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A mechanism for inhibition in visual search

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Abstract— Observers can use explicit foreknowledge of a feature of an upcoming target to guide search. However, little is known about observers' use of explicit foreknowledge that a specific feature will not match the upcoming target. In a series of experiments, we presented observers with either "ignore" cues that validly indicated the color of a nontarget item (rather than the color of the target item) in the upcoming display, or "neutral" cues. Surprisingly, observers unable to use "ignore" cues to speed search; instead, knowing the color of a nontarget item on the upcoming display slowed search. This cost for "ignore" cues compared to neutral cues was consistent across several experiments using several different types of "ignore" cues. We conclude that observers are unable to explicitly avoid selecting items appearing in to-be-ignored colors. Instead, we propose observers use a strategy of immediately selecting the irrelevant item in order to subsequently inhibit it.

***Index Terms*—visual search, inhibition, attention**

I. Introduction

Observers are often faced with overwhelmingly complex visual environments. Some aspects of visual processing are capacity-limited; observers are often unable to extract the information needed to make decisions about subsequent behavior in parallel across the entire visual field. This can be problematic when an observer is searching for a specific target, such as a pair of keys on a cluttered desk. Therefore, it is often necessary for observers to select a subset of visual information for additional processing.

This selection process can be guided in two ways. Selection can be automatically guided towards items with high local feature contrast, i.e. "salient" items [1]-[3]. Alternatively an observer can bias their selection towards certain aspects of the display, such as locations or features, which are known to be task-relevant. For example, foreknowledge of a target location [4] or a target-defining feature [5]-[9] can bias selection towards items matching those criteria. This guidance need not be explicit; for example, attention can be guided towards [10] or away from [11] recently selected locations without the observers' awareness. In some cases, salient irrelevant items can capture an observers' attention, regardless of their top-down set [12], though there is evidence that this only occurs when that salient item matches a task-relevant dimension [13], [14].

A great deal of research has been devoted to how observers can initiate a top-down set to guide the selection process by prioritizing relevant aspects of a given scene; for example, an observer can find their friend in a crowd more quickly if they know their friend is wearing a red shirt. However, not much is known about whether observers can explicitly de-prioritize irrelevant aspects of that same scene; for example, if that same observer only knows that their friend is not wearing a green shirt, will this information aid their search process?

There is evidence that selection can be guided away from irrelevant items *implicitly*. Observers are slower to select targets appearing in a recently selected location under some circumstances, an effect known as "inhibition of return" [11]. This can serve a valuable function, preventing re-selection of recently attended items and thus making search more efficient [15]. Objects (such as letters) and features (such as color) can also be implicitly de-prioritized by the visual system in some conditions [16], [17].

However, explicitly tapping into these mechanisms can prove challenging. The contents of working memory are known to influence attention [18]-[21]. Though this may be flexible rather than automatic [22]-[25], there is nevertheless a clear functional overlap between these two systems behaviorally, as well as anatomically [26]-[28]. Additionally, taxing working memory resources is known to reduce top-down inhibitory processes [29].

In order to initiate an explicit top-down set, an observer must rehearse the contents of that set in working memory. This is beneficial when an observer is attempting to guide selection towards a target item; however, if the observer is rehearsing an item that is to be ignored, they must overcome the tendency of guiding selection towards the contents of working memory. There is some evidence that attempting to inhibit during the selection process has deleterious effects; for example, Tsal & Makovski [30] found an "attentional white bear effect", wherein attention was guided towards a location known to be irrelevant.

Still, in some cases observers can overcome this limitation. In a study by Munneke, Van der Stigchel, & Theeuwes [31], observers were asked to find a target letter among four fixed locations. On some trials, one of these locations was cued, indicating that the target would not appear in that location on the upcoming trial. Observers found the target more quickly on cued trials. Additionally, flanker-like interference [32]

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from the letter appearing at the to-be-ignored location was reduced on cued trials. This is consistent with numerous other studies finding evidence that irrelevant locations can be successfully inhibited [33]–[36].

