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Inhibitory tagging in an interrupted visual search

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Inhibition of return facilitates visual search, biasing attention away from previously examined locations. Prior research has shown that, as a result of inhibitory tags associated with rejected distractor items, observers are slower to detect small probes presented at these tagged locations than they are to detect probes presented at locations that were unoccupied during visual search, but only when the search stimuli remain visible during the probe-detection task. Using an interrupted visual search task, in which search displays alternated with blank displays, we found that inhibitory tagging occurred in the absence of the search array when probes were presented during these blank displays. Furthermore, by manipulating participants' attentional set, we showed that these inhibitory tags were associated only with items that the participants actively searched. Finally, by probing before the search was completed, we also showed that, early in search, processing at distractor locations was actually facilitated, and only as the search progressed did evidence for inhibitory tagging arise at those locations. These results suggest that the context of a visual search determines the presence or absence of inhibitory tagging, as well as demonstrating for the first time the temporal dynamics of location prioritization while search is ongoing.

Initially, when observers focus attention on a location, they more readily detect stimuli at the attended location than at other locations. However, if observers are not motivated to maintain attention at the cued location, this initial facilitation is followed by inhibition: Observers become slower to detect stimuli at the cued location than at uncued locations (Posner & Cohen, 1984). This inhibitory mechanism, known as *inhibition of return* (IOR; Posner, Rafal, Choate, & Vaughan, 1985), biases processing in favor of sampling new information in the visual field. The biasing of attention away from previously attended stimuli and toward new ones has particular relevance in the context of visual search performance. During visual search, by associating inhibitory tags with search items that they have already examined, observers can avoid reinspecting these items, thereby increasing search efficiency (e.g., Klein, 1988).

Inhibitory tagging occurs during visual search, both in traditional laboratory search tasks (Müller & von Mühlenen, 2000; Takeda & Yagi, 2000) and in searches of more complex or naturalistic displays (Klein & MacInnes, 1999; MacInnes & Klein, 2003; Thomas et al., 2006). When observers must detect a luminance probe following an attention-demanding search task, they are slower to detect a probe appearing at a location occupied by a visual search distractor item (*on probe*) than they are to detect a probe appearing in an empty location (*off probe*). In the original study of inhibitory tagging in visual search, Klein (1988) found that when participants performed a serial visual search, this difference in reaction time (RT) to detect *on* probes versus *off* probes was greater than when participants performed a parallel (preattentive) visual search (e.g., Treisman & Gelade, 1980). Klein interpreted this result as evidence of inhibitory tagging in visual search; in serial searches, participants had to allocate attention to individual search items, and this allocation of attention led to the formation of inhibitory tags, which in turn led to the greater *on–off* probe difference in serial than in parallel search conditions.

Although Klein's (1988) initial study provided an intuitively appealing view of inhibitory tagging as a mechanism that facilitates visual search, subsequent experiments failed to replicate its findings (e.g., Klein & Taylor, 1994; Wolfe & Pokorny, 1990). In these experiments, once a participant had completed the visual search task, the search display was removed shortly before the luminance probe was presented. Although the participants were slower to detect *on* probes than *off* probes, this difference was the same regardless of whether they had performed a serial or parallel visual search, suggesting that forward masking, rather than inhibitory tagging, was driving the *on–off* probe difference. However, subsequent research showed that when the visual search display remains visible during the probe-detection task, the *on–off* probe difference is once again greater for serial visual searches than for parallel visual searches, suggesting that inhibitory tagging does facilitate visual search but that evidence for inhibitory tagging can be observed only when the search display

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remains continuously present (e.g., Klein & MacInnes, 1999; Müller & von Mühlenen, 2000; Takeda & Yagi, 2000). These studies suggest that inhibitory tags survive only for as long as the search items with which they are associated remain visible.

Why would the disappearance of search items entail the release of inhibitory tags? In cuing paradigms, there is evidence that IOR is tagged to both objects and environmental locations (e.g., Abrams & Dobkin, 1994; Tipper, Driver, & Weaver, 1991; Tipper, Weaver, Jerreat, & Burak, 1994); participants are inhibited in detecting probes on objects that have moved to a new location but are also inhibited in detecting probes at a cued location even when the object on which the cue appeared has moved. In visual search paradigms, however, the vast majority of evidence suggests that environmental locations are not specifically tagged but, rather, that tags are tied specifically to search objects at these locations; if a search item is no longer present, there is no evidence that inhibitory tagging persists at the location that this item occupied. There are, however, important differences between the cuing and search paradigms. In cuing paradigms, the task involves both spatial and temporal uncertainty: The participants do not know when or where the cue or target will appear. The task occurs in an unstable environment, with objects briefly appearing and disappearing at various locations. In contrast, in traditional visual search, the task involves only spatial uncertainty: The participants do not know where the target is, but the search environment remains stable throughout the trial. So whereas cuing tasks are about identifying an event—the appearance of a target (following a nontarget cue) at an unspecified time—search tasks are about finding an object (the search target). It is not surprising, then, that objects may play a more crucial role in IOR during visual search than during cuing tasks. If so, one might expect that, as has been observed several times in the literature, when the objects in a visual search display disappear, inhibitory tags likewise disappear, whereas, when a visual search display remains visible, inhibitory tags persist along with the search objects. After all, if inhibitory tagging really serves as a mechanism to prevent observers from revisiting distractor items in visual search, one would expect these tags to disappear once these objects are gone.

