Vision Research 50 (2010) 220–228

Contents lists available at ScienceDirect

Vision Research

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

Searching for inhibition of return in visual search: A review

Zhiguo Wang [a,b,*], Raymond M. Klein [c]

[a] State Key Laboratory of Brain and Cognitive Science, Institute of Psychology, Chinese Academy of Sciences, Beijing, China
[b] Graduate University of Chinese Academy of Sciences, Beijing, China
[c] Dalhousie University, Halifax, Nova Scotia, Canada

ARTICLE INFO

Article history:
Received 29 June 2009
Received in revised form 14 October 2009

Keywords:
Attention
Visual search
Inhibition of return
Eye-movement
Foraging

ABSTRACT

Studies that followed the covert and overt probe-following-search paradigms of Klein (1988) and Klein and MacInnes (1999) to explore inhibition of return (IOR) in search are analyzed and evaluated. An IOR effect is consistently observed when the search display (or scene) remains visible when probing and lasts for at least 1000 ms or about four previous inspected items (or locations). These findings support the idea that IOR facilitates foraging by discouraging orienting toward previously examined regions and items. Methodological and conceptual issues are discussed leading to methodological recommendations and suggestions for experimentation.

1. Introduction

Visual foraging behavior, such as looking for your car in the parking lot or a friend in a crowded party, is very important for human beings in daily living. To guarantee successful foraging behavior there must be some mechanism that guides (or biases) attention to uninspected locations to sample information. Inhibition of return (IOR), which was first discovered by Posner and Cohen (1984) see Klein (2000) for a review, has been put forward as such a mechanism (Itti & Koch, 2001; Klein, 1988; Shore & Klein, 2000).

In their seminal paper on IOR, Posner and Cohen (1984) developed a model task in which non-predictive peripheral cues were followed by targets that require simple detection responses. They found that response time (RT) to targets appearing at a previously cued location are faster than to those appearing at an uncued location (facilitation effect) so long as the cue–target asynchrony (CTOA) was short. However, this facilitation effect evolves into an inhibition effect when CTOA exceeds 200 ms, as exhibited by slower RTs for targets presented at a cued location than for targets at an uncued location. Posner and Cohen (1984) proposed that the function of IOR is to encourage orienting toward novel items:

> "We believe that the inhibition effect evolved to maximize sampling of the visual environment. Once the eyes move away from the target location, events that occur at that environmental location are inhibited – with respect to other positions. This would reduce the effectiveness of a previously active area of space in summoning attention and serve as a basis for favoring fresh areas at which no previous targets had been presented. The long-lasting nature of inhibition (1.5 s or more) seems to be about the right length to ensure that the next movement or two will have a reduced probability of returning to the former target position" (p. 550).

Extending this functional explanation of IOR, Klein (1988) proposed that IOR might facilitate foraging in tasks that require attention-demanding serial inspections by discouraging orienting toward previously examined regions and items. On the one hand, compared to completely random (memoryless) search, some amount of memory for where attention had been would make search more efficient (Horowitz & Wolfe, 2003). On the other hand, in the context of a 'winner-take-all' algorithm that might control orienting (cf. Itti & Koch, 2001) a mechanism, like IOR, that could overcome the salience of a "winning" item once it had been inspected would be necessary to avoid perseverative orienting. Klein and colleagues tested this foraging facilitator proposal of IOR with two different paradigms[1]: the covert probe-following-search paradigm (Klein, 1988, 1989, as reported in Klein & Taylor, 1994) and the overt probe-following-search paradigm (Klein & MacInnes, 1999,; MacInnes & Klein, 2003). Their logic was simple: if and when

* Corresponding author. Address: Institute of Psychology, Chinese Academy of Sciences, 4A Datun Road, Chaoyang District, Beijing 100101, China. Fax: +86 010 6483 7182.
E-mail address: wangzg@psych.ac.cn (Z. Wang).

[1] Some studies presented probes during search. For convenience, we use "probe-following-search" as a label to refer to studies reviewed in the present paper because search usually stops when the probe appears.

0042-6989/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.visres.2009.11.013

IOR is operating as a foraging facilitator, then inhibitory tags would be left at locations that had been inspected and consequently the processing of probes presented at these old locations would suffer compared to probes presented at new locations. Essentially, a search task is used to hypothetically generate IOR while the probe task is use to measure it (see Fig. 1). Over 20 years have elapsed since the first "probe-following-search" study by Klein (1988) and as such we thought a review of the methods and findings stimulated by this seminal study would be useful.

1.1. Covert probe-following-search paradigm

Following Posner and Cohen's (1984) cue-and-target logic, Klein (1988) tested the foraging facilitator proposal of IOR by combining a search task with a probe-detection task (covert probe-following-search paradigm). Shortly after participants responded to a difficult search task, a luminance probe was presented at locations occupied by the search array (on-probe) or at empty locations (off-probe). If IOR is operating in difficult search, inhibitory tags would be left at all or some locations occupied by distractors in the search display, as a result reaction time to on-probes should be longer than to off-probes. Klein recognized that there might be costs and benefits for probe detection rooted in the physics of the display (proximity to the contours of display items) or to real or perceived probabilistic relations between the display layout and the probed locations. He, therefore, included an easy (pop-out) search task to serve as a baseline condition to control for such factors. In pop-out search target is detected "pre-attentively", no serial deployment of attention is involved, and therefore inhibitory tags would not, by hypothesis, be generated. Consequently, there should be no IOR at the locations of distractors following pop-out search. According to the foraging facilitator proposal the RT difference between on- and off-probe (for convenience, we call it on-probe cost, from now on) should be larger for the difficult search task than for the easy search task (see Fig. 1).

1.2. Overt probe-following-search paradigm

One disadvantage of the covert probe-following-search paradigm developed by Klein (1988) is that the shifting of attention must be assumed, and even under this assumption, the precise sequence of shifts is unknown. An alternative approach is to require the observer to use an overt and observable behavior to search the display. This alternative, overt, approach was first used by Klein and MacInnes (1999). In their study, participants searched for a camouflaged target, "Waldo" in pictures from Martin Handford's series of "Where's Waldo?" books while their eye position was monitored on-line. Finding "Waldo" is a difficult task that, in most pictures, requires foveation to overcome the camouflage techniques used by the author, and often takes many seconds of inspection. After several saccades a probe was presented either at a previously fixated location (on-probe) or at one of 5 equi-eccentric novel locations (off-probe). As soon as they detected a probe, participants were instructed to stop searching for "Waldo" and to make a saccadic response to the probe. Probes were classified according to the ordinal position relative to the current fixation and were labeled as 1-back (generated based on the immediately preceding fixation location) or 2-back (generated base on the fixation just prior to the last one). As illustrated in Fig. 2, for two-back probes, off-probes were the same distance from the current fixation as on-probes and varied according to their angular distance from the previously fixated (on-probe) location. The IOR foraging facilitator proposal predicts longer saccadic response time (SRT) to on-probes than to off-probes and the finding, from the Posner cuing paradigm, that there is a gradient of inhibition around a previously cued location (e.g., see Bennett & Pratt, 2001; Klein, Christie, & Morris, 2005; Maylor & Hockey, 1985), suggests that there should be a gradient of decreasing inhibition as the angular distance between the off-probe location and the on-probe location increases.

As noted above, the critical difference between the covert and overt paradigm is that with the covert paradigm the locations vis-