While these data suggest that locations can be explicitly inhibited, the evidence for explicit inhibition of irrelevant features is mixed. There is some evidence that features can be inhibited in search when they are associated with previously rejected distractors (as part of the *visual marking effect* [37]-[39], but see [40] for a bottom-up account of this effect) but it is unclear if this is an explicit strategy on the part of the observer or an implicit carryover effect. Friedman-Hill & Wolfe [41] found no evidence for explicit inhibition of irrelevant features in a search task. Woodman & Luck [23] recently found evidence for a "template for rejection," suggesting that observers could explicitly inhibit irrelevant items in search. However, in both of these studies observers were given a color to ignore on every trial; therefore it is unclear whether initiating at top-down set to ignore results in more or less efficient search.

In the present experiments, we seek to clarify the nature of explicit top-down inhibition of irrelevant features in visual search. Using a design adapted from Munneke et al. [31], we directly compare trials where an observer is directed to ignore a specific color ("ignore trials") to trials where no top-down ignoring set is initiated ("neutral trials"). If explicit inhibition of irrelevant features is possible and allows for more efficient search, responses should be faster on ignore trials compared to neutral trials. If this inhibition is not possible, or if the influence of working memory cannot be overridden, responses should be the same or slower on ignore trials compared to neutral trials.

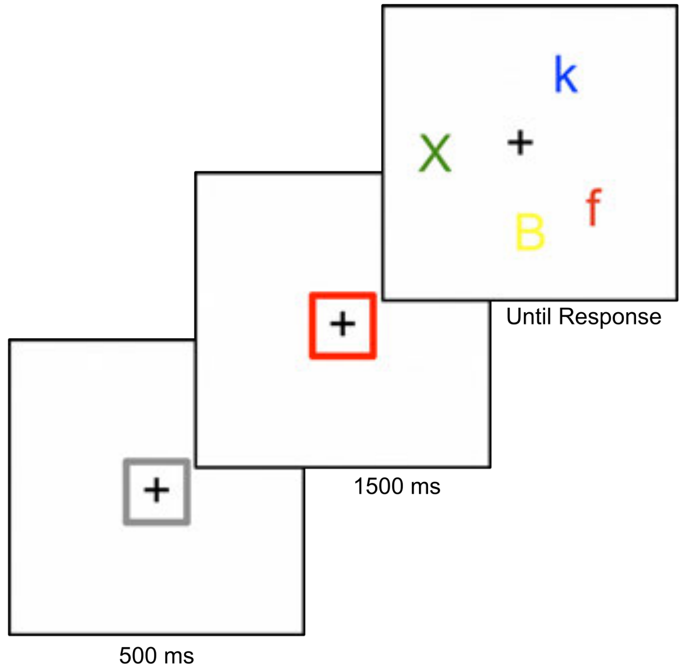

Fig. 1: An example of an ignore trial in Experiment 1. The red square border indicates that the target will not appear in red on the upcoming trial. On neutral trials, the gray box would change into a multi-colored square border giving the participants no information about target or distractor colors on the upcoming trial. Here the target "B" (appearing in yellow), and a lowercase "f" is present (appearing in red), making this an example of an incompatible trial.

II. Experiment 1

Methods

Participants. Sixteen Johns Hopkins University undergraduate students (mean age = 19.4 years; 6 male) with normal or corrected-to-normal visual acuity and normal color vision participated in sessions lasting 30-60 minutes. Participants received extra credit in undergraduate courses as compensation. Participants gave informed consent, and the protocol was approved by the Johns Hopkins Homewood Institutional Review Board.

Apparatus. Images were displayed on a Dell Pentium 3.6 GHz computer with a Dell 1907 FP monitor. Stimulus presentation and data analysis were performed using programs written in Matlab (Mathworks) and using PsychToolbox software [42]. The screen had a refresh rate of 75 Hz, and the resolution of the screen was 1280 x 1024 pixels.