Although appealing on the surface, the idea that inhibitory tags persist only as long as the search items that they are associated with remain visible rules out the possibility that IOR can function as a facilitator in more complex search situations, such as when a visual search is interrupted. When observers view brief presentations of a search display interspersed with blank displays or other interruptions, they are able to use information from previous looks at a search display to quickly resume their search when the display reappears (Lleras, Rensink, & Enns, 2005, 2007; Shen & Jiang, 2006; van Zoest, Lleras, Kingstone, & Enns, 2007). This ability to perform interrupted visual search suggests that perhaps observers can maintain inhibitory tags even in the absence of the search display. Is the lack of evidence in the literature for inhibitory tagging in the absence of search displays a consequence of the type of search performed or an inherent characteristic of tagging? Do inhibitory tags in visual search come and go with the search items to which they are attached, or can the visual system flexibly assign and maintain tags to reflect the requirements of the particular search at hand? If IOR is truly a mechanism that aids visual search, it would be maladaptive for the visual system to clear inhibitory tags during momentary interruptions to the search task. We present evidence suggesting that the circumstances under which observers maintain inhibitory tags are more flexible than has previously been indicated. Although observers performing traditional visual searches release inhibitory tags once the search display is removed (e.g., Klein & MacInnes, 1999; Müller & von Mühlenen, 2000; Takeda & Yagi, 2000), when it is adaptive for observers to hold onto inhibitory tags after removal of the search display, as is the case in interrupted search, they do in fact maintain these tags. Finally, we also exploited the uniqueness of the interrupted search paradigm in stretching out the duration of search trials to probe distractor locations before the visual search was actually completed. In doing so, we found that, early in a trial, search locations are in fact prioritized and only become tagged with inhibition later in the trial as the search progresses.

EXPERIMENT 1

In order to investigate inhibitory tagging in interrupted visual search, we presented participants with a serial interrupted search task in which they looked for the presence of a T-shaped target in a field of L-shaped distractors. The participants viewed the search display for short intervals that were interspersed with presentations of a blank display containing only a fixation cross. Following completion of the search task, the search display was removed. On half of the trials, the participants then performed a probe-detection task in which they quickly responded to a small probe dot presented either at a location previously occupied by a distractor item (*on* probe) or at a previously empty location (*off* probe). Previous studies of inhibitory tagging in visual search have shown that, when the search display is removed before probes appear, the RTs to detect these probes do not show the typical IOR pattern, suggesting that observers maintain inhibitory tags only as long as they can see the search display. However, by placing the participants in the context of an interrupted visual search, where maintaining inhibitory tags across blank intervals would presumably help them to perform the search task, we hoped to create conditions under which we would find evidence for inhibitory tagging in the absence of a search display.

Method

Participants. Eighteen undergraduate students participated in one experimental session approximately 45 min long. The participants received course credit for their participation.

Stimuli and Apparatus. The participants viewed a black fixation cross; black T and L shapes oriented 0º, 90º, 180º, or 270º from their upright positions; and black probe dots presented on a white background on a 17-in. color monitor with a resolution of 1,024 × 768 pixels and a refresh rate of 60 Hz. The participants

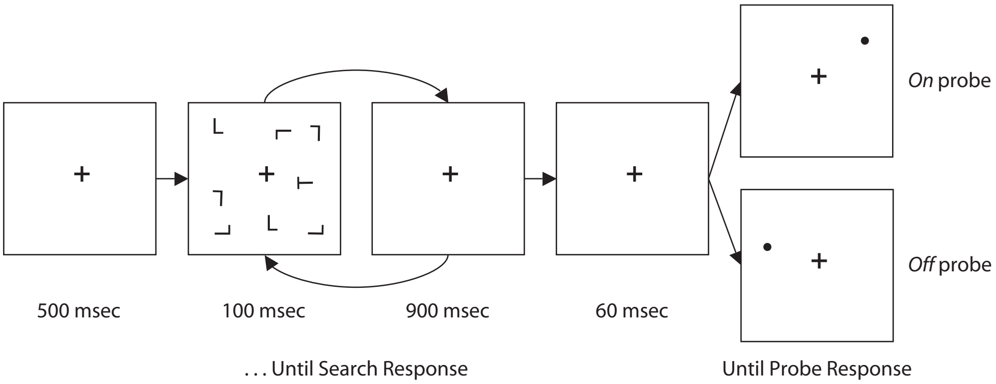

Figure 1. Sequence of events for a probe-detection trial in Experiment 1. Items are depicted larger than their actual size in the experiment.

sat approximately 16.5 in. from the computer monitor. At this distance, individual T and L stimuli subtended approximately 0.54º of visual angle, and probe dots subtended approximately 0.10º of visual angle. Search grids subtended approximately 6º–8º of visual angle, depending on set size. All responses were collected via a standard computer keyboard.

Procedure. Figure 1 shows the sequence of events for a probe-detection trial. Each trial began with the presentation of a central fixation cross that remained on the screen throughout the trial. After 500 msec, a search display with either 8 or 16 items appeared on the screen for 100 msec. This search display alternated with a 900-msec blank display (which included a fixation cross) until the participants made a response to the search task (or 20 sec had elapsed). The participants searched for a T shape and used the down arrow key to report the T's presence and the right arrow key to report its absence. For target-present trials, the search display consisted of 15 or 7 L-shaped distractors (depending on set size) and one T-shaped target; for target-absent trials, all items on the display were L-shaped distractors.

On probe-detection trials, 60 msec after the participants had made their search response, a small probe dot appeared on the screen with a fixation cross. This probe could be presented either at a location previously occupied by one of the distractor items from the search display (*on* probe) or at a previously empty location that had been unoccupied during search display presentations (*off* probe). Probe location was balanced between the left and right visual fields. The participants pressed the left shift key as soon as they detected the probe. The probe display remained on screen until the participants had made their detection response.

Design. The participants completed 10 practice trials for which data were not analyzed and 10 blocks of 32 trials each. Within a block, 50% of all trials were set size 16, and 50% were set size 8. Within each set size, 50% of the trials were target-present trials, and 50% were target-absent trials. On 50% of these trials, a probe-detection display was presented, 50% of these being *on* probes and 50% being *off* probes.

Results and Discussion

Trials in which the participants failed to complete the search task within 20 sec or made an incorrect search response were eliminated from the analyses (7.7% of trials), as were trials in which the search task or probe-detection RTs fell above or below two standard deviations from an individual participant's mean for a particular cell of the design (4.3% of trials).

