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Dissociations and interactions between attention guidance from negative templates maintained in visual working memory and long-term memory

Aditya Prakash [*], Andrew Hollingworth

Department of Psychological and Brain Sciences, The University of Iowa, United States of America

A R T I C L E I N F O

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A B S T R A C T

Visual attention can be guided away from objects known to be irrelevant to the current task. These negative templates (specifying distractor features) can be maintained in visual working memory (VWM) and in long-term memory (LTM). LTM-based negative templates allow for direct suppression of to-be-avoided feature values, observable in the earliest selective operations during search (i.e., implemented proactively). However, there is mixed evidence regarding whether VWM-based negative templates are likewise implemented directly and proactively. Here, we contrasted LTM- and VWM-based negative guidance within the same visual search experiment. There were two broad lines of findings. First, the two sources of guidance dissociated on several measures of oculomotor orienting during visual search, including: a) the polarity of initial guidance, b) the latency of initial orienting, and c) the pattern of guidance across an extended search trial. We conclude that the two forms of guidance are implemented by fundamentally different mechanisms. Second, we created conditions in which the two forms of guidance were potentially operational within the same trial, testing their interaction. Both were expressed within a trial when they specified different sets of objects. However, VWM-based biases dominated when the two biases were placed in competition, indicating that online attentional sets tend to overshadow learned biases in the computation of priority.

Goal-directed behavior depends on attending efficiently to those portions of a complex environment that are currently task relevant (Land & Hayhoe, 2001). This often requires visual search to localize appropriate objects. Search can be a laborious process when there is little to guide attention, but it can be made more efficient when the visual properties of task-relevant objects are known, allowing the visual system to prioritize plausible candidate items based on their appearance (e.g., Wolfe, 1994). Such guidance is typically conceptualized as the application of a *search template*, a representation of the target's visual features that interacts with perceptual processing to modulate the salience/priority of objects as candidates for the recruitment of attention and gaze. Although search templates are usually positive, indicating target properties, they can also be negative, indicating the properties of items that should be avoided (Carlisle, 2023; Hollingworth, 2022). When given a negative cue, participants will often make their search more efficient by avoiding template-matching objects, thereby reducing the number of items that need to be attended before the target can be found (Beck et al., 2018; Carlisle & Nitka, 2019; Conci et al., 2019; Hollingworth, 2022; Zhang & Carlisle, 2023).

Both positive and negative search templates depend on memory for relevant attributes. They can be supported by visual working memory (VWM), when the properties of relevant objects frequently change. They can also be supported by long-term memory (LTM), when these properties remain constant across a history of searching similar arrays (Carlisle et al., 2011). Guidance by templates can be further distinguished by whether the guidance is direct versus indirect and whether it is proactive versus reactive. By *direct*, we mean that selection is implemented by modulating priority on the cued dimension in accordance with the information provided by the cue. For example, if the color *red* is cued, perceptual stimuli would be filtered on the dimension of color to increase (for a positive cue) or decrease (for a negative cue) the priority of red items relative to non-red items (Bundesen, 1990; Desimone & Duncan, 1995; Wolfe, 1994). An example of *indirect* guidance would be to re-code a color cue into a spatial template by marking, and then prioritizing/deprioritizing, the locations of red items, without necessarily modulating priority directly through the dimension of color. By *proactive*, we mean that the parameters of guidance are established before the appearance of the search stimulus, so that filtering and

* Corresponding author.at: Department of Psychological and Brain Sciences, The University of Iowa, Iowa City, IA 52240, United States of America.
E-mail address: adityavaradarajan-prakash@uiowa.edu (A. Prakash).

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selection can occur, theoretically, as early as the first sweep of sensory processing following stimulus onset. A *reactive* form of control occurs if the parameters of guidance are not established until after the appearance of the search stimulus. That is, under reactive control the parameter values implementing guidance cannot be pre-configured and must be established from observed properties of the search stimulus.[1]

The two factors of direct/indirect and proactive/reactive guidance are often functionally related. Indirect forms of guidance will often be reactive. For example, if one knows that the target will be red, but one does not know the upcoming locations of the red items, translation to a spatial template cannot be implemented until after the array has appeared and the locations of the red items become perceptually available. Similarly, direct forms of guidance will tend to support proactive control, given that knowledge of the relevant value will allow one to pre-configure guidance parameters. However, these functional relationships need not always apply. For example, if one *does* know the upcoming locations of red items, a red cue could be translated into a spatial template (indirect), and the parameters of spatial prioritization could be configured, before the appearance of the search stimulus (proactive) (see, e.g., Han & Kim, 2009, Experiment 4; Moher & Egeth, 2012, Experiment 4). Nevertheless, direct control will generally allow for proactive selection biases to be applied at the very beginning of a search episode, whereas indirect control will typically be delayed by the need to re-configure guidance parameters based on the observed properties of the search stimulus.

There are several methods for assessing whether direct, proactive control has been implemented. The first is to examine whether early oculomotor selection, such as the first saccade during search, reflects cue-consistent biases, since the timing of this orienting behavior would provide minimal opportunity to sample the search array and reconfigure the template (e.g., Beck et al., 2018; Gaspelin et al., 2017). The second method is to interrupt visual search early in the trial with a briefly presented probe consisting of one or more to-be-reported stimuli (an *intra-search* probe), with the logic that differential performance as a function of probe-item location reflects the early spatial locus of attention. In this task, letters appear at all search locations, and participants report as many letters as they can. (e.g., Gaspelin et al., 2015; Hauck et al., 2024). The third method is to use a probe stimulus that is presented before or instead of the search array to characterize the pre-configuration of attentional control settings (a *pre-search* probe). If perceptual processing of the probe value is modulated in accordance with the information contained in the cue, one can infer that perceptual biases were established directly and before search array onset (e.g., Addleman & Störmer, 2022).

The three approaches have different strengths and limitations. The eye movement method provides a transparent measure of the behavior of interest (selection during visual search), and it can track changes in guidance across the course of a search event, since gaze position is a continuous measure of selection rather than a discrete sample. However, eye tracking may not be sensitive to subtle shifts of covert attention that do not lead to an overt shift of gaze. The intra-search probe method assesses the spatial locus of attention during the behavior of interest. However, the locus of spatial attention is assessed only in discrete samples; the time at which the sample is obtained might not correspond to the critical point during search when a certain guidance operation is functional. In addition, the probe stimuli are not typically masked, which could allow for shifts of attention after probe offset (i.e., within iconic memory). The pre-search probe method has the capability to characterize perceptual biases before search commences. For example, if perceptual sensitivity to a probe that matches a cued color value is altered, one can infer that perceptual stimuli were filtered directly on the dimension of color and that the parameters of the filtering operation were established before search stimulus onset (e.g., Addleman & Störmer, 2022). However, biases observed in the pre-search probe method are not typically obtained within the behavior of interest (visual search) or for the stimuli of interest (multiple items that compete for selection) and thus inferences about the functional role of probe-assessed biases in visual search itself are necessarily indirect. Given these strengths and limitations, the most persuasive evidence is obtained if different approaches generate complementary results.

Current research converges to indicate that positive cues tend to generate guidance that is both direct and proactive. Positive cues lead to a higher probability that the first object fixated matches the cued value rather than a distractor value (Beck et al., 2018; Kugler et al., 2015). They increase the probability of letter report at cue-consistent locations early in the search trial in the intra-search probe method (Zhang et al., 2020). Finally, they increase sensitivity to the cued feature value in a pre-search probe task (Addleman & Störmer, 2022; Folk et al., 1992). This mechanism of direct, proactive enhancement applies both to positive templates in VWM, where the target-defining feature varies from trial to trial (Addleman & Störmer, 2022; Beck et al., 2018; Zhang et al., 2020), and to positive templates in LTM, where the target-defining feature is consistent across trials (Chang & Egeth, 2019; Folk et al., 1992; Kugler et al., 2015).

The critical question motivating the present study is whether *negative* cues also generate guidance that is direct and proactive. That is, it is well established that people can directly pre-configure control parameters to increase the priority of items that match a positive cue. Can people also directly pre-configure control parameters to effectively *decrease* the relative priority of items that match a negative cue? Direct, proactive guidance from negative cues would be observed as 1) a reduction in the probability that the first selective operations within a trial were directed to cue-matching objects (as assessed by the early saccade and intra-search probe methods) and/or 2) a reduction in sensitivity to cue-matching items, relative to a neutral baseline, in a pre-search probe task.

Current research provides provocative evidence that this may depend on whether the template is maintained in VWM or in LTM. Direct, proactive guidance from negative templates in LTM has been observed in several studies. Stilwell and Vecera (2022) found that after a training period in which one color was always associated with distractors, there was a reliable reduction in the probability that items matching this color were fixated at the very beginning of the search trial. Similarly, work utilizing the additional singleton paradigm has shown that repeated exposure to the same singleton distractor color leads to a reduced probability that first saccades are directed to this item (Gaspelin et al., 2017; Stilwell & Gaspelin, 2021). Converging evidence was obtained by Hauck et al. (2024; see also Chang & Egeth, 2019; Gaspelin & Luck, 2015) in an intra-search probe task: early probe-letter report was reduced at locations containing feature values with a history of being associated with distractors. Finally, in a contingent-capture variant of the pre-search-probe method, Kim and Cho (2024) found that a pre-cue matching a known distractor color recruited attention less robustly than did a pre-cue presented in a neutral color. A possible cause of these examples of learned suppression is decreased perceptual response to frequently-selected-against stimulus values (sometimes termed *habituation*), producing lower-than-chance probability of attending to corresponding items (Adam & Serences, 2021; Chelazzi et al., 2019; Gaspelin et al., 2025).

[1] Our use of the term “proactive control” aligns closely with previous studies. However, our use of “reactive control” differs from the usage of some other researchers. “Reactive guidance” or “reactive control” has sometimes been used specifically in the context of initial capture by a salient distractor: Control is implemented as a reaction to the state of being captured, requiring suppression (Geng, 2014; Liesefeld et al., 2024). We use the term more broadly to apply to any situation where the parameter values of the guidance operation are established from the observed properties of the search stimulus itself and are not pre-configured. This brings the term into closer correspondence with the term “proactive,” with similar scope, so that both terms are aligned with common usage: guidance parameters are established either before (proactive) or after (reactive) the appearance of the relevant search stimulus.