Stimuli. On each trial, four English letters appeared surrounding a fixation cross which appeared at the center of the screen. The fixation cross subtended .55 degrees of visual angle. These letters were randomly selected to appear among 140 possible locations within an imaginary square surrounding fixation. The distance between fixation and the edge of this square subtended 6.2 degrees of visual angle. Each letter subtended a visual angle of approximately .76 degrees.

On every trial, one of either a capital "B" or "F" was randomly selected to appear as the target letter. Additionally, a lowercase "b" or "f" distractor letter was selected to appear. This lowercase "b" or "f" was randomly selected to be *compatible* with the target letter, meaning that it shared the identity of the uppercase "B" or "F", on 50% of all trials. On the remaining trials, the lowercase "b" or "f" was *incompatible,* meaning that it did not share the identity of the uppercase "B" or "F". The remaining two letters were a "k" and an "x" on every trial, one of which was randomly chosen to be uppercase. Each of the four letters was randomly selected without replacement to appear in one of four colors (blue, red, green, and yellow).

Prior to each trial, a cue appeared at the center of the screen. The cue began as a gray square border. The border appeared .38 degrees of visual angle from fixation, and subtended .1 degrees of visual angle themselves. On a randomly selected 50% of all trials, the cue was a "neutral" cue, meaning each pixel in the border was randomly selected to appear in one of the four possible target colors. On the remaining trials, the cue was an "ignore" cue, and instructed participants to ignore a specific color. On these "ignore" trials, the border turned into a solid color (one of the four possible target colors).

Design and Procedure. Each trial began with the presentation of a gray border at the center of the screen surrounding fixation for 500 ms. Following this, the cue appeared (meaning the color of the border changed) for 1500 ms. On "Ignore" cued trials, the letter appearing in the to-be-ignored color was always the distractor "b" or "f". Participants were explicitly told that these cues meant the target letter would be guaranteed not to appear in this color on the upcoming trial, and these cues were 100% valid. "Neutral" cues gave the participants no additional information about the color of any target or distractor items on the upcoming trial. Following cue presentation, the four letters appeared on the screen, and remained until participants responded (Figure 1). Participants were told to determine whether a capital "B" or "F" was present. They indicated their response by pressing the "z" key if a "B" was present, and the "/" key if an "F" was present. They were instructed to respond as quickly and accurately as possible. Following their response, there was a 500 ms. intertrial interval during which a blank black screen was presented.

Participants began the experiment with 36 training trials (without any cues), and were given feedback after each practice trial. After this initial training phase, there were 10 blocks of 50 trials each, the first of which was considered a practice block. After each block, participants were given an opportunity for a brief rest.

Results and discussion

All responses faster than 100 ms or slower than 2000 ms were removed from all analyses. This resulted in the elimination of 0.3% of all trials. Additionally, all error trials were removed from response time analyses, resulting in the removal of 3 % of all remaining trials. One participant was removed from all analyses for high error rate (> 3 standard deviations above the mean).

We conducted a 2x2 ANOVA with factors of cue type (ignore vs. neutral) and compatibility (compatible vs. incompatible) on response time. We found no benefit to the ignoring cues; instead, participants were slightly slower to respond on ignore trials (726 ms) compared to neutral trials (716 ms), though this did not approach significance, $F(1,14) < 1$. (Figure 2). Additionally, errors were more frequent on cued trials (3.5%) compared to neutral trials (2.5%), an effect that approached significance, $F(1,14) = 4.15$, $p = .06$.

Responses were faster on compatible trials (694 ms) than on incompatible trials (747ms), $F(1,14) = 29.49$, $p < .001$. There was no effect of compatibility on accuracy, $F(1,14) < 1$. There was no interaction for either response time, $F(1,14) = 2.96$, $p > .1$, or accuracy, $F(1,14) = 2.41$, $p > .1$.

These results suggest that feature-based inhibition is not possible in visual search. Instead, when observers attempted to ignore a specific color, they appeared to conduct a less efficient (rather than more efficient) search. This occurred despite the fact that the cues were always valid, meaning that the number of possible target items was reduced from four to three. This attempt at feature-based inhibition had no significant effect on the processing of the to-be-ignored letter.