Before we can address the issue of inhibitory tagging in an interrupted search task, it is first necessary to demonstrate that the search task required the participants to attend to individual items in the search display; if the participants were able to complete the search preattentively, there would be no reason for them to create inhibitory tags. Mean RTs for the interrupted search task are shown in Figure 2. Search slopes (defined as an increase in RT per item in the search task) were calculated for target-present and target-absent conditions (target present, $M = 172$ msec/item; target absent, $M = 324$ msec/item).[1] A paired-sample t test showed that these slopes were significantly different [$t(17) = -10.60$, SD difference $= 60.6$, $p < .001$]. This difference between slopes for target-present versus target-absent trials demonstrates that the participants were inefficient in the interrupted visual search task, suggesting that they processed the search array by directing attention to individual items or regions in the display. These are the search circumstances under which we might expect to find evidence of inhibitory tagging.

Our primary question of interest was whether the participants would be slower to detect *on* probes than *off* probes, as we would expect if inhibitory tags associated with distractor items persisted when the search display

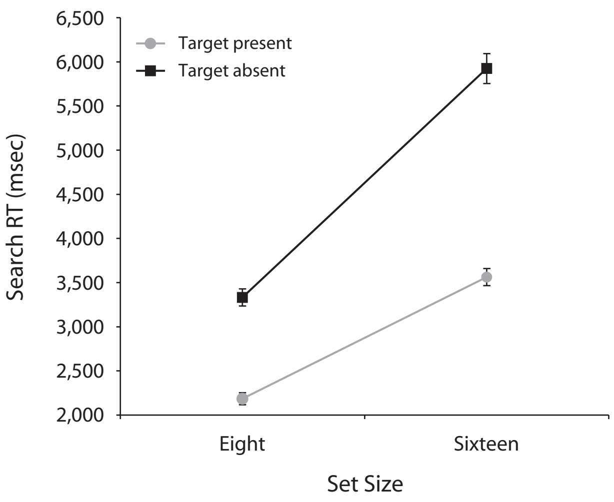

Figure 2. Mean search reaction times (RTs) in Experiment 1.

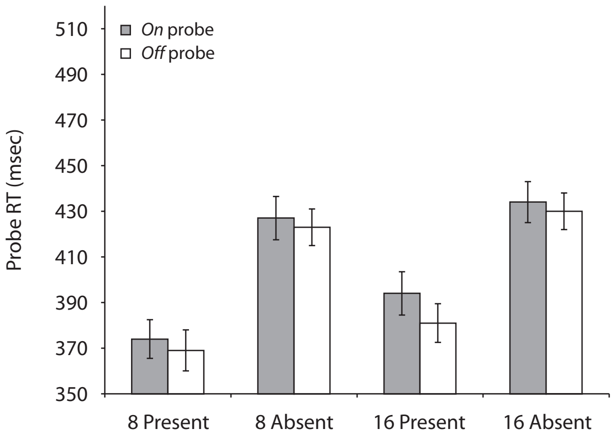

Figure 3. Mean probe-detection reaction times (RTs) in Experiment 1.

was no longer visible. Figure 3 shows the mean RTs for the probe-detection task. As can be seen from the figure, across set sizes of 8 and 16 and across both target-present and target-absent trials, the participants were consistently slower to detect *on* probes than they were to detect *off* probes, even though the magnitude of the difference was decidedly small. A probe type (*on* vs. *off*) × target type (present vs. absent) × set size (8 vs. 16) ANOVA confirmed these impressions, with significant main effects of probe type [$F(1,17) = 7.77$, $MS_e = 3,532$, $p = .01$], target type [$F(1,17) = 54.21$, $MS_e = 1,599$, $p < .01$], and set size [$F(1,17) = 5.59$, $MS_e = 819$, $p = .03$] and no significant interactions (all ps $> .2$).[2] These results show that, although the search display was no longer visible, participants were still inhibited from returning attention to a location previously occupied by a distractor item. In other words, the context of the interrupted visual search encouraged the participants to maintain inhibitory tags in the absence of the search display.

Whereas most earlier experiments examining inhibitory tagging in visual search looked for differences in *on–off* probe RTs between serial and parallel searches in order to compensate for the masking present in both types of searches, preattentive searches do not lend themselves well to study in an interrupted search paradigm. Typically, only one brief presentation of the search display is necessary for participants to complete a parallel search, precluding a true interrupted visual search with multiple inspections of the search display. In our paradigm, then, we were unable to look for *on–off* probe RT differences in a preattentive interrupted search and to compare those differences with those that we obtained in our serial interrupted search. Although this may leave open the possibility that the *on–off* probe differences that we did observe were due to forward masking rather than to inhibitory tagging, the characteristics of our displays make this interpretation of the results unlikely. We largely avoided the problem of distractors in the search display masking the probe by using brief display presentation times (100 msec) and presenting probes after a participant's search response had been recorded; on a typical probe trial, the probe actually appeared 515 msec after the display, thereby eliminating any possible reduction in visibility due to forward masking, which typically requires much shorter interstimuli intervals (less than 100 msec; see Breitmeyer, 1984). The interval between display offset and probe onset was less than 100 msec on only 3.2% of trials. When these potential masking trials are dropped from our analysis, we are still left with the same pattern of results: significant main effects of probe type [$F(1,17) = 10.23$, $MS_e = 157$, $p = .01$], target type [$F(1,17) = 58.93$, $MS_e = 25,433$, $p < .01$], and set size [$F(1,17) = 7.38$, $MS_e = 747$, $p = .02$] and no significant interactions (all ps $> .2$). These results suggest that inhibitory tagging, rather than forward masking, was responsible for the significant *on–off* probe difference that we obtained.

EXPERIMENT 2A

Most experiments examining IOR in visual search have found that inhibitory tags persist only as long as the search display remains visible to the participants, but we have found that inhibitory tags can remain even in the absence of the search display when the participants perform an interrupted visual search. Although the participants in our first experiment were consistently slower to detect small dot probes that were presented in locations previously occupied by distractor items from the interrupted search than they were to detect probes that were presented in previously empty locations, this difference was, on average, only 6.5 msec. Presumably, RTs to detect dot probes were influenced primarily by a decaying location-based IOR. However, as we have already noted, objects may play an important role in IOR (e.g., Tipper et al., 1991), an aspect of which the design of our first experiment did not take full advantage. In Experiment 2A, we asked participants to perform an interrupted visual search that encouraged not only location-based IOR, but also object-based IOR, with the expectation that we would find more robust evidence of inhibitory tagging in the absence of a search display.