On the other hand, evidence of direct, proactive guidance has not been observed consistently for negative cues maintained in VWM. This has been assessed with all three of the main methods available in literature. Using the early-saccade method, Beck et al. (2018) found that the probability of fixating negative-cue-matching objects at the onset of a search trial was actually *increased* relative to neutral items. Specifically, participants first saw a color cue indicating a color that would not contain the target (negative cue). This was followed by a search array with items drawn in several colors. The first object fixated at the onset of the search trial was reliably more likely to be a negatively cued color than an uncued color: The polarity of guidance at the onset of search was not consistent with direct, proactive suppression, instead indicating that negative cues led to the initial enhancement of cue-matching items. In a more recent study, however, Zhang and Carlisle (2023) did not replicate the finding of initial oculomotor capture by negative-cue-matching stimuli, but they also found no initial avoidance of those stimuli.

The search-probe method has also been applied to the question of VWM-based guidance from negative cues, in three studies (Hauck et al., 2024; Moher & Egeth, 2012; Zhang et al., 2020). In Zhang et al. (2020), the report of letters at the locations of negatively cued items was not reduced at an array-probe SOA of 25 ms but was reduced at SOAs of 100 ms and longer. Note, however, that interpretation of these data is limited by the fact that the stimuli drawn in the two colors (the negatively cued color and the possible target color) were spatially segregated by hemifield, potentially allowing for efficient translation into a spatial template (Beck & Hollingworth, 2015). In Hauck et al. (2024), the colored items in the search array were spatially intermixed. At an array-probe SOA of 100 ms, there was no evidence of suppression for negatively cued colors. In both experiments, there was also no evidence that attention was initially captured by negative-cue-matching stimuli. And finally, in both experiments, positive cues led to enhanced letter report at the same SOAs at which negative cues showed no suppression. In a variant of the intra-search probe paradigm, Moher and Egeth (2012) presented a dot probe at different latencies following the appearance of the search array. At short SOAs, dot detection RT was lower when the dot appeared in the location of a negatively cued item relative to a neutral item, a result similar to the initial enhancement of items matching a negative cue observed by Beck et al. (2018).

Finally, Addleman and Störmer (2022) examined the same question using the pre-search probe method. A negative color cue was presented, followed by a search array of colored items. On a subset of trials, a single probe stimulus (colored or grayscale) was briefly presented instead of the usual search array. Sensitivity to the presence of color in the probe increased, rather than deceased, for probe stimuli that matched the negative cue color.[2] Thus, the results converge with other studies failing to find proactive suppression based on negative cues in VWM, and they converge with the Beck et al. (2018) and Moher and Egeth (2012) findings of initial enhancement of negative-cue-matching values.

In sum, studies examining negative-cue guidance suggest that there may be a difference in the initial polarity of attentional guidance between negative templates maintained in VWM and negative templates maintained in LTM. If this is true, it would suggest an important dissociation between the mechanisms by which different memory systems implement suppression of known distractor values. However, evidence that VWM-based guidance from negative cues generates early enhancement, rather than suppression, has not always been observed (Hauck et al., 2024; Zhang et al., 2020; Zhang & Carlisle, 2023). Moreover, the one study that directly compared negative-cue guidance from LTM and VWM in a single paradigm found no VWM-based enhancement effect (Hauck et al., 2024). Consequently, the matter of the initial polarity of guidance from VWM-based negative templates requires resolution, ideally in a paradigm in which one can simultaneously observe initial guidance from negative cue information maintained in LTM.

1. Present study

In the present study, we implemented such a paradigm using the early saccade method. The basic approach was to characterize eye movement behavior with respect to search-array items that either matched a consistent, learned distractor value (LTM guidance) or a trial-specific negative cue value (VWM guidance). The structure of the experiment was as follows, illustrated in Fig. 1. In a training session, participants completed a visual search task in which one color was always associated with distractors, termed the *consistent distractor color* (CDC). In a test session, trial-by-trial negative cues were introduced while continuing to maintain the LTM-based contingency (i.e., the color that never contained the target in the training session also never contained the target in the test session). This allowed us to examine, for trials intermixed within the same experimental session, oculomotor orienting driven by negative cue information maintained in LTM versus in VWM.

We had two main goals. The first was to test whether negative-cue guidance from LTM and VWM depend on dissociable mechanisms. This was conducted both for the polarity of initial guidance and for the extended pattern of guidance across a trial. To examine initial guidance, we probed the probability that the first object fixated on a trial matched the template value maintained in VWM or in LTM. For long-term learning, this was assessed in the training session and on neutral-cue trials of the test session by examining the probability that the first object fixated during search was the CDC. We predicted that this probability would be reliably lower than baseline, indicating direct, proactive suppression of the learned distractor color (e.g., Gaspelin et al., 2017; Stilwell & Vecera, 2022). For VWM-based guidance, we examined the probability that the first object fixated matched the trial-by-trial negative cue color. We predicted that this probability would be reliably higher than baseline (Beck et al., 2018), indicating that VWM maintenance of negative cue values necessarily generates initial enhancement of matching items.

To characterize the longer-scale evolution of guidance across a trial, we included a subset of trials in the test session in which the set size was increased from three items to 30 items. For VWM-based guidance, we predicted a pattern of early attraction toward negative-cue-matching objects, followed by later avoidance of those objects (Beck et al., 2018; Moher & Egeth, 2012). For LTM-based guidance, we probed fixation probabilities across neutral trials of the test session to examine whether avoidance would be expressed consistently across the entire duration of an extended search. Qualitative difference in the pattern of guidance across extended search would provide converging evidence that negative guidance from VWM and LTM depend on distinct mechanisms.

Our second major goal was to test how the forms of guidance are implemented when they specify different objects in a search array and when they specify the same object. That is, do the two forms of guidance jointly contribute to establish the priority of different items, and when they specify the same item, how are they combined? On the former topic, we examined whether VWM- and LTM-based negative templates can guide attention simultaneously. This was tested on Negative-cue trials of the test session. On such trials, the array contained a negatively cued color, the CDC, and a neutral color. We examined whether both biases would be expressed, relative to the neutral color, when both types of guidance were potentially available.

On the latter topic, we examined the interaction between VWM and LTM biases when both specified the same object. To do this, we included a subset of negative-cue trials in the test session where the negative-cue value was also the CDC. In a similar manipulation, Stilwell and Vecera (2019) found a search RT advantage when some array items matched a

[2] In Experiment 2 of Addleman and Störmer (2022), this effect approached the traditional (i.e., $p < .05$) criterion for statistical significance, with $p = .104$. In a replication experiment, the effect surpassed that threshold, with $p = .001$.

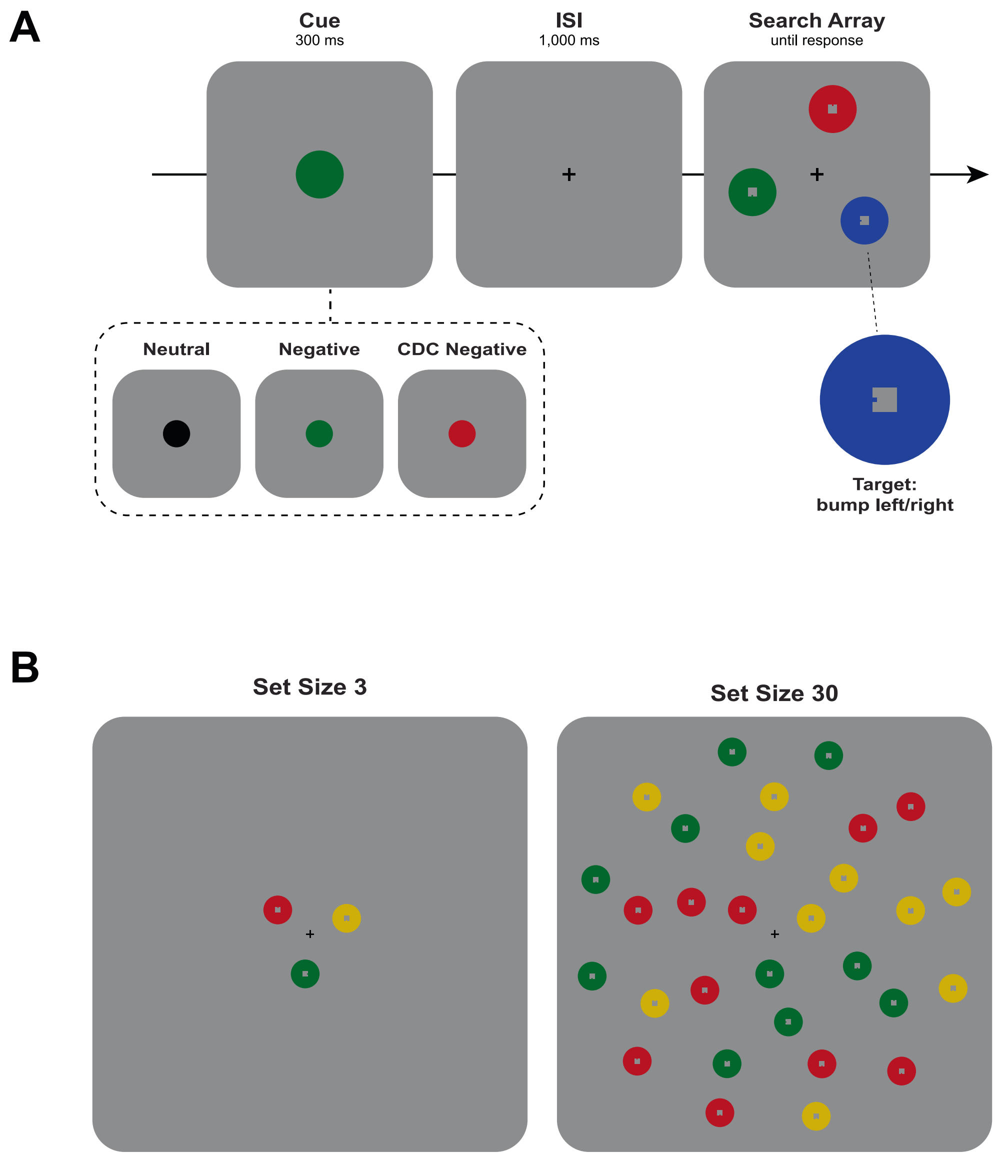

Fig. 1. Overview of method. A) On each trial of the experiment, participants first saw a cue for 300 ms that was either neutral (black) or negative (a color that would not contain the target attribute). After a 1000-ms ISI, a search array was presented consisting of colored disks. One disk had an internal "bump" on the left or right (target). The others had bumps on the top or bottom (distractors). For each participant, one color was chosen as the experiment-wide consistent distractor color (CDC). In the examples in this figure, the CDC is red. This color appeared in every search array but never contained the target attribute. In a Training Session, all trials had neutral cues. In the Main Session, the cue could either be neutral, negative (one of the non-CDC colors) or CDC negative (the CDC). B) In the Training Session, all trials were set size three. In the Main Session, set size was either three or 30. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

learned distractor color (indicating successful avoidance with reduction in effective set size), but this advantage was reversed when the distractor value was explicitly cued at the beginning of the trial (indicating possible attraction toward the distractor color when it was maintained in VWM despite the fact that it had a history of never containing the target). If these differences in overall RT reflected, at least in part, differences in the polarity of initial guidance from VWM and LTM, then we expected that, in our study, the probability of fixating the CDC would be reliably higher than baseline when it was explicitly cued as to-be-ignored. That is, guidance based on VWM would outcompete guidance based on LTM (Berggren et al., 2020; Hollingworth & Kershner, 2025).