In the previous experiment, we used symbolic color cues to instruct the participant to ignore a particular color. It is possible that these cues primed a response to that color at a lower-level sensory processing stage, thus preventing them from successfully inhibiting that color [43]. Additionally, it's possible that by presenting a new cue prior to each trial, participants were accruing switch costs [44] that obscured any inhibitory effects. In Experiment 2, we replaced the color cues with word cues instructing the participant to ignore a particular color (or word cues indicating a neutral trial).

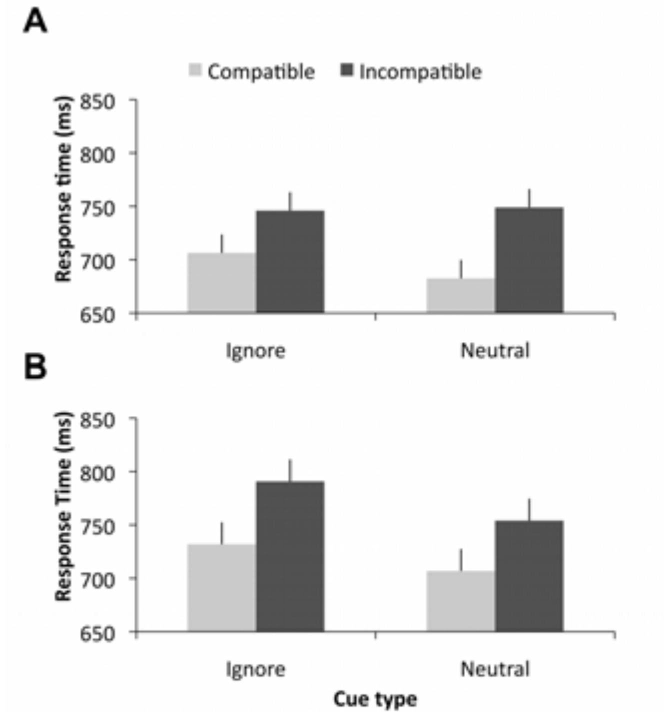

Fig. 2: a) Results from Experiment 1. Responses to ignore cued trials were not faster than responses to neutral trials. Responses were numerically slower on ignore trials, though this difference did not approach significance. These data do not support a "template for rejection"; instead, they suggest that observers are unable to use an explicit feature-based inhibition strategy. b) Results from Experiment 2. Responses were significantly slower on ignore trials compared to neutral trials, providing converging evidence that an explicit feature-based inhibition strategy may not be useful in visual search.

Additionally, we made each cue valid for the subsequent eight trials, thereby minimizing the frequency of switching top-down control settings by creating "mini-blocks."

III. Experiment 2

Methods

Sixteen Johns Hopkins University undergraduate students (mean age = 19.6 years; 4 male) with normal or corrected-to-normal visual acuity and normal color vision participated in sessions lasting 30-60 minutes. Participants received extra credit in undergraduate courses as compensation. Participants gave informed consent, and the protocol was approved by the Johns Hopkins Homewood Institutional Review Board.

Apparatus and stimuli were similar to Experiment 1. Prior to one in every eight trials, a word cue appeared. On a random 50% of all trials, this cue instructed participants to ignore a particular letter ("Ignore [color]"). On the remaining trials, the word "neutral" appeared. Participants were instructed that these cues would apply (and be valid) for eight consecutive trials. In other words, if the cue instructed them to "Ignore red," the target would not appear in red on the subsequent eight trials. These cues subtended approximately 8.4 degrees of visual angle horizontally and approximately .96 degrees of visual angle vertically. These cues were presented for one second, followed by one second of fixation. Following this, the four letters appeared on the screen.

Participants again started with 36 practice trials with feedback. Following this, they received eight blocks of 64 trials each. The first block was considered practice.

Results

All responses faster than 100 ms or slower than 2000 ms were removed from all analyses. This resulted in the elimination of 0.5% of all trials. Additionally, all error trials were removed from response time analyses, resulting in the removal of 2.6% of all remaining trials.