We once again presented participants with a serial interrupted search task in which they looked for the presence of a T-shaped target in a field of L-shaped distractors. Once the participants completed the search task, the search display was removed and, on 50% of the trials, was replaced with a probe display. Unlike in Experiment 1, in which probes were small dots, in Experiment 2A, we used the same L shapes both as distractors in the search array and as probes. In the case of *on* probes, the probe was identical to the distractor that had occupied that location in the search display. In the case of *off* probes, a new L shape was presented at a previously unoccupied location in the search display. By using *on* probes that were essentially repetitions of distractor items from the search display, we attempted to maximize the contribution of object-based IOR to the inhibitory tagging in this search task. In addition, by using the same L shapes as both distractors and probes, we also avoided the possibility of forward masking of the probe.

Method

Participants. Sixteen undergraduate students participated in one experimental session approximately 45 min long. The participants received course credit for their participation.

Stimuli and Apparatus. The stimuli and apparatus were identical to those in Experiment 1, with the exception that, instead of viewing small dot probes, the participants saw L-shaped probes.

Procedure and Design. The procedure and design of Experiment 2A were the same as those in Experiment 1, with the following exception: On probe-detection trials, 60 msec after the participants had made their search responses, a probe stimulus appeared on a display consisting of the fixation cross and the L-shape probe. This probe could be either a repetition of one of the distractor items from the search display, appearing at the same location and orientation as the earlier distractor (*on* probe), or a brand new L shape appearing at a location that had been unoccupied during search display presentations (*off* probe).

Results and Discussion

Trials in which the participants failed to complete the search task within 20 sec or made an incorrect search response were eliminated from the analyses (11.4% of trials), as were trials in which the search task or probe-detection RTs fell above or below two standard deviations from an individual participant's mean for a particular cell of the design (7.4% of trials).

We again examined search RTs to ensure that the participants were performing an attention-demanding search. Mean RTs for the interrupted search task are shown in Figure 4. The mean search slope for the target-present condition was 146 msec/item, whereas the mean search slope for the target-absent condition was 296 msec/item. A paired-sample t test indicated that these slopes were significantly different from one another [$t(15) = -7.40$, *SD* difference $= 81.6$, $p < .001$], once again demonstrating that the participants were inefficient in the interrupted visual search task and searched by directing attention to individual items or regions of the search array.

We were primarily interested in whether we would find evidence of inhibitory tagging in an interrupted search when probe items were the same objects as distractor items.

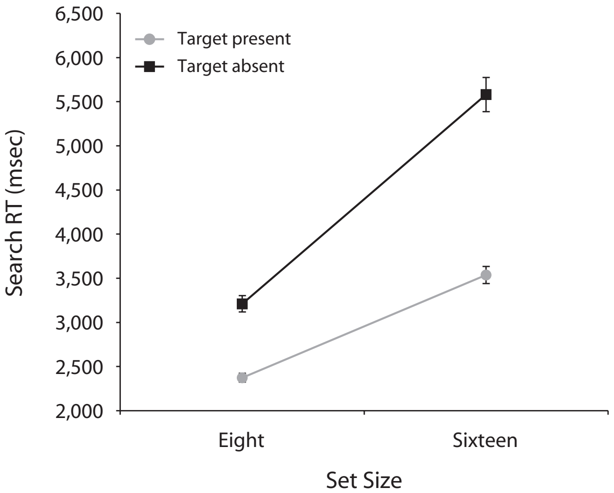

Figure 4. Mean search reaction times (RTs) in Experiment 2A.

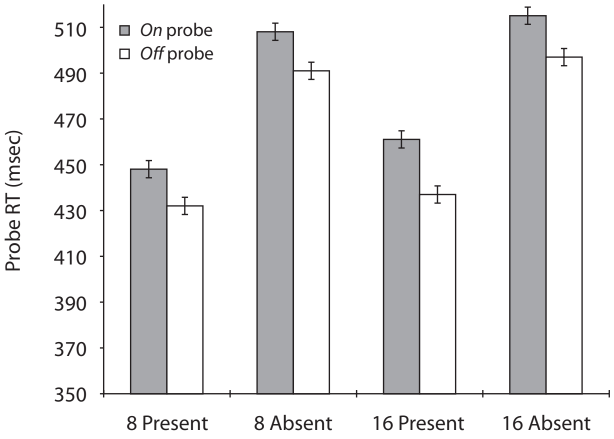

Figure 5. Mean probe-detection reaction times (RTs) in Experiment 2A.

Figure 5 shows the mean RTs for the probe-detection task. A probe type (*on* vs. *off*) × target type (present vs. absent) × set size (8 vs. 16) ANOVA showed that the participants were consistently slower to detect *on* probes (repetitions of an L-shaped distractor from the search array) than they were to detect *off* probes (brand new L shapes in previously unoccupied locations) across both set sizes and target types; there were significant main effects of probe type [$F(1,15) = 5.92$, $MS_e = 11{,}212$, $p = .03$] and target type [$F(1,15) = 31.06$, $MS_e = 109{,}512$, $p < .01$], no main effect of set size [$F(1,15) = 0.93$, $MS_e = 1{,}891$, $p = .35$], and no significant interactions (all ps $> .6$). These results replicate the findings of Experiment 1, once again showing that inhibitory tags can persist in the absence of a search display when visual search is interrupted, presumably because the context of an interrupted search encourages participants to maintain inhibitory tags across disappearances of the search display. In addition, we have demonstrated that this somewhat unusual IOR effect is not dependent on the type of probe used; we found evidence for inhibitory tagging using both small dot probes and distractor shape probes. Finally, we have also shown that the effects of IOR are more robust when participants respond to distractor shape probes—the overall RT difference between *on* and *off* probes in Experiment 2A was 18.8 msec, nearly triple the size of the RT difference in Experiment 1—most likely because these probes encourage the formation of both location- and object-based IOR.