Examining how different sources of bias are combined is central to understanding how priority is computed within an integrative priority map (Anderson et al., 2021; Awh et al., 2012; Theeuwes, 2019; Wolfe, 2021). In these models, multiple sources of bias—such as physical salience, current goals, and selection history—are integrated within a composite representation of relative priority, which controls the spatial allocation of covert attention and gaze. Although a great deal of research has been devoted to understanding how physical salience and goal-directed biases are integrated (for a review, see Luck et al., 2021), there are other key dimensions that distinguish guidance mechanisms, and these have often received little study. Our experiments probed the combination of guidance from VWM and guidance from LTM, with the LTM bias consisting of a type of selection history: learned distractor rejection. Thus, the work can inform how online template representations (maintained in VWM) interact with, and potentially compete with, biases generated from long-term selection history.

2. Method

2.1. Participants

The choice on N was based on the finding of initial attraction toward negative-cue-matching items in Beck et al. (2018). In that study, the within-participant contrast between first object fixation probability for matching versus non-matching objects produced an effect size of $d_z = 1.06$, which would require 10 participants to achieve 80% power for $\alpha = 0.05$, calculated using G*Power. Conservatively, we chose an N of 24. The participants (18–30 years old; 15 female, eight male, one non-binary) were recruited from the University of Iowa's SONA subject pool and were compensated for their time with course credit. All reported normal or corrected-to-normal vision. All human participant procedures were approved by the University of Iowa Institutional Review Board.

2.2. Apparatus

Stimuli were presented on an LCD monitor (resolution: 1920 × 1080 pixels) with a refresh rate of 100 Hz at a viewing distance of 77 cm, maintained by a chin and forehead rest. Stimulus presentation was limited to a 1280 × 960 pixel central region of the screen. The participant's right eye was tracked using an EyeLink 1000 plus eye tracker, with a sampling rate of 1000 Hz. Responses were collected using a USB button box. The experiment was controlled by *E*-prime 3.0 software (Schneider et al., 2002).

2.3. Stimuli

All stimuli were presented against a uniform gray background (RGB: 148,148,148). Search arrays consisted of either three or 30 colored disks. Each disk was 1.26 degrees visual angle (dva) in diameter. At the center of each disk was a square region (0.24 dva × 0.24 dva) drawn in the background color. Within the square was 0.08 dva × 0.08 dva "bump" that was located on one edge of the square. One object in the search array, the target, had a bump on the left or right (randomly chosen). All other objects had a bump on the top or bottom (also selected randomly for each object). The bump feature was very small for two reasons: 1) to ensure that target detection required object fixation and 2) to ensure that participants could not guide their selection of candidate objects based on the presence or absence of the target feature. For the three-item arrays, the items were placed around a virtual circle (3.54 dva diameter). The angular position of the first item was selected randomly, with each additional item offset by 120° around the virtual circle. For the set-size 30 trials, the central, 3-item ring was surrounded by three additional concentric rings (at diameters of 7.86 dva, 12.16 dva, and 16.42 dva) containing six, nine, and 12 items respectively. These were constructed in the same manner as the 3-item ring with the necessary modifications to inter-item separation (60°, 40°, and 30°, respectively). The target item was selected randomly from among the 30 items. For the cue display, a single disk was presented centrally and was the same size as the search stimuli. There were four, highly discriminable color values: Red (RGB: 191,0,0), blue (RGB: 0,0,220), green (RGB: 0,128,0), and yellow (RGB: 192,192,0).

2.4. Design

At the beginning of each experiment, one of the four possible stimulus colors was selected randomly as the CDC for each participant. This color appeared on every trial yet never contained the target bump. The other three colors were equally likely to be the target.

A *training session* was used to establish learned distractor rejection for the CDC. The session consisted of 80 search trials, all of which used three-item arrays. The "cue" was always black (i.e., neutral). Because it provided no information, participants were instructed before the training session that the black disk simply indicated that the trial was about to begin. In each three-item array, one item was always the CDC. The colors of the other two items were randomly chosen from the remaining three colors, and one of these two items was randomly selected as the target.

Participants then completed a *test session* of 288 trials. Before starting the test session, participants were informed that the disk appearing before the search array would sometimes be colored, and that search array items drawn in this color would never contain the target. They were also informed that a subset of trials would have a much larger number of items in the search display (30) and were given one practice trial of set size 30. The 288 experimental trials were divided between set size three (192 trials) and set size 30 (96 trials). The set size 30 trials allowed us to examine the evolution of guidance across extended search; they also incentivized participants to maintain and use the negative cue, as participants could eliminate 10 items from search on set size 30 trials. Within each set size, the trials were evenly divided into three conditions. The *Neutral* condition matched the training session. The cue was black. One third of the items were drawn in the CDC and one third each in two colors selected randomly from the remaining color alternatives. The target was randomly selected from the non-CDC items. In the *Negative Cue* condition, one cue color was selected randomly from the non-CDC colors. One third of the array items had the cued color, one third the CDC, and the final third a color drawn randomly from the remaining color alternatives (one of which was randomly selected to contain the target attribute). Finally in the *Negative CDC* condition, the CDC color was negatively cued. The array composition was the same as in the Neutral condition: one-third CDC and one third each in two of the remaining colors. Note that, just as in the training session, every trial contained the CDC, but this color was never the target color. Trials in the two set sizes and three conditions were randomly intermixed.

2.5. Procedure

Upon arriving for the experimental session and providing informed consent, participants were given oral and written instructions. Next, the eye tracker was calibrated using a 9-point calibration routine. The eye tracker was re-calibrated at the beginning of each of the main sessions and within a session whenever estimated gaze position at the beginning of a trial deviated from the central fixation point by more than approximately 0.5 dva.

Each search trial was initiated by the experimenter after validating central fixation. There was a 300-ms blank screen, followed by the cue display for 300 ms, a 1000-ms blank ISI, and the search array. Participants were instructed to find the item with a bump on the left or right and report the bump location with a left or right button press, respectively. They were instructed to perform this task as quickly and as accurately as possible. The search array remained visible until response. Following an incorrect response, the word "Incorrect" was presented in red text for 2000 ms. No feedback was provided following correct responses. Finally, there was a 300-ms blank, intertrial ISI. Participants completed the 80-trial training session, followed by the 288-trial test session.

After the end of the main experiment, participants completed an "awareness" test. This was included to establish whether there was explicit knowledge of the identity of the CDC. Participants were first asked whether they noticed if one color was less likely to contain the target than the other colors, reporting "yes" or "no" with a corresponding button press. Specifically, participants were asked, "Were you aware that any color of disk was less likely to contain the target bump than other colors?" Independently of their response to this question, participants then completed a four-alternative forced choice task. The four possible colored disks were presented in a row on the screen. Participants indicated which color they thought had been least likely to contain the target bump by pressing the corresponding key on the button box.

2.6. Data analysis

Search accuracy, reaction time, and gaze position during each trial were recorded. Mean accuracy in the training session was 98.5%. Mean accuracy in the test session was 98.6% and did not differ as a function of condition (Neutral = 99.0%, Negative = 98.3%, and Negative CDC = 98.3%; $F(2,46) = 1.043$, $p = .36$, adj $\eta_p^2 = 0.043$) or set size, $F(2,23) = 0.422$, $p = .52$, adj $\eta_p^2 = 0.018$.[3] There was also no reliable interaction, $F(2,46) = 1.152$, $p = .33$, adj $\eta_p^2 = 0.048$. Error trials were eliminated from analysis, leading to the elimination of 1.44% of trials. We also eliminated trials if the latency of the first entry of the eyes into an object region was less than 90 ms (too short to have been driven by the content of the array) or greater than 1000 ms (outside the typical range of saccade latency and likely to reflect strategic delay of the first saccade). Saccade latency trimming led to the elimination of 0.72% of the remaining data.

Saccades were defined by a combined velocity (>30 dva/s) and acceleration (>8000 dva/s^2) threshold. Regions of interest were defined around each of the search array objects (1.77 dva diameter).

2.7. Transparency and openness

The study complies with the JARS/MARS reporting framework. We report how we determined our sample size, all data exclusions (if any), all manipulations, and all measures in the study. The study was not preregistered. The study materials and data are available upon request.

3. Results

Our primary analyses were conducted over the eye-movement data. To examine the initial expression of the negative template, our first set of analyses characterized oculomotor orienting behavior with respect to the first object fixated in the array. The second set of analyses characterized overall search behavior and the evolution of guidance across an extended trial, focusing primarily on set size 30. The third set of analyses examined whether negative templates led to search time benefits by examining the elapsed time to fixation of the target object as a function of cue condition. The fourth set of analyses concerned whether later avoidance of cue-matching items was contingent on initial fixation of an item with that color (i.e., test of "search and destroy"). The final set of analyses were conducted over the awareness test results.

3.1. Initial orienting behavior

3.1.1. First object fixation probability

This analysis concerned the first object fixated in the array. Specifically, we determined the probability that the first object fixated in the array belonged to each of three analytic categories: the CDC, the negatively cued color, or a neutral color.[4] The primary data were obtained from the test session (288 trials). For the sake of completeness, we first report data from the 80 trials of the training session, although these results are limited by the fact that in early stages of this session, participants would not have yet learned the relation between CDC and target probability. The results from the test session are displayed in Fig. 2.

3.1.1.1. Training session. The purpose of the training session was to establish long-term, learned distractor rejection for the CDC. The trials in this session were all Neutral condition, set-size three. For the first-object-fixated analysis, there were two neutral colors in each array (one of which contained the target attribute) and one CDC (which never contained the target attribute). First-object-fixation probability was reliably lower for the CDC (M = 0.307, SD = 0.051) than for the neutral items (M = 0.347, SD = 0.026), $t(23) = -2.54$, $p = .018$, $d_z = -0.52$. Thus, we obtained evidence that during the training session, participants developed proactive avoidance of the CDC.

3.1.1.2. Test session. The test session implemented the complete design, with Neutral trials, Negative trials, and CDC Negative trials. We report the analyses in each of these conditions in the next three sections. There was also a manipulation of set size (three and 30). For each cue condition, there was no reliable interaction between the type of first object fixated and set size. Thus, we collapsed set size in the analyses that follow. The fixation probability results are displayed in the left column of Fig. 2.

