; Desimone & Duncan, 1995). When people receive task-relevant information prior to a visual search task (i.e., positive cues), they can bias their attention toward the goal-related items, resulting in faster target detection (Vickery, King, & Jiang, 2005; Wolfe, Horowitz, Kenner, Hyle, & Vasan, 2004). Thus, prior knowledge about target properties can positively weight the processing of important information. In addition to focusing attention on target properties, visual search can be accelerated by negatively weighting the processing of task-irrelevant information. That is, it is possible to guide attention away from to-be-ignored distractors by giving information about task-irrelevant stimuli before the task (i.e., negative cues).

Woodman and Luck (2007) argued that maintaining distractor characteristics can guide attention away from distractors. In their experiment, participants were asked to hold a colored shape in working memory and then to perform a visual search task in which the memorized item appeared as a distractor (invalid trials) or did not appear (neutral trials). Critically, they instructed participants that the memorized item would *not* appear as the target. The results showed that reaction times (RTs) in invalid trials were faster than those in neutral trials, which led to the conclusion that prior knowledge about distractor properties can be used to deprioritize the processing of distractor items. By using a cueing paradigm, Arita, Carlisle, and Woodman (2012) also showed that prior knowledge about distractor color sped up visual search. They provided distractor color as negative cue prior to the search display and found that participants detected the target faster in the negative cue condition. Those results also support the idea that observers can use prior information about to-be-ignored characteristics to guide attention away from distractors.

Moher and Egeth (2012) examined the time course of visual search with negative cues, proposing that observers select the to-be-ignored items early in search and subsequently inhibit them at later search stages. In their experiment 4, after the presentation of a negative cue, colored placeholders were presented prior to the search display. The colored placeholders were the same color and presented at the same location as the upcoming search items, and the stimulus onset asynchrony (SOA) between the placeholders and search display was 100, 800, or 1500 ms. They found the RT costs in the short SOA condition

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https://doi.org/10.1016/j.actpsy.2018.07.003
Received 27 December 2017; Received in revised form 9 July 2018; Accepted 10 July 2018

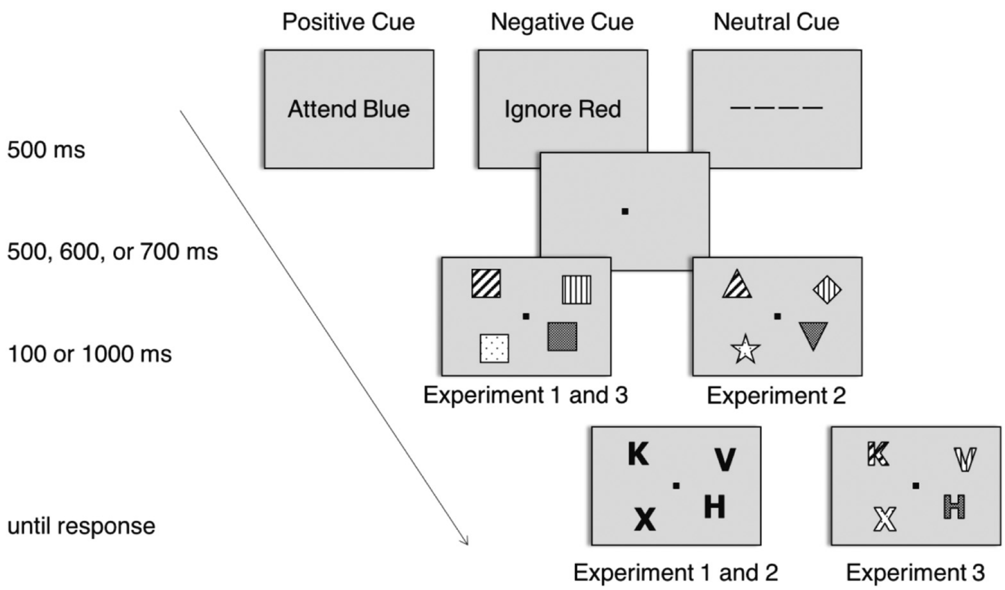

Fig. 1. Example trials in three cue conditions (positive, negative, and neutral cues). Participants were asked to indicate whether an "X" or "N" was present as quickly and accurately as possible. Colored placeholders presented prior to the visual search display consisted of squares (Experiment 1 and 3) or four different shapes (Experiment 2) that indicated the locations of upcoming search letters for a variable duration (100 or 1000 ms). Search items were presented in white (Experiments 1 and 2) or the same color as the colored placeholders (Experiment 3). Positive and negative cues showed target and distractor candidate locations, respectively. Neutral cues showed no information. This figure is not to scale.