EXPERIMENT 2B

To further ensure that the RT differences between *on* and *off* probes were the result of inhibitory tagging, we ran a control experiment using a yoked design in which participants passively viewed the same search arrays as those used in Experiment 2A before making a probe-detection response. Because the participants in this experiment did not have to search for the presence or absence of a target while viewing the search displays, there was no reason for them to form or maintain inhibitory tags associated with items in these displays. If the *on–off* probe RT differences that we observed in Experiment 2A were the result of masking, repetition blindness, a new-object advantage, or other artifacts due to the unique probe procedure, we should see the same pattern of RT differences when the participants detect probes after passively viewing search arrays. If, however, the *on–off* probe RT differences in Experiment 2A are attributable to inhibitory tagging, we should see no *on–off* probe RT differences in the passive viewing control.

Method

Participants. Sixteen undergraduate students participated in one experimental session approximately 45 min long. The participants received course credit for their participation.

Stimuli, Apparatus, Procedure, and Design. The stimuli, apparatus, and design were identical to those used in Experiment 2A. Each participant in Experiment 2B was yoked to a corresponding participant in Experiment 2A, passively viewing the identical array that the participant in Experiment 2A searched. The number of repetitions of each array was also yoked, such that the participant in the present experiment would see however many repetitions of the search array the matched participant in Experiment 2A viewed before making his or her response. The participants in the present experiment were instructed to keep their eyes fixated in the center of the display as the search array flashed on and off, without worrying about what was presented on the screen. They were required to respond only on probe trials, in which they had to press the left shift key as soon as they detected the presence of a lone L shape.

Results and Discussion

Figure 6 shows the mean probe-detection RTs for the passive viewing experiment. Because there were no significant effects associated with set size in Experiment 2A, we collapsed our data across that factor for analyses in Experiment 2B. A probe type (*on* vs. *off*) × target type (present vs. absent) ANOVA showed that there was no significant main effect of probe type [$F(1,15) = 0.38$, $MS_e = 1,953$, $p = .55$], no significant main effect of target type [$F(1,15) = 3.67$, $MS_e = 5,742$, $p = .08$], and no significant interaction [$F(1,15) = 0.05$, $MS_e = 6,207$, $p = .83$]. These results show that when the participants passively viewed exactly the same displays that the participants in Experiment 2A had actively searched, unlike the participants in Experiment 2A, they were no faster to detect a probe item appearing at a previously unoccupied location than they were to detect a probe appearing at a previously occupied location. This lack of an *on–off* probe RT difference during passive viewing helps to confirm that the results of Experiment 2A cannot be attributed to the uniqueness of our probe procedure but, rather, that they are a product of inhibitory tagging.

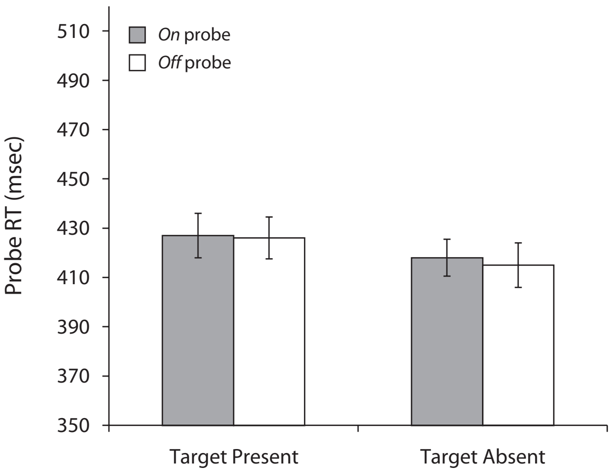

Figure 6. Mean probe-detection reaction times (RTs) in Experiment 2B.

In summary, the results of Experiment 2B provide us with strong evidence that the probes that we used in Experiment 2A do not, themselves, create a spurious IOR look-alike effect but, rather, that what we observed in Experiment 2A was truly a result of inhibitory tagging during visual search. But, if we do attribute those results to IOR, what does it mean that IOR goes away during passive viewing conditions? One could argue that the mere act of staring at a display means attending to it and, therefore, that IOR ought to be observed even in the passive viewing condition. However, such logic overlooks the goal of an IOR-like mechanism in vision. To us, it seems noncontroversial to argue that the underlying function of IOR is to prevent revisitations to inspected locations (or objects) that have recently been inspected and tagged as not containing the sought-after information. From this view, the participants in the search task are engaging in a reject-as-they-go approach: Each item or location is scrutinized. If a target is found, the search ends; if not, this location/object is rejected as a distractor and revisitations are discouraged. We argue that it is this type of scrutiny in a scene that does not take place during passive viewing: Although people may be attending to items in the scene, there is no need to reject objects or locations as distractors, since there is actually no task set defining such status. Similarly, one would argue that IOR ought not to be observed when participants are asked to scrutinize a scene in order to recall it at a later time. It would be maladaptive to put an IOR-like mechanism in place that might discourage observers from revisiting difficult-to-memorize locations in the scene. In fact, this hypothesis has been tested empirically and proven to be true. Dodd, Van der Stigchel, and Hollingworth (2009) showed that when participants are asked to view the same set of scenes while performing different tasks on these scenes, IOR was observed only when the task was to search for a target, but not when observers were asked to memorize the scene or to judge some other attribute of the scene. The findings of Dodd et al. fit nicely into our characterization of IOR as a goal-dependent mechanism, and our findings of no-IOR in the passive viewing condition of Experiment 2B are clearly consistent with their work.

EXPERIMENT 3

The data from Experiments 1 and 2A show that inhibitory tags persist in the absence of a visual search display when participants perform an interrupted search, presumably because the context of the search task motivates the visual system to maintain these tags across interruptions.