The Neutral condition allowed us to assess initial guidance from a negative template maintained in LTM, operationalized as learned distractor rejection for the CDC. The first-object-fixation probability was reliably lower for the CDC than for neutral items, $t(23) = -3.62$, $p = .001$, $d_z = -0.74$. Given that the Neutral condition of the test session was the same as the training session, the consistency of results between sessions indicates that the learned avoidance of the CDC persisted into the experimental session despite the inclusion of additional, interleaved cuing conditions.[5]

The Negative Cue condition allowed us to assess initial guidance from a negative template maintained in VWM. The three colors in each array were divided into three analytic categories: Negatively cued color, neutral color (which contained the target attribute), and CDC. To assess VWM-based guidance, we compared initial fixation probability for the negatively cued item compared with the neutral item. As predicted, the first-object-fixation probability was reliably higher for the negatively cued item compared with the neutral item, $t(23) = 6.08$, $p < .001$, $d_z = 1.24$. Thus, we observed the predicted dissociation in initial polarity of guidance from negative templates maintained in LTM and VWM. In contrast with the initial avoidance observed for LTM-based negative templates, VWM-based negative templates produced initial attraction toward matching items.

The Negative Cue condition also allowed us to assess whether VWM- and LTM-based biases are implemented in concert. The CDC item was still present in these displays, and thus we could test whether there continued to be avoidance of this item, relative to the neutral-color item, even in the presence of robust guidance from VWM. The first-object-fixation probability was reliably lower for the CDC compared with the neutral color, $t(23) = -2.52$, $p = .019$, $d_z = -0.52$. Thus, there

[3] We report adjusted η_p^2, which corrects for the positive bias inherent in standard η_p^2 (Mordkoff, 2019).

[4] This analysis included some trials on which more than one saccade was required to bring the eyes to an object region. The pattern of data was the same when restricting this analysis to the 77.3% of trials that required only a single saccade to bring the eyes to an object region. We also examined the 22.7% of trials on which the first saccade did not land in an object region, assigning these saccades to the nearest object in the array. The pattern of results replicated the main analysis.

[5] A possible alternative explanation for the pattern of CDC avoidance involves inter-trial effects rather than long-term suppression. Specifically, on Neutral trials, a neutral color on trial N could have matched the target color from trial N-1. In contrast, the CDC item could never have matched the target color from trial N-1, since the CDC was never the target. If there was a bias to attend to the color of the target on the previous trial, then the first fixation probability difference could have been generated by attraction to neutral items that matched the previous target color rather than avoidance of the CDC (we thank a reviewer for suggesting this possibility). To test this, we limited the analysis of the Neutral condition to those trials where the N-1 target color was not present in the array. We continued to observe a lower probability that the first object fixated was the CDC (M = 0.302, SD = 0.034) compared with one of the two neutral colors (M = 349, SD = 0.017), $t(23) = -4.53$, $p < .001$, $d_z = -0.92$, consistent with our assumption that avoidance reflected long-term featural suppression of the CDC.

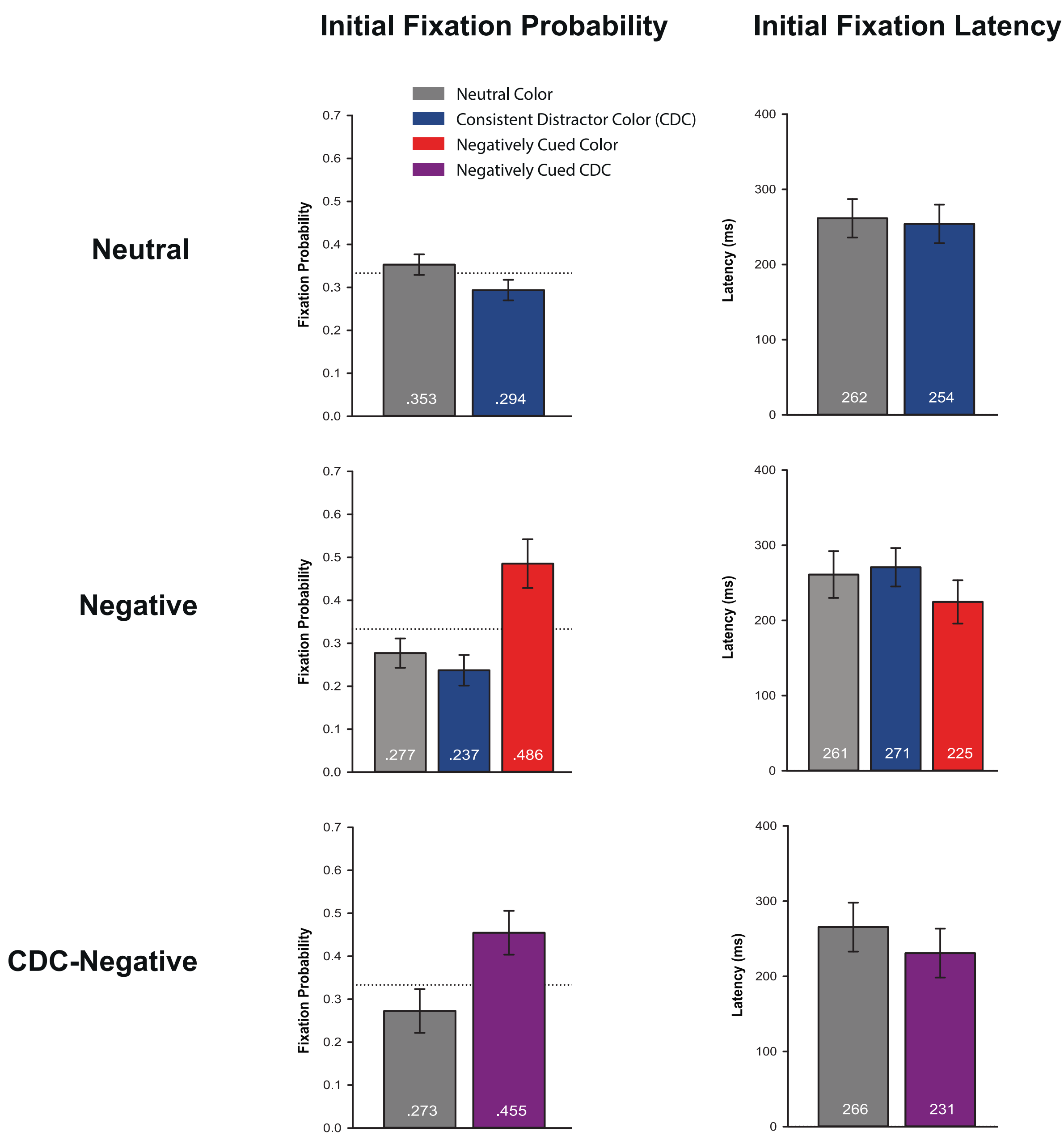

Fig. 2. Results from analyses of initial orienting behavior. The left column shows initial fixation probability for each item type as a function of cuing condition. The right column shows latency to first object fixation. Error bars are condition-specific, within-participant 95% confidence intervals (Morey, 2008).

continued to be LTM-based avoidance in terms of the first object fixated.

Finally, in the CDC Negative Cue condition, the trial-by-trial negative cue was the CDC color. Given that our results thus far indicate a difference in the polarity of initial guidance from LTM- and VWM-based negative cues, this condition effectively places those biases in competition. We compared the initial fixation probability for the negatively cued CDC item relative to the two neutral items. The first-object-fixation probability was reliably higher for the negatively cued CDC color compared with neutral items, $t(23) = 4.07$, $p < .001$, $d_z = 0.832$. Despite exhibiting significant avoidance of the CDC color in the other conditions, when this same information was presented explicitly and maintained in VWM, we observed capture rather than avoidance. Thus, the polarity of guidance imposed by VWM took precedence over the polarity of guidance imposed by LTM (see also Stilwell & Vecera, 2019). It would be interesting to compare the probability of fixating the negatively cued item when that item was the CDC (the present condition) versus when it is not (the Negative Cue condition, above). However, this is compromised by the fact that in the latter condition, the CDC was also present, and observed avoidance of that item may have potentially influenced the probability of fixating the Negatively cued item.

3.1.2. *First object orienting time*

In addition to examining the initial probability of fixation as a function of object type, we examined whether the observed differences in probability were associated with differences in initial orienting time. Specifically, when the first object fixated was either neutral, negative-cue-matching, or the CDC, were there systematic differences in the speed with which gaze was directed to these object types? These analyses were limited to the test session and to the set-size three trials. The orienting latency results are displayed in the right column of Fig. 2.

First, we compared orienting latency in the Neutral condition for the CDC relative to neutral colors. The latency until first object fixation did not differ as a function of whether the first object fixated was a neutral item or the CDC, $t(23) = 1.46$, $p = .157$, $d_z = 0.30$. In the second analysis, we compared orienting latency in the Negative Cue condition for the negatively cued item relative to the neutral color. The latency until first object fixation was reliably lower when the first object fixated was the negative-cue color compared with the neutral color, $t(23) = -6.71$, $p \leq 0.001$, $d_z = -1.37$. Finally, we compared orienting latency in the CDC Negative condition for the negatively cued CDC item relative to the two neutral colors. As in the Negative Cue condition, the latency until first object fixation was lower when the first object fixated matched the CDC compared with a neutral color, $t(23) = -5.39$, $p \leq 0.001$, $d_z = -1.10$.

In sum, the bias to direct gaze initially to items that matched a VWM-based negative template was associated with reduced orienting latency to these items, consistent with initial enhancement, rather than suppression, of the relative priority of items matching the negative cue. This result is consistent with previous evidence demonstrating that VWM maintenance reduces saccade latency to matching items (Hollingworth et al., 2013b). In contrast, for items matching a LTM-based negative template (the CDC in the Neutral condition), there was no observable difference in orienting latency relative to neutral items.

3.1.3. The relation between first object orienting time and first object fixation probability

As reported above, there were reliable differences in the mean probability of orienting to different object types as a function of condition. There were also differences in the mean latency of orienting. We next examined whether there was a relation between orienting time and fixation probability within each of the key conditions.

We first examined Neutral trials in the test session to assess whether the probability of orienting to the CDC was modulated by orienting latency. These data are presented in Fig. 3A. The analysis employed logistic regression, with centered elapsed time to first object fixation as the predictor and a dichotomous outcome indicating whether the first fixated object was the CDC or one of the two neutral items. A linear mixed-effects model was used, including a random intercept for participant and a by-participant random slope for orienting latency.[6] There was no reliable effect of orienting latency on CDC fixation probability, $\beta = -0.009$, $SE = 0.147$, $Z = -0.059$, $p = .953$, with the probability of fixating the CDC remaining quite consistent across the range of latency.