(100 ms) and RT benefits in the long SOA conditions (800 and 1500 ms). They interpreted these results as suggesting that observers with prior knowledge about distractor features first select to-be-ignored items and then subsequently inhibit them. They termed this process as "*search and destroy*." Thus, visual search with negative cues is effective at later stages of visual search.

The idea of the "search and destroy" process was supported by recent eye-movement studies (Beck, Luck, & Hollingworth, 2017; Kugler, 't Hart, Kohlbecher, Einhäuser, & Schneider, 2015). Kugler, Hart, Kohlbecher, Einhäuser, and Schneider (2015) provided participants positive or negative cues prior to the visual search task. The proportion of fixations on relevant items was higher in the positive cue condition than in the negative cue condition, indicating that negative cues are more inefficient than positive cues. They further analyzed how guidance of eye movements developed from fixation to fixation, showing that although the first fixation following negative cue presentation is incorrectly directed toward an irrelevant item above the chance level, guidance of gaze toward relevant items was improved with successive fixations within a search. These results may correspond to the idea of "search and destroy" process (Moher & Egeth, 2012) in that to-be-ignored items are first selected and then subsequently inhibited to guide attention toward relevant items. Thus, distractor inhibition operates at later stages of visual search.

Studies have shown that negative cueing effects were smaller than positive cueing effects (Arita et al., 2012; Beck & Hollingworth, 2015; Becker, Hemsteger, & Peltier, 2016). These studies have consistently indicated that target-detection times in positive cue conditions were faster than those in negative cue conditions. Thus, positive and negative cues can have different attention-guiding effects in visual search. However, the idea of "search and destroy" implies that distractor inhibition must be effective at later stages of visual search (Moher & Egeth, 2012). Therefore, it would be useful to examine the functional difference between positive and negative cueing effects by separating the visual search process into the early and late stages.

One fMRI study directly compared regions and activations during the visual search task with positive and negative cues (Reeder, Olivers, & Pollmann, 2017). They found that RTs with a positive cue were faster than those with a negative cue, and that RTs with a negative cue were faster than those with a neutral cue, suggesting that visual search with negative cues is more inefficient than that with positive cues. fMRI signals recorded during the preparatory period between cue presentation and the search task showed that whereas positive cues enhanced the activity in visual areas, negative cues reduced it, suggesting that observers used negative cues to suppress activation in the visual cortex in anticipation of the appearance of to-be-ignored items. This observation may indicate that the visual cortex receives feedback inhibition from frontal regions to prepare for the appearance of to-be-ignored items. Such an underlying neural mechanism may contribute to the functional difference between positive and negative cueing effects.

In sum, past studies have demonstrated that negative cues lead to more inefficient search than positive cues, and that negative cues become effective at later stages of visual search. However, the functional difference between positive and negative cues has not been fully determined. The first possible explanation is that the difference between positive and negative cueing effects can only be explained by their time course of the visual search process. This idea leads to the assumption that negative cues can be used as effectively as positive cues at later stages of visual search. That is, distractor inhibition could provide attentional enhancement when there is enough time for a negative cue to be used. Thus, it may take much time for negative cue relative to positive cue to exert a facilitatory influence on visual search, which would explain the observed inefficiency of visual search with negative cue. The second possibility is that distractor inhibition remains more inefficient than attentional enhancement even at later stages of visual search. The observed differences in neural response between cue types (Reeder et al., 2017) could indicate that distractor inhibition is relatively ineffectively compared with attentional enhancement throughout visual search. Thus, it is still unclear whether the differences between positive and negative cueing effects are derived from the delayed distractor inhibition or from the sustained ineffectiveness of the use of negative cues.

To address this issue, the present study examined the effects of positive and negative cues over the course of visual search. Fig. 1 shows a modification of the procedure by Moher and Egeth (2012) in which we manipulated cued set size (CSS) by changing the number of to-be-attended or to-be-ignored items (Fig. 2). This manipulation allowed us not only to compare their effects on visual search directly under the balanced task setting, but also to evaluate their search processes by analyzing search slopes and intercepts. The search slopes and intercepts of positive and negative cues can be calculated by fitting a linear regression of RT against CSS. The search slope is a key aspect of visual search that reflects search efficiency (Liesefeld, Moran, Usher, Müller, & Zehetleitner, 2016; Wolfe, 1998, 2007). The search slope is defined as the slope of RT over display set size, which shows the time needed to scan a single item. Efficient search leads to a shallower search slope, and attentive search produces a steeper slope. In contrast, the intercept