However, the results of Experiments 1 and 2A do not prove that the participants associated inhibitory tags with only actively searched distractor items instead of using these tags as placeholders for all items in the search display. In Experiment 3, we asked whether persistent inhibitory tags are exclusively associated with distractor items on which the participants focused their attention or whether inhibitory tags are also associated with unattended items in the search display. To address this issue, we manipulated the participants' attentional set, asking them to perform an interrupted visual search task in which half of the distractor items were in an attended color and half were in an unattended color. If the *on–off* probe RT difference that we observed in Experiments 1 and 2A is an attentional effect—if inhibitory tags are associated only with actively searched-for distractor items—the participants in Experiment 3 should be slower to detect probes appearing at locations previously occupied by distractor items in the attended color (*attended* probes) than to detect probes appearing at locations previously occupied by distractor items in the unattended color (*unattended* probes) or probes appearing in previously empty locations (*off* probes).

Method

Participants. Sixteen undergraduate students participated in one experimental session approximately 45 min long. The participants received course credit or were paid $8 for their participation.

Stimuli and Apparatus. The stimuli and apparatus used for Experiment 3 were identical to those used for Experiment 2A. However, instead of black T and L shapes, the participants in Experiment 3 viewed red and blue shapes.

Procedure and Design. The sequence of trial events was identical to that in Experiment 2A. Search displays contained 16 items: Half were red, and half were blue. The participants were told at the beginning of the experiment to which color they should attend. On target-present trials, the target was always presented in the attended color. Likewise, on probe-detection trials, the probe was always presented in the attended color. Attended and unattended color presentations were counterbalanced across participants.

On probe-detection trials, the L probe could appear in one of three different types of locations. In the *attended probe* condition, the L probe appeared at the location of an attended-color distractor, and it was in the same orientation as the distractor that had previously occupied that location. Similarly, in the *unattended probe* condition, the L probe appeared at the location of an unattended-color distractor, and it was also in the same orientation as the L shape that had previously occupied that location. Finally, in the *off probe* condition, a new L shape appeared at a previously unoccupied location.

The participants performed 10 practice trials, followed by 10 blocks of 32 trials each. Fifty percent of all probe-detection trials were *off* probe trials, 25% were attended probe trials, and 25% were unattended probe trials. Within each of these types of trials, half of the trials were target-present and half were target-absent trials.

Results and Discussion

As in Experiments 1 and 2A, trials in Experiment 3 were dropped if a participant made a search error (6.4% of trials) or if either the search or the probe-detection RT for an individual participant fell above or below two standard deviations from the mean for that individual's cell in the design (7.0% of trials).

Figure 7 shows the mean search RTs for Experiment 3,[3] whereas Figure 8 displays mean probe-detection RTs. As

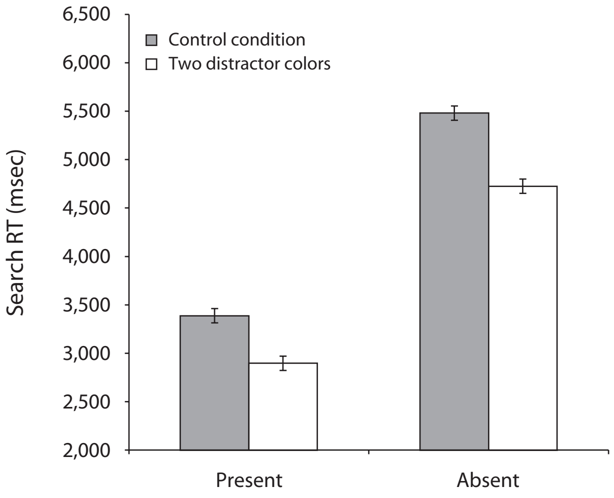

Figure 7. Mean search reaction times (RTs) in Experiment 3.

can be seen from Figure 8, the participants were slower to detect *attended* probes than they were to detect either *unattended* or *off* probes across both target-present and target-absent trials. A probe type (*attended* vs. *unattended* vs. *off*) × target type (present vs. absent) ANOVA showed a significant main effect of probe type [$F(2,30) = 3.24$, $MS_e = 3{,}319$, $p = .05$], a main effect of target type [$F(1,15) = 12.32$, $MS_e = 51{,}523$, $p = .003$], and no interaction between probe and target type [$F(2,30) = 0.53$, $MS_e = 370$, $p = .59$]. LSD pairwise comparisons showed that there was no difference between probe RTs for *unattended* versus *off* probes (95% confidence interval [CI] for difference lower bound $= -7.63$, 95% CI for difference upper bound $= 9.25$). This result shows that the participants were inhibited from returning attention to probe items that were presented in the same location as the distractor items in the search display, but only when these probe items were part of the attended set of distrac-

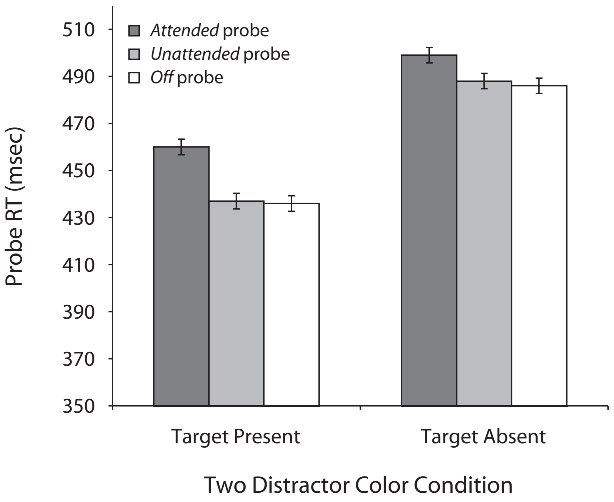

Figure 8. Mean probe-detection reaction times (RTs) in Experiment 3.

tor items. In other words, inhibitory tags were associated only with actively searched items. This finding is an interesting contribution to the literature on IOR. In the context of cuing tasks, the influence of attentional set on IOR is actually not yet well understood, and empirical findings are somewhat mixed, with perhaps a tendency to find some modulation of IOR by attentional set (e.g., Gibson & Amelio, 2000; Pratt & McAuliffe, 2002; Pratt, Sekuler, & McAuliffe, 2001). Our present results do suggest that attentional set can influence the formation of inhibitory tags in the context of a visual search task.