We next examined the Negative Cue condition, assessing the probability of fixating the negative-cue matching item (Fig. 3B). There was a reliable negative relation between orienting latency and fixation probability, $\beta = -1.421$, $SE = 0.234$, $Z = -6.084$, $p < .001$. That is, capture by the negative-cue-matching item decreased significantly with increasing latency.

Finally, we examined the CDC Negative Cue condition, assessing the probability of fixating the CDC item that had been negatively cued (Fig. 3C). Similarly to the standard Negative Cue condition, there was a reliable negative relation between orienting latency and CDC fixation probability, $\beta = -1.094$, $SE = 0.233$, $Z = -4.685$, $p < .001$. Note that in both negative cue conditions, there was nonlinearity introduced by a relative decline in fixation probability for the very shortest latencies. This is likely caused by the fact that some proportion of the extremely rapid orienting times reflected anticipatory saccades that were programmed before the onset of the search array and were thus unguided.

In sum, these analyses identified an additional dissociation between VWM and LTM guidance, in the relation between first object orienting latency and first object fixation probability. VWM-based negative cues showed stronger capture by matching items with shorter orienting latency. This is consistent with a relatively automatic bias to attend to VWM-matching items, a bias that could be counteracted, to some extent, by delaying initial orienting (see similar pattern in the extended search data, below). No such pattern was observed for LTM-based guidance in the Neutral condition, with modest avoidance observed across the range of latency. Moreover, the pattern of orienting to the CDC item in the CDC Negative Cue condition followed the pattern in the standard Negative Cue condition rather than the pattern in the Neutral condition, indicating that when combined, VWM-based guidance tended to overshadow guidance by LTM.

3.1.4. First object dwell time

We analyzed the dwell time for each item type within each condition. This was defined as the elapsed time from the beginning of the first fixation on an object to the end of the last fixation on that object (for one or more consecutive fixations that fell within an object region). We limited this analysis to the set-size three trials, since this set size keeps the possible object types constant for selection as the next saccade target. For example, if the CDC were the first object fixated at set size three Neutral condition, the other two alternatives would always be the two neutral colors. These analyses were also limited to the main session. Finally, we removed dwell times on items that contained the target attribute, since participants never had to exit these items.

In the Neutral condition, we compared dwell time on the neutral distractor item (M = 239 ms, SD = 49.6) and the CDC item (M = 226 ms, SD = 41.3). Participants exhibited shorter dwell on the CDC item, $t(23) = 2.20$, $p = .038$, $d_z = 0.45$.

In the Negative Cue condition, we compared dwell time on the negatively cued item (M = 219 ms, SD = 31.8) and the CDC items (M = 233, SD = 43.3), $t(23) = -1.87$, $p = .074$, $d_z = -0.382$. There was no statistically significant difference, though the numerical trend was consistent with shorter dwell on the negatively cued distractors versus CDC-matching distractors. Note that we could not compare negatively cued item dwell times to a neutral baseline, because the neutral item always contained the target.

In the CDC Negative Cue condition, we observed shorter dwell on the negatively cued CDC item (M = 211 ms, SD = 33.5) versus the neutral distractor (M = 241 ms, SD = 53.4), $t(23) = -3.93$, $p < .001$, $d_z = -0.80$). Thus, capture by the negatively cued CDC item was accompanied by relatively rapid disengagement from this item.

3.2. Extended search behavior

The set-size 30 trials in the test session allowed us to analyze selection beyond the first object fixated, potentially illuminating the evolution of search behavior across a trial. These results are displayed in Fig. 4. Two analyses characterized effects on fixation probability. First, we calculated the trial-level probability that any given fixation (that fell within an object region) was directed to one of the three analytic categories (neutral color, negatively cued color, or CDC). This allowed us to characterize biases expressed across the entire trial (see left column of Fig. 4). In the second analysis, we conditionalized these data according to ordinal object fixated during a trial (i.e., the first object fixated, second object fixated, and so forth). The results are displayed in the right column of Fig. 4. For this analysis, an entry into an object region could potentially encompass multiple individual fixations. Transitions between objects were defined as a change in the object region fixated. So, for example, a participant might devote two fixations to the first object, with the next fixation falling on a location not occupied by an object, and the next falling on a different object. This latter entry would then be

[6] In each of the three mixed-effects analyses reported in this section, model selection began with a fully elaborated random effects structure. We then systematically removed components whose exclusion did not significantly impair model fit, as assessed by likelihood-ratio tests (Matuschek et al., 2017). For the Neutral condition, the best-fit model did not require either a random slope for orienting latency or a random intercept for participant. For the remaining two analyses, however, the best-fit model required both the intercept and slope components. For consistency, the final random effects structure in all three analyses included a random intercept for participant and a random slope for orienting latency.

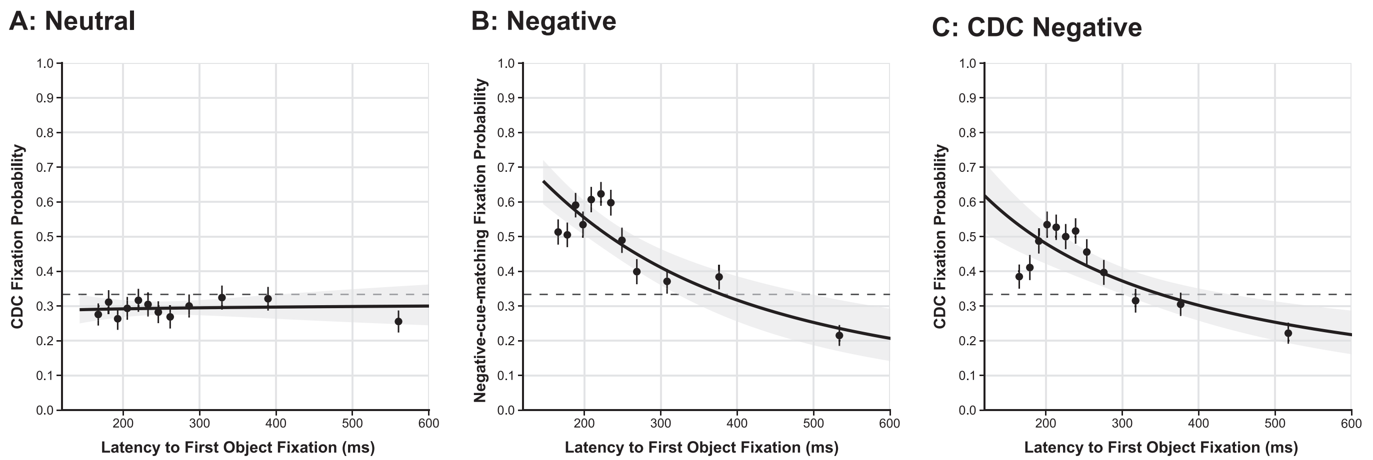

Fig. 3. Empirical and model-predicted relation between first object fixation latency and first object fixation probability for **A)** the CDC item in the Neutral condition, **B)** the negative-cue-matching item in the Negative Cue condition, and **C)** the CDC item in the CDC Negative Cue condition. Binned points (12 quantile-based bins) show the observed probabilities as a function of fixation latency, with vertical bars indicating standard errors. The solid black lines depict the predicted probability from the logistic mixed-effects model, with the gray ribbon depicting the 95% confidence interval. Chance probability is indicated by the dashed gray line.

considered the second object fixated. If gaze left an object region but returned to that object without an intervening fixation on a different object region, this was not treated as a transition (i.e., this entire group of fixations was assigned to the same ordinal object fixated). This analysis was limited to the first 13 objects fixated in a trial. As ordinal object fixated increases, the number of trails included in the analysis decreases due to trial completion. We set a criterion of at least 40% included trials, on average, which produced the cutoff at the 13th object fixated. In both analyses, we eliminated the entry into the final target region immediately preceding the response, since the category of this entry was determined by the task (i.e., the trial necessarily ended with a fixation on a target-colored object, which would potentially overestimate the probability of fixating this object type). These analyses are reported below, broken down by cuing condition.[7]

3.2.1. Neutral condition

For trial-level fixation probability, participants exhibited a significantly lower overall probability of fixating the CDC item versus neutral items, $t(23) = -4.09$, $p < .001$, $d_z = -0.81$. For the ordinal object fixation probability data, participants exhibited an avoidance effect for the CDC item throughout the trial. A one-way, repeated measures ANOVA was performed across the first 13 ordinal object fixation probabilities of the CDC color. There was no effect of ordinal object fixated, $F(12, 276) = 1.25$, $p = .248$, adj $\eta_p^2 = 0.02$, suggesting that the learned avoidance of the CDC was sustained, with similar magnitude, across the entire trial.

3.2.2. Negative cue condition

First, we compared negative-cue-matching items with neutral items. For trial-level fixation probability, the probability of fixating negatively cued items was reliably lower than for neutral items, $t(23) = -10.83$, $p < .001$, $d_z = -2.21$. Thus, despite showing initial attraction toward negatively-cued items, participants were ultimately able to avoid those items, such that at the level of an extended search trial, the overall pattern was avoidance. For the ordinal object fixation probability analysis there was a clear pattern of initial capture by negatively cued items followed by later avoidance.[8] The higher probability of fixating negative-cue-matching objects early in the trial (compared with neutral items) transitioned to successful avoidance of those items. Specifically, there was a main effect of ordinal object fixation number on the probability of fixating the negatively cued item, $F(12, 276) = 39.5$, $p < .001$, adj $\eta_p^2 = 0.62$. This was driven by a reduction in the probability of fixating the negatively cued item between the 1st (M = 0.527, SD = 0.14) and 4th (M = 0.105, SD = 0.09) ordinal objects on a trial, with the probabilities for objects fixated after the 4th remaining at this relatively low level.

Second, we compared CDC items with neutral items. For trial-level fixation probability, the probability of fixating CDC-matching items was reliably lower than for neutral items, $t(23) = -3.10$, $p = .005$, $d_z = -0.63$. Thus, participants implemented both types of guidance (based on VWM and LTM) within trials.

3.2.3. CDC negative cue condition

In the CDC Negative Cue condition, the overall probability of fixating the negatively cued CDC items was significantly lower than the probability of fixating neutral items, $t(23) = -14.05$, $p < .001$, $d_z = -2.87$. Similar to the negatively cued items in the Negative Cue condition, participants exhibited a strong, overall avoidance of the cue-matching items despite initial capture by these items. For the ordinal object fixation probability data, there was a main effect of ordinal object fixation number on the probability of fixating the negatively cued CDC items, $F(12, 276) = 27.7$, $p < .001$, adj $\eta_p^2 = 0.53$. This was driven by a steep drop in the probability of fixating the negatively cued CDC items between the 1st (M = 0.468, SD = 0.111) and 4th (M = 0.107, SD = 0.076) ordinal object fixations. Overall, the pattern of selectivity in the CDC Negative Cue condition corresponded closely to that in the Negative Cue condition.