We conducted a 2x2 ANOVA on cue type and compatibility. There was a main effect of cue type on response time, with participants responding more *slowly* on ignore trials (761 ms) compared to neutral trials (730 ms), $F(1,15) = 6.78$, $p < .05$. There was no main effect of cue type on accuracy, $F(1,15) = 2.77$, $p > .1$, though the trend was in the same direction as Experiment 1, with more errors on ignore trials (3.2%) compared to neutral trials (2.2%). Additionally, participants responded more quickly on compatible trials (719 ms) compared to incompatible trials (772 ms), $F(1,15) = 22.44$, $p < .001$. Unlike Experiment 1, there was an effect of compatibility on accuracy as well, with a higher error rate on incompatible trials (3.6%) compared to compatible trials (1.8%), $F(1,15) = 10.51$, $p < .01$. There was no significant interaction for response time or accuracy, Fs < 1.

To determine whether there was any change in the effect of cue type within each mini-block of eight trials, we split trials into the first half of the mini-block (first four trials following the cue) and the second half (last four trials following the cue). We conducted a 2x2x2 ANOVA with factors of block half, cue type, and compatibility on response time. Critically, while we still found a main effect of cue type, $F(1,15) = 6.1$, $p < 05$, there was no interaction between block and cue type, $F(1,15) < 1$, nor was there a three-way interaction, $F(1,15) < 1$. This suggests that the cost of the ignoring cue remained consistent throughout each mini-block.

These data replicate the results from Experiment 1. In this task, participants attempting to engage an explicit feature-based inhibition mechanism find the target more *slowly* than when no such mechanism is engaged.

IV. Discussion

In both experiments, we found a consistent cost to cueing the color of a nontarget item on the upcoming trial. This is directly in conflict with the notion of a "template for rejection" [23]. Instead, our results suggest that an explicit feature-based inhibition strategy is not an efficient approach to visual search. This is true even if an observer is given multiple consecutive trials to inhibit the same color. Interestingly, the cues did not alter the compatibility effects, suggesting that the cue to ignore a specific color did not increase or decrease the level of processing devoted to the letter appearing in the to-be-ignored color.

One plausible explanation for these results is that when cued to ignore a specific color, participants instead immediately select an item matching that color. This would explain why search was less efficient on ignore trials compared to neutral trials, rather than equivalent between the two types. Selection of the to-be-ignored letter could be a consequence of participants rehearsing the to-be-ignored color in working memory, and thus involuntarily directing attention towards this item. Alternatively, participants could be engaging in a strategy of purposefully seeking out the to-be-ignored item in order to apply inhibition to that item. The latter strategy fits with the results of Woodman & Luck [23], who found that participants were faster to respond on ignore trials if an item appeared in the to-be-ignored color. According to our account, this could be explained by the fact that they sought out the to-be-ignored item, resulting in slower response times when no to-be-ignored item was present.

To test the prediction that participants were initially selecting the to-be-ignored item, we are currently conducting a study using probe dots [45] to probe the focus of attention during observers' search. If observers are selecting the to-be-ignored item, they should be faster to respond to probes appearing at the location of that item compared to the location of other items early in the search process. Our data so far support our prediction; when probe dots are presented early in the search process, participants respond more quickly to a probe dot appearing at the distractor location compared to probe dots appearing at other locations (453 ms vs. 485 ms, $p < .05$).

This mechanism for inhibition, which is inefficient in our task, may be useful in certain situations. For example, it may be that after participants seek out and select one item matching the to-be-ignored color, inhibition spreads to all items matching this color. This would result in more efficient search following ignore cues with larger displays. This spread of inhibition is consistent with results in the visual marking literature [46]-[49].

Additional research is needed to understand the role of explicit feature-based inhibition in visual search during different types of search tasks. However, these results suggest that explicit feature-based inhibition may not be an efficient strategy in visual search. Instead, observers attempting to explicitly inhibit nontarget features end up selecting items matching those features, thus delaying selection of the target.

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