EXPERIMENT 4

The data from Experiments 1 and 2A suggest that inhibitory tags persist in the absence of a visual search display when participants perform an interrupted search, presumably because the search context motivated the visual system to maintain these tags. In previous studies showing inhibitory tagging in visual search, to-be-detected probe items have always been presented following the completion of visual search, suggesting that, even though participants are finished with the search task, they still hang on to the inhibitory tags associated with that task for at least a short time afterward, at least when the search display is continuously visible (e.g., Klein & MacInnes, 1999; Müller & von Mühlenen, 2000; Takeda & Yagi, 2000). As in those studies, in Experiments 1–3, we presented probes after the participants had completed the search task and found a similar result: The participants did seem to hang on to the inhibitory tags for a little while after the completion of the search task, even though the search task had been completed and the search displays had been turned off *several hundred* milliseconds beforehand. What has been missing in all of these previous studies is an examination of the role that these inhibitory tags play in performance *before* the search is completed. Arguably, one would hope that the postsearch probing technique is assessing something about how observers searched the display and is not some postresponse artifact. Thanks to the unique nature of the interrupted search paradigm, which functionally stretches out search times over several seconds (and several display presentations), we can now easily address this issue by sometimes probing participants before they have had a chance to complete the search task (i.e., while search is still ongoing).

Method

Participants. Twenty-two undergraduate students participated in one experimental session approximately 45 min long. The participants received course credit or were paid $8 for their participation.

Stimuli and Apparatus. The stimuli and apparatus used for Experiment 4 were identical to those used for Experiment 2A.

Procedure and Design. We asked the participants to search a display with 16 items for a T-shaped target amidst L-shaped distractors. Their task was to find the T-shaped target and to press the down arrow key if the target was facing to the left and the right arrow key if it was facing to the right. As in Experiments 1, 2A, and 3, the search display would appear for 100 msec and then be replaced by a display containing only a fixation cross for 900 msec. The participants were told that at any time during the search task, a lone L shape could appear onscreen and remain there until they pressed the left shift key. In reality, an L probe would appear in place of the search display after one, two, or three repetitions of the search display (i.e., 900 msec after offset of the previous search display). If the participants completed their search before the probe was programmed to appear, the probe was presented 60 msec after their search response, as in Experiment 2A.

The participants performed 10 practice trials, followed by eight blocks of 48 trials each. To increase our sample of probe responses that occurred before visual search completion, unbeknownst to the participants, a target was present in the search display on only 50% of trials. Therefore, although the participants believed that there was a target on every trial for them to find and that, on many trials, they were too slow to find this target and discriminate which way it faced before the probe appeared, in fact, there was often simply no target to be found. On trials in which a target was present, the search display was presented up to three times. If a participant did not respond to the search display after the third presentation, a probe was presented in place of a fourth presentation of the search display. For the 50% of trials in which search displays lacked a target, the probe was presented equally often in place of the second, third, or fourth presentation of the search display. *On* and *off* probes were counterbalanced across conditions.

To keep the participants motivated to actively search for the target instead of always simply waiting for a probe to appear, we introduced a scoring system and encouraged them to maximize their scores. The participants were awarded 10 points for every correct search response that they made and 1 point for every probe-detection response that they made in under 500 msec. Following every trial, the participant's score appeared for 500 msec before a new trial began.

Results and Discussion

For trials in which a target was present in the search display, the participants were, on average, 60% accurate in finding the target and reporting the direction that it faced within three repetitions of the display. We analyzed only the probe-detection RT data for trials in which probe presentation occurred during visual search (i.e., before the participants made a discrimination response), eliminating trials in which the participants made a false alarm response (15%) and trials in which probe-detection RTs fell above or below two standard deviations from the individual participant's mean for a particular cell of the design (5%).

Figure 9 displays mean probe-detection RTs for the acceptable trials in which probe presentation occurred during visual search. As can be seen from the figure, when the participants had to detect a probe after only one repetition of the search display, they actually tended to be faster

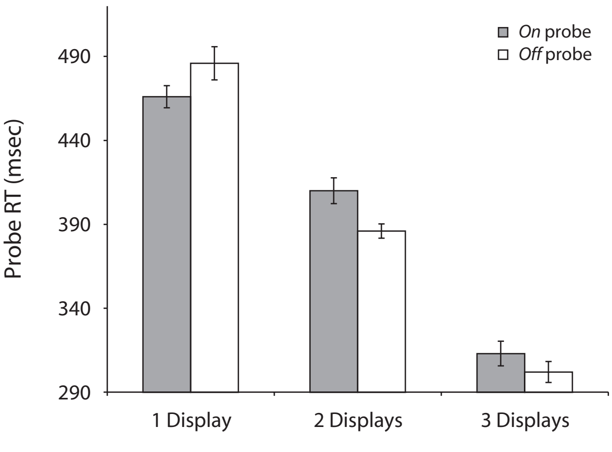

Figure 9. Mean probe-detection reaction times (RTs) in Experiment 4.

to detect *on* probes than *off* probes, showing a facilitation for probes that were repetitions of distractor items from the search display, whereas after two or three repetitions of the search display, they showed the inhibitory effect, in which they were faster to detect *off* probes than *on* probes. A probe type × number of display repetitions ANOVA showed a significant main effect of number of display repetitions [$F(2,42) = 109.98$, $MS_e = 119{,}098$, $p < .001$] and no main effect of probe type [$F(1,21) = 0.91$, $MS_e = 22{,}115$, $p = .35$] but did show a significant interaction between probe type and display repetitions [$F(2,42) = 3.26$, $MS_e = 71{,}973$, $p = .048$]. The main effect of number of display repetitions is presumably the result of the increasing probability that a probe would appear after each iteration of the search display. That is, if the probe did not appear after the first search display presentation, it would have to appear after the second, third, or fourth presentation; if it failed to appear after the second display, there was an even greater chance that it would appear after the next display, and so on. This type of increasing hazard function has been known to increase response preparation and shorten RTs as a function of the increasing foreperiod from the start of the trial to target onset (e.g., Drazin, 1961; Woodrow, 1914). Thus, we can attribute the overall RT speedup with increasing number of display presentations to this preparatory/anticipatory effect.