[7] Chance-level for fixating a particular item type changes as objects are fixated during a trial. For example, if the participant has fixated two negative-cue matching items at set size 30, only 8 of the original 10 items remain, changing the chance level for fixating a negative-cue matching item subsequently. To account for varying levels of chance across a trial, we calculated, for each ordinal object value, the dynamic chance level for each item type given the history of objects fixated previously on the trial. The observed probability of object fixation was divided by the chance probability and then log transformed, so that positive values corresponded to higher than chance fixation probability, and negative values corresponded to lower than chance probability (for further details of this calculation, see Beck et al., 2018). These data produced the same pattern of results as the raw probability data reported in Figure 4. The log probability ratio data are reported in Supplemental Figure 1.

[8] Note that the values in Figure 4 for the first ordinal object fixation probability differ slightly from those reported in Figure 2, as the latter included both set sizes 3 and 30, whereas the former included only set size 30.

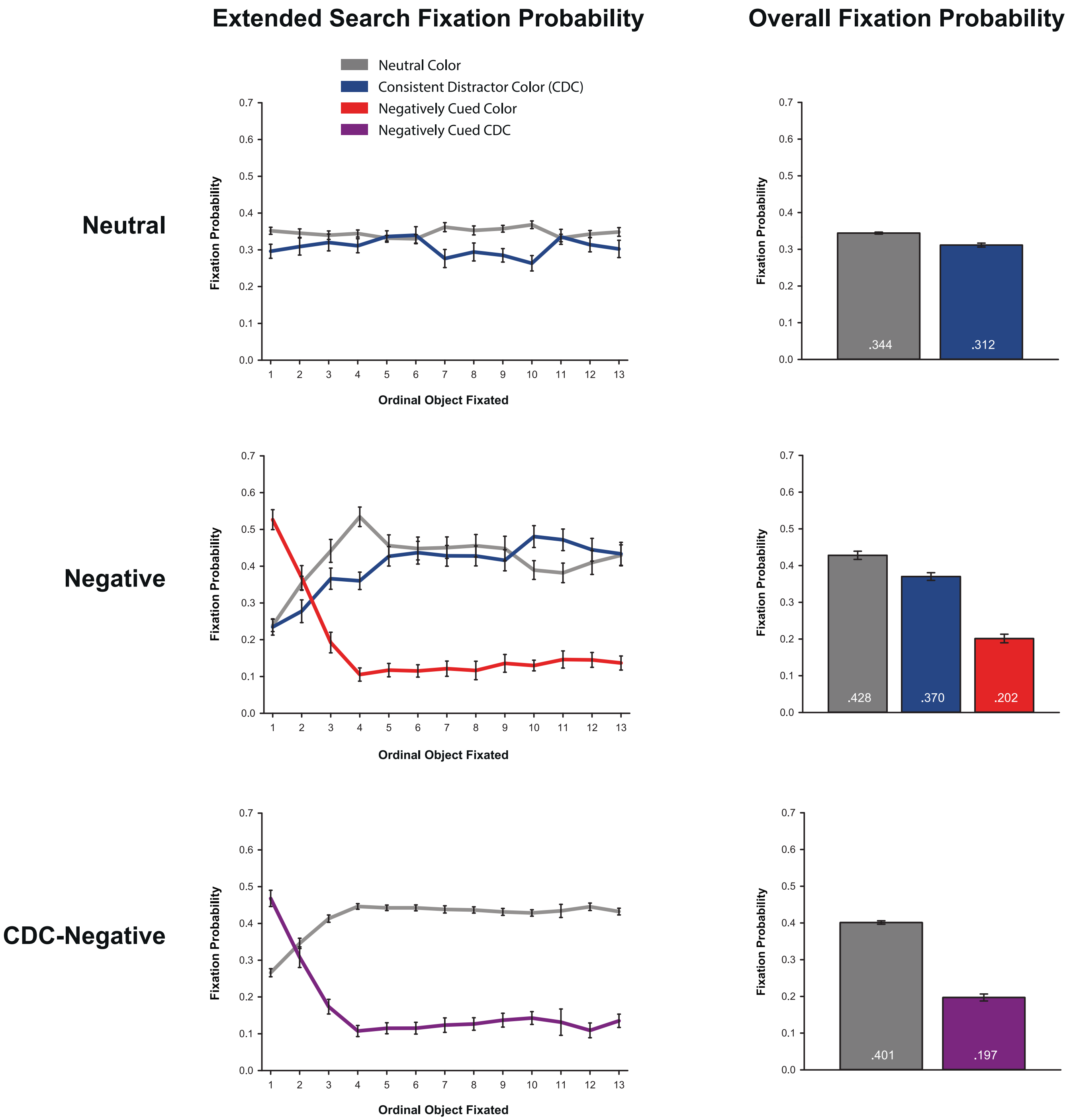

Fig. 4. Results from analyses of extended search behavior on set size 30 trials. The left column shows fixation probability for each item type as a function of ordinal object fixated and cuing condition. The right column shows trial-wide probability of fixation as a function of item type and cuing condition. Error bars for the ordinal object fixated data are standard errors of the means. Error bars for trial-wide fixation probability are condition-specific, within-participant 95% confidence intervals (Morey, 2008).

3.3. Search time

To test whether negative cues maintained in VWM influenced the time taken to find the target, we examined the elapsed time until fixation on the target item as a function of cue condition (hereafter termed *search time*). If there were multiple entries into the target region before the manual response, this value reflected the last entry preceding the response. Search time, like manual RT, reflects overall search efficiency, although it can be more accurate and precise than manual RT given that it does not include variability associated with discriminating the target value and executing the manual response. Manual RT produced the same pattern of results. For each of the conditions in which a trial-by-trial negative cue was presented, we compared search time with the Neutral condition to assess whether the VWM-based negative cues produced a search time advantage. These results are displayed in Fig. 5.

First, we compared the Negative Cue condition and the Neutral condition. For set size 30, search time was reliably lower in the Negative Cue condition than in the Neutral condition), $t(23) = -2.49$, $p = .020$, $d_z = -0.51$. Thus, the ability to avoid negative-cue-matching items later in the trial counteracted the effect of initial capture, resulting in an overall

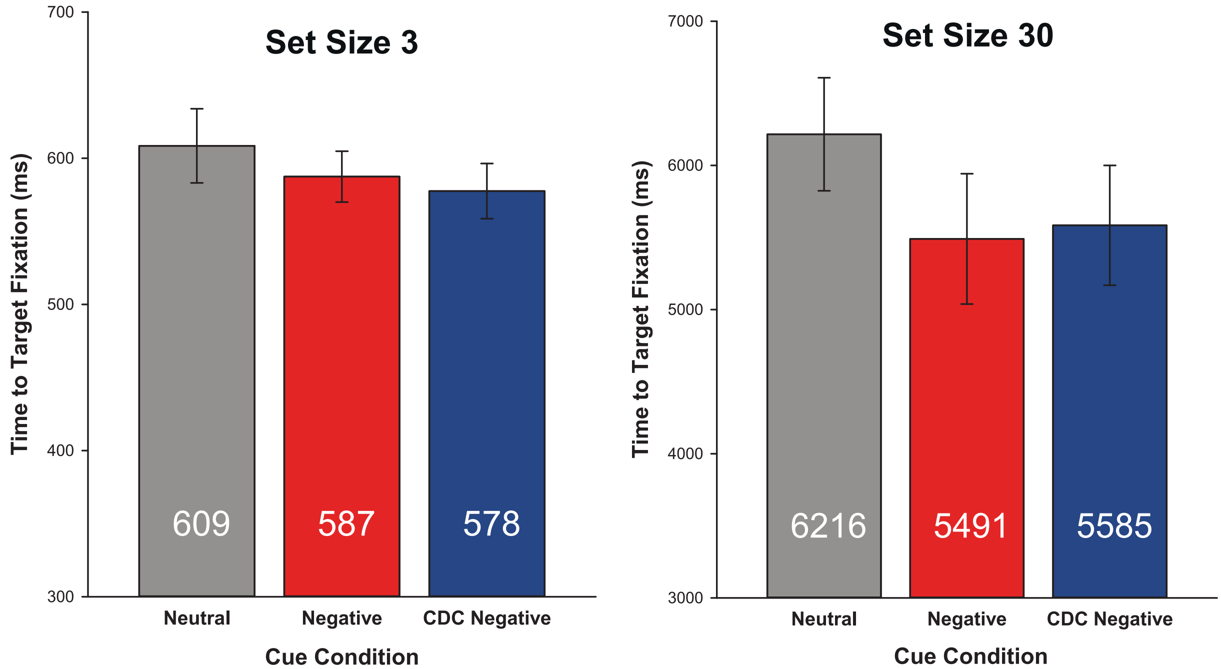

Fig. 5. Search time results as a function of cuing condition for set size three and 30. Error bars are condition-specific, within-participant 95% confidence intervals (Morey, 2008).

benefit for negative cues in search time. For set size three, there was no significant difference in search time between these two conditions, $t(23) = 1.36$, $p = .186$, $d_z = 0.28$. Given that there was a reliable negative-cue capture effect on fixation probability, one might expect that the search time results would have indicated reliably *slower* orienting to the target in the Negative Cue condition compared with the Neutral condition at set size three. The absence of such a pattern is explained, at least to some extent, by differences in the dwell time on negative-cue-matching objects compared with neutral objects. Specifically, when a negative-cue-matching distractor was the first object fixated, dwell time on this object was reliably shorter (M = 219 ms, SD = 31.8) than when a neutral distractor was the first object fixated in the Neutral condition (M = 239 ms, SD = 49.6), $t(23) = -2.90$, $p = .008$, $d_z = -0.59$. Thus, participants appeared to be able to disengage gaze more efficiently from a negative-cue-matching item than from a neutral item (also see within-condition analysis of dwell times, above), potentially offsetting the cost generated by a higher probability of fixating those items.

Second, we compared the CDC Negative Cue condition with the Neutral condition. For set size 30, search time was reliably lower in the CDC Negative Cue condition than in the Neutral condition, $t(23) = -2.39$, $p = .026$, $d_z = -0.49$. As in the Negative Cue condition, we did not observe a CDC Negative Cue benefit at set size three, $t(23) = 1.91$, $p = .069$, $d_z = 0.39$. Again, initial capture by the CDC item was likely to have been offset by shorter dwell time on that object. Specifically, participants exhibited significantly shorter dwell times on negatively cued CDC items in the CDC Negative Cue condition (M = 211 ms, SD = 33.5) compared with neutral items in the Neutral condition (M = 239 ms, SD = 49.6), $t(23) = -3.79$, $p < .001$, $d_z = -0.78$. Moreover, participants exhibited significantly shorter dwell times for negatively cued CDC items, even compared with dwell times on the CDC items in the Neutral condition (M = 226 ms, SD = 41.3), $t(23) = -2.25$, $p = .034$, $d_z = -0.46$.

Finally, we examined whether there was a difference in search time between the Negative Cue condition and the CDC Negative Cue condition. This contrast is to some extent unbalanced. In the Negative Cue condition, participants had two distinct sources of information to guide search (the CDC-matching items and the negative-cue-matching items). In the CDC Negative Cue condition, participants had just one, since the relevant distractors were specified redundantly. Nevertheless, there was no significant difference between search time in the two conditions in the set size 30 trials, $t(23) = -0.276$, $p = .785$, $d_z = -0.06$. For the set-size three trials, there was also no significant difference in search time between the Negative Cue condition and CDC Negative Cue condition, $t(23) = 0.962$, $p = .346$, $d_z = 0.20$.

3.4. *Test of search and destroy*

Given that we observed initial capture by negatively cued items, and given that we observed subsequent avoidance of these items later in the trial, we assessed whether there was a relation between initial capture and later avoidance (Moher & Egeth, 2012). A similar test was conducted in Beck et al. (2018): Later avoidance was observed robustly regardless of whether there was initial capture. For the present test, we limited this analysis to the set-size 30 Negative Cue trials. Specifically, we compared the probability of fixating a negative-cue-matching item 1) given that the first or second object fixated was a negatively cued item (capture) or 2) given that neither the first nor second object fixated was a negatively cued item (no capture). The first two objects fixated were not included in the probability calculations; that is, the test of later avoidance was limited to the third object fixated and later. To account for evolving levels of chance for fixating a negatively cued item, we expressed fixation probability as a log probability ratio (observed probability divided be chance probability), as described in footnote 7. Negative values correspond to lower-than-chance probability. The data for capture and no-capture trials are presented in Supplemental Fig. 2. Robust avoidance was observed regardless of initial capture. Consistent with the findings of Beck et al. (2018), our analysis suggests that initial capture was not necessary for subsequent negative-cue-matching avoidance.

3.5. *Awareness test*

Following the experiment, participants completed two awareness test questions. Participants first reported whether they noticed that one color was less likely to contain the target than other colors. Nine out of 24 participants reported “Yes” to this question. Of the nine who report "yes", six were correct. Independently of this response, participants were then asked to choose one out of the four possible colors as the item that was least likely to contain the target. Twelve out of 24 correctly chose the CDC, which was reliably higher than expected by chance, X^2 (9, N = 24) = 8.0, p = .004. We examined the overall probability of fixating the CDC in the set-size 30 trials of both the Neutral and the CDC Negative condition, restricted to 1) the participants who correctly reported the color of the CDC independent of their explicit awareness report and 2) the participants who reported being aware of and correctly reported the color of the CDC. The former 12 participants had overall probabilities of fixating the CDC at 0.30 and 0.19 for the Neutral condition and CDC Negative Cue condition respectively, compared with 0.32 and 0.21 for the 12 participants with incorrect report. The six participants who reported awareness of the CDC and reported its identity correctly had overall probabilities of fixating the CDC at 0.29 and 0.19. We draw no strong conclusions from these results given that such comparisons are underpowered (Vadillo et al., 2016). Nevertheless, the numerical results do not suggest that participants who became aware of the CDC color were differentially successful at avoiding that color.

4. Discussion

In the present study, we sought to characterize the mechanisms by which negative attentional templates (specifying the attributes of task-irrelevant items) are implemented, contrasting guidance from templates maintained in LTM and in VWM. Previous research has indicated that negative templates maintained in LTM are implemented both proactively (with the parameters of guidance established before the onset of the search array and expressed in the earliest orienting behaviors) and directly (with suppression implemented through the same dimension as learning). In contrast, there is suggestive evidence that negative templates maintained in VWM are implemented reactively (with the parameters of guidance established only from observed properties of the search array) and indirectly (through either feature-based or spatial recoding). Here, we directly compared the use of LTM-based negative templates and VWM-based negative templates in a single experiment, predicting that the two forms of guidance would be dissociable in terms of the initial polarity of guidance and in the pattern of guidance across an extended search trial. In addition, we examined how the two forms of guidance are combined when they specify either the same object or different objects in a search array.

4.1. Dissociable Mechanisms of Guidance from Negative Templates Maintained in VWM and LTM

First, we examined the polarity of initial guidance from negative templates maintained in LTM and VWM. When a consistent distractor color (CDC) was learned and maintained in LTM, we observed that the first object fixated during search was less likely to match the CDC compared with neutral colors. In contrast, when a trial-by-trial negative cue was maintained in VWM, we observed initial attraction toward matching items. Thus, we observed a robust dissociation in the polarity of initial guidance.

Second, we examined the evolution of guidance across an extended search trial, as attention and gaze were directed to a sequence of objects in set-size 30 arrays. Again, we observed a dissociation between LTM and VWM. For LTM-based guidance, there was consistent avoidance across the entire trial duration. In contrast, VWM-based guidance showed a strong patten of initial capture followed by later avoidance. The transition between capture and avoidance for VWM-based guidance occurred at the second to third object fixated during a trial. By the fourth object fixated, the probability of fixating a template-matching distractor was minimized to near-floor levels, and effective avoidance was maintained throughout the remainder of the trial. In addition to a dissociation in the pattern of guidance, the two mechanisms also dissociated in the ultimate magnitude of avoidance. After the cost of initial capture, VWM allowed for efficient avoidance, whereas the avoidance effect based on LTM was consistently modest in comparison.

The two forms of guidance produced additional dissociations on the timing of oculomotor orienting during search. Specifically, negative templates maintained in VWM produced shorter saccade latencies for initial eye movements directed to matching items compared with neutral items. In contrast, negative templates maintained in LTM did not produce shorter saccade latencies to matching items. Moreover, capture by VWM-matching items decreased with increasing orienting latency, whereas the probability of fixating the CDC remained consistent across the range of latency. Finally, there was one oculomotor measure on which VWM- and LTM-based negative templates produced similar effects. Both were associated with shorter dwell times on template-matching items compared with neutral items, although there was a numerical trend toward shorter dwell time for VWM-matching items compared with LTM-matching items.

The present experiment supports our hypothesis that negative templates maintained in VWM and LTM implement guidance through dissociable mechanisms. Our results are consistent with previous demonstrations that LTM-based negative templates produce guidance that is direct and proactive, as assessed by early oculomotor avoidance (Gaspelin et al., 2017; Stilwell & Gaspelin, 2021; Stilwell & Vecera, 2022), by the intra-search probe method (Chang & Egeth, 2019; Gaspelin et al., 2015; Hauck et al., 2024), and by the pre-search probe method (Kim & Cho, 2024). Existing work suggests that this mechanism of direct, proactive avoidance may emerge through statistical learning and habituation (Adam & Serences, 2021; Turatto et al., 2018; Turatto & Pascucci, 2016; Won & Geng, 2020). Consistent exposure, even passively, to a distractor feature value may lead to attenuated responses to this feature value across the visual system, decreasing the relative priority of matching items.

In contrast, the present results suggest that guidance from negative templates in VWM is implemented reactively rather than proactively and likely through an indirect process of template recoding. The fact that the VWM-based negative templates produced initial attraction to, rather than avoidance of, matching items provides clear evidence that the ultimate avoidance observed here was not established proactively, i.e., before the onset of the search array. Several studies converge with the present result to show initial attraction toward cue-matching items (Beck et al., 2018; Moher & Egeth, 2012) and initial perceptual enhancement of cue-matching items (Addleman & Störmer, 2022). Other studies show no difference between cue-matching and neutral items in initial guidance (Hauck et al., 2024; Zhang & Carlisle, 2023). No studies have reported initial avoidance of negative-cue-matching distractors.

Why might some studies have observed initial capture by VWM-matching items whereas others have not? The clearest contrast in results is between the present study and Zhang and Carlisle (2023), who did not find an initial oculomotor capture effect. The empirical difference is likely explained by two factors. First, Zhang and Carlisle (2023) used circular search arrays in which the array items always appeared in the same locations, and the relevant- and irrelevant-color items were often segregated by hemifield. In a replication of their study, we found that this type of array structure often led to highly scripted search patterns, with participants frequently making the same initial saccade at the beginning of trial (e.g., to the top of the array) followed by systematic clockwise or counterclockwise fixation of the individual array elements (Prakash & Hollingworth, 2025). Such spatially scripted biases may have reduced sensitivity to theoretically relevant biases, such as an initial featural bias generated by a VWM-based negative cue (i.e., capture). The present method minimized such competing guidance processes by 1) randomizing the item locations and 2) introducing multiple concentric rings of stimuli at set size 30 that created spatially irregular displays. Second, there is an important difference between how a fixation on an object was defined in the present study and in Zhang and Carlisle (2023). In the present study, a fixation was considered to have landed on an object only if it fell within a region closely surrounding that object. In Zhang and Carlisle (2023), a fixation was assigned to a particular object if it was in a pie-shaped region extending from central fixation to the object. Thus, their analysis likely included a substantial proportion of first saccades that did not land on an object, potentially reducing sensitivity to guidance effects by including saccades that were not strongly guided.

In summary, there is currently no published evidence to indicate that VWM-based negative cues can be configured to generate proactive avoidance. Instead, the balance of evidence, including the robust capture effects observed here, indicates that attention is initially attracted toward negative-cue-matching items. To know what value to avoid when search commences, one must remember the cued value, and when the cue changes on a trial-by-trial basis, maintenance is supported by VWM. This will engage active representations of the cued value across the perceptual system, which will in turn interact with new perceptual processing to increase the relative salience of matching items (Desimone & Duncan, 1995; Hamker, 2004; Schneegans et al., 2014). Attention will be attracted, ironically, to the very items a person intends to avoid. For an equivalent phenomenon in the spatial domain, see Tsal and Makovski (2006). The implication is that it may simply be impossible, mechanistically, to use VWM to directly deprioritize a particular feature value, as the fundamental nature of VWM representation necessitates a facilitatory interaction.