Of greater interest to our questions about inhibitory tagging is the significant interaction between probe type and the number of display repetitions. In line with the results of our earlier experiments, when participants looked at the search display multiple times, we found evidence of inhibitory tagging, with participants being faster to respond to probes in previously unsearched locations than to probes that were repetitions of a distractor item. The fact that these probes were presented while the participants were still actively engaged in the visual search task lends support to our claim that it is the context of an interrupted search that motivates participants to maintain inhibitory tags even in the absence of the search display. Interestingly, however, we saw a reversal of the IOR pattern when the participants had to respond to a probe after only having seen the search display once. Presumably, early in the search process, observers prioritized to-be-inspected locations, and we believe that this IOR reversal reflected that positive prioritization. The participants responded more quickly to *on* probes than to *off* probes after one presentation of the search display, because this single presentation allowed enough time to segregate and prioritize locations but not enough time to inspect (and hence to attach inhibitory tags to) many of these locations. As the participants saw additional repetitions of the display, they had time to inspect and tag more items, and hence to build up more IOR, leading to the crossover effect that we observed. Finally, we should note that the *on–off* difference effect appeared to be additive to the overall main effect of number of displays. This is not entirely surprising: If we take the *on–off* probe RT differences as reflecting differences in attentional and search processes, those processes ought to be independent of any anticipatory effects observed in the simple response to the probe stimulus.

GENERAL DISCUSSION

Previous research has shown that inhibitory tagging serves as an adaptive mechanism for improving visual search efficiency by discouraging revisitations of already searched items and biasing attention toward items that have yet to be examined. However, this research has imposed a limitation on inhibitory tags, suggesting that they persist only as long as the search display remains visible. We have shown that, when the context of a visual search motivates participants to hold aspects of the search display in memory, as is the case in an interrupted visual search, inhibitory tags persist even in the absence of the search display. In Experiment 1, participants performed an interrupted visual search and were slower to detect luminance probes presented in a location previously occupied by a distractor item than to detect probes that appeared at previously empty locations from the search display, even though these probes were presented when the search display was no longer visible. This evidence of inhibitory tagging was even stronger in Experiment 2A, in which participants again performed an interrupted search and were slower to detect probes that were repetitions of distractor objects from the search display than to detect new distractor-like objects, again even though these probes were presented after the search display was gone. In Experiment 3, we showed that this inhibitory tagging in the absence of the search display was an attentional effect. In this experiment, inhibitory tags were associated only with distractor items that fit the participants' attentional set: Probes appearing in the same locations as unattended distractor items were detected just as quickly as novel probes that appeared at previously unoccupied locations in the display. In Experiment 4, we showed that inhibitory tagging in the absence of the search display occurs when probes are presented during the search task, but only after participants have had sufficient exposure to the search display: Initially, search locations seem to be, in fact, positively prioritized (rather than deprioritized by IOR). Taken together, the results of these experiments suggest that inhibitory tags are more robust than previously believed and can survive the disappearance of the search display if the participants have a reason to maintain them in memory.

Although our results seem contrary to prior findings on inhibitory tagging in visual search that failed to find evidence for inhibitory tags once the search display had been removed (e.g., Klein & MacInnes, 1999; Müller & von Mühlenen, 2000; Takeda & Yagi, 2000), we feel that our results should not nullify the conclusions of these earlier studies but, rather, that they suggest that these conclusions be expanded. When participants perform a traditional visual search in which the search display remains continuously visible, there is no reason for the visual system to maintain inhibitory tags after the search items disappear. At that point, the search is complete, and the objects associated with that search are gone. However, in an interrupted search, most of the visual search actually occurs during intervals in which the to-be-searched-for items are invisible, so the visual system has a compelling reason to hang onto inhibitory tags when the objects disappear. In sum, our study shows that inhibitory tags are not always tied to visible stimuli but that the context of a visual search must be taken into account when making predictions about when and how IOR will aid search. Furthermore, our results suggest an adaptive flexibility in the visual system; when observers have a good reason to hold onto inhibitory tags in the absence of a search display (as is the case during an interrupted search), they do, whereas, when there is no advantage to maintaining inhibitory tags in the absence of a search display—as is the case in continuous searches, such as those employed by Klein and MacInnes (1999), Müller and von Mühlenen (2000), and Takeda and Yagi (2000)—they do not. In other words, our research indicates that IOR might not strictly be an automatic attentional effect but that top-down considerations, such as our intentions and the manner in which we interact with the visual world, can moderate how and when IOR is observed.

AUTHOR NOTE

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NOTES

1. Although these search slopes may seem prohibitively high, they are to be expected from an interrupted search paradigm. Although the participants certainly are working toward completing the search during blank intervals (e.g., Lleras et al., 2005), if they do not have enough information to confidently complete the search, they must wait until the display reappears and they can sample more information, thereby inflating their search times.

2. One may have expected interactions between probe type and target type (with a greater *on–off* probe RT difference for target-absent than for target-present trials) because of the greater potential for an *on* probe to have been presented at a tagged location in this case. However, search RTs were substantially (many hundreds of milliseconds) longer for target-absent than for target-present trials, leaving open the possibility that any gain in the number of inhibitory tags for target-absent trials was offset by decay of these tags over the longer search time.

3. This figure also shows the search RTs of 16 additional participants who performed in a control condition in which all 16 items in the search display were the same color. As can be seen in this figure, although the participants in both conditions viewed 16-item displays, the participants in the same-color control condition were consistently slower in their searches [$F(1,30) = 4.36$, $MS_e = 7,854,006$, $p = .05$], suggesting that our manipulation of attentional set was effective; the participants were able to selectively focus attention on items in the attended color, spending less time overall searching, because they did not have to direct focused attention to items in the unattended color.

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