If it is not possible to deprioritize a particular feature value through VWM maintenance, how is efficient avoidance ultimately implemented? We argue that the type of efficient avoidance observed later in a trial in the present study depends on a reactive mechanism of template recoding. One possible form of template recoding is feature based (Becker et al., 2015; Hollingworth, 2022): The participant recodes the negative template specifying the to-be-avoided feature value into a positive template based on the observed features of the non-template-matching items in the array. A second possibility is spatial recoding (Beck & Hollingworth, 2015; Zhang & Carlisle, 2023): The participant recodes the negative feature template into a spatial template based on the observed locations of non-template-matching items. The use of feature-based or spatial recoding will likely depend on the properties of the search display. For example, displays consisting of only a small number of feature values would be amenable to positive feature recoding for the non-cued value(s), such as attending to the blue items instead of the red items when red is negatively cued (Hollingworth, 2022). Arrays composed of multiple relevant feature values, e.g., many non-cued color values, are more likely to be amenable to spatial recoding (Beck & Hollingworth, 2015; Zhang & Carlisle, 2023).

Two studies support spatial recoding as a plausible mechanism allowing for ultimate avoidance (Beck & Hollingworth, 2015; Zhang & Carlisle, 2023). In both studies, a VWM-based negative color cue was displayed before each trial. They key manipulation was the degree of spatial intermixing of matching and nonmatching colors within the search array. Consistent with spatial recoding, the search advantage provided by a negative cue was modulated by spatial intermixing. Spatially segregated displays (relatively easy spatial recoding) produced larger search RT benefits than did spatially intermixed displays (relatively difficult spatial recoding). Although both studies support the spatial recoding hypothesis, we note that Zhang and Carlisle (2023) did not interpret their data this way. They argued that it would not be possible to code the locations of task-relevant objects in spatially intermixed arrays, and thus any evidence for a negative-cue RT advantage (relative to a neutral cue) in the spatially intermixed condition would constitute evidence against spatial recoding and in favor of direct suppression. However, the assumption that spatial recoding could not be applied to the intermixed arrays was never substantiated, and since their arrays contained 12 items, half of which matched the negative cue, there were only six relevant locations, making it perfectly plausible that participants could have engaged in spatial recoding (either of the entire array or of sequential subsets). As argued by Beck and Hollingworth (2015), a spatial recoding account predicts that for spatially intermixed displays, the utility of a negative cue will be reduced or eliminated compared with segregated displays. This is precisely what was observed in both studies. Even for the substantially larger, spatially intermixed arrays in the present set-size 30 trials, the presence of a negative cue advantage in search time is still perfectly consistent with spatial recoding, as recoding could occur iteratively over sub-regions of the display, in much the same way that a positive template is applied sequentially to groups of items in a standard visual search task (Pashler, 1987).

To recode a negative template, is it necessary to first attend to the to-be-ignored value to later avoid it? Such a possibility would be consistent with the "search and destroy" framework discussed in Moher and Egeth (2012), in which an initial bias toward negatively cued items plays a functional role in establishing later avoidance. Our data do not necessarily eliminate this possibility, but we found no evidence to support it. Robust later avoidance was observed whether or not a cue-matching item was fixated early in the trial (see also Beck et al., 2018). Thus, we prefer to conceptualize the initial attraction not as playing a functional role in later avoidance but as simply reflecting attention capture by items matching the content of VWM (Olivers et al., 2006; Soto et al., 2005). The shorter saccade latency to cue-matching items is also consistent with a capture effect driven by enhanced perceptual salience of a memory-matching item (Hollingworth et al., 2013a; Hollingworth et al., 2013b) rather than a strategic effect to support later avoidance.

Finally, is it possible for negative-cue guidance based on VWM to be reactive but also implemented by direct suppression? For example, Zhang and Carlisle (2023) argued that despite finding no evidence for initial avoidance of negative-cue-matching items, and thus no evidence for proactive suppression, later avoidance was nevertheless based on direct suppression of the cued value. Although we cannot eliminate this possibility, it faces a substantial explanatory hurdle. The hypothesis rests on the assumption that seeing the negatively cued color in the array is required to establish the guidance parameters for direct suppression but that seeing the same color in the cue display before the array is not sufficient to establish the same guidance parameters. In other words, to be internally consistent, the hypothesis would need to provide an account of why direct suppression cannot be established from the cue itself and must be delayed until after the cued value becomes visible in the array. In contrast, a recoding account provides a natural explanation for why avoidance is not observed early in a trial: the translation of the negative cue into an alternative template requires perceptual registration of the properties of the array and a process of template recoding, which delays the implementation of avoidance.

4.2. Interactions between VWM- and LTM-based guidance

Our second major goal was to examine how biases from LTM and VWM are combined to influence priority. This took two forms: 1) examining whether both biases would be expressed when they specified different objects in an array and 2) examining how they would interact when they specified the same objects, particularly in the early stages of a trial when the two biases had different polarities (i.e., initial avoidance versus initial attraction).

On the first issue, we found that in the Negative Cue condition, both biases were expressed within a trial, leading to a simultaneous pattern of attraction-avoidance for VWM-matching items and modest but consistent avoidance for LTM-matching items (see Fig. 4). Specifically, in the Negative Cue condition each array was divided evenly between the negatively cued color, the CDC, and a neutral color that contained the target attribute. In addition to the previously described pattern of VWM-based attraction-avoidance, we observed that throughout the trial, there was a lower fixation probability for the CDC items than for neutral items. Thus, the priority of specific items during search reflected both biases. This is broadly consistent with accounts of attentional control holding that biases from explicit goals (based on the trial-by-trial cue) and biases from selection history (based on consistent rejection of the CDC as a distractor) are combined within a common representation of attentional priority (Anderson et al., 2021; Awh et al., 2012; Theeuwes, 2019).

On the second issue, the CDC Negative condition provided an opportunity to examine how the two biases are combined when they specify the same items. Early in a trial, the two biases had different polarities. For this early interaction, we found that guidance was dominated by VWM. Even though participants had learned to avoid the CDC color, when that color was presented as a trial-by-trial negative cue, we observed initial capture that was similar in magnitude to the capture generated for cue-matching items in the Negative Cue condition that were not the CDC color. Stilwell and Vecera (2019) observed a similar effect on overall search times. Moreover, the extended pattern of attraction-avoidance was highly similar in the CDC Negative Cue condition and the Negative Cue condition, as can be seen by comparing these two conditions in Fig. 4. Thus, the results suggest that when placed in competition, biases based on VWM representations overshadow biases based on selection history. This conclusion must be qualified, however, given that we had a relatively short learning session, and there may well be circumstances where statistical learning of distractor attributes generates stronger levels of guidance that may compete more effectively with VWM.

Nevertheless, converging evidence indicates that attentional biases from VWM representation tend to outcompete LTM-based biases. Berggren et al. (2020) had participants search for two possible target colors on each trial, one that was static across trials, and thus depended on LTM, and one that changed on a trial-by-trial basis, and thus depended on VWM. Even though both colors were physically presented before every trial, and despite equal informativeness, VWM-based cues led to substantially more efficient search, reflected in both RT and the N2PC ERP component. Moreover, in a companion to the present study, Hollingworth and Kershner (2025) examined the individual and combined effects of VWM-based guidance and guidance from a LTM-based *positive* template (i.e., learning of a color value that had a higher than baseline probability of containing the target attribute). As here, VWM dominated initial guidance, even though LTM was predictive of the target object and VWM was not predictive of the target object. Thus, there is emerging evidence that VWM representations produce guidance that outcompetes guidance from LTM, even under circumstances that maximize the relative utility of LTM-based guidance. This has important implications for understanding the mechanisms of bias combination in an integrative priority map. Instead of reflecting a simple linear combination of biases, VWM-modulated input appears to be given precedence in the computation of priority. This raises the intriguing possibility that the expression of long-term selection history effects may be limited to situations in which there is no, or minimal, competing template state maintained online (i.e., as a trial-by-trial template value in VWM).

Later in an extended trial of the CDC Negative Cue condition, the polarities of the two biases were the same, avoidance. It would be theoretically interesting to assess whether VWM- and LTM-based biases of the same polarity produce compound effects, as a direct test of whether they jointly affect a common priority representation. Such an issue is difficult to assess in the present experiment, given the high likelihood that later avoidance based on VWM was implemented through template recoding. This issue could be better tested, however, in the context of positive biases from both LTM and VWM, where there would be no need recode the VWM template.

4.3. Conditions under which negative templates benefit search

Since the first demonstration of VWM-based negative cue benefits (Arita et al., 2012), there have been questions about whether the results were replicable, and if so, under what conditions. Specifically, some studies have failed to observe an overall RT advantage for negative cue trials relative to neutral trials (Becker et al., 2015; Berggren & Eimer, 2021; Cunningham & Egeth, 2016; Williams et al., 2020). The present results, in which we observed a consistent RT benefit at set size 30, demonstrate that such an effect will be observed only if the cost of initial capture is outweighed by the benefit of later avoidance. This will occur only under a limited set of circumstances. Critically, there must be a relatively large number of template-matching items, so that after initial capture, there remain enough template-matching items that effective set size can be reduced by avoiding them. Consistent with this, RT benefits tend to be observed with relatively large set sizes and thus a large number of matching items (Beck & Hollingworth, 2015; Hollingworth, 2022). A second factor is the difficulty of the search task, so that the potential time savings for avoiding any particular distractor item are maximized (Conci et al., 2019). This will be further enhanced if the search task requires object fixation, as here, since fixating known distractors will require slow reorienting of gaze rather than rapid reorienting of covert attention. Finally, RT benefits will scale with the ease of negative template recoding. In Hollingworth (2022) the use of only two colors in each array, which supported feature-based recoding, led to a large negative cue advantage. In addition, the ease of spatial recoding has been demonstrated to reliably influence the magnitude of the overall negative cue benefit (Beck & Hollingworth, 2015; Zhang & Carlisle, 2023), as discussed above. In the present set size 30 trials, we implemented two of these three conditions—many cue-matching objects and a very difficult search task that required object fixation—and we observed a robust negative cue advantage.

5. Conclusion

The present study demonstrates that the implementation of negative attentional templates derived from long-term learning and from online, VWM representation are implemented via dissociable mechanisms. Long-term templates based on statistical learning are implemented proactively, with avoidance observed from the very first orienting behaviors in a trial, plausibly through a direct process of feature habituation for frequently ignored values. In contrast, negative templates maintained in VWM are not implemented proactively, with a pattern of initial attraction toward matching items followed by later avoidance. This is likely caused by two processes: 1) higher initial priority of items that match the content of VWM, leading to early capture, followed by 2) template recoding that allows for efficient avoidance. In addition, we demonstrate that when both forms of guidance are potentially available, they jointly influence selection priority. However, when they are in conflict, guidance by VWM dominates guidance by long-term learning. That is, an online goal to avoid a particular value overshadows a learned habit to avoid that value, even when the effect of the former is ironic capture rather than avoidance.

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CRediT authorship contribution statement

Aditya Prakash: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation. **Andrew Hollingworth:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Data availability

https://osf.io/v2fdx/?view_only=6e794a399dea42a2a0318744ffbc0da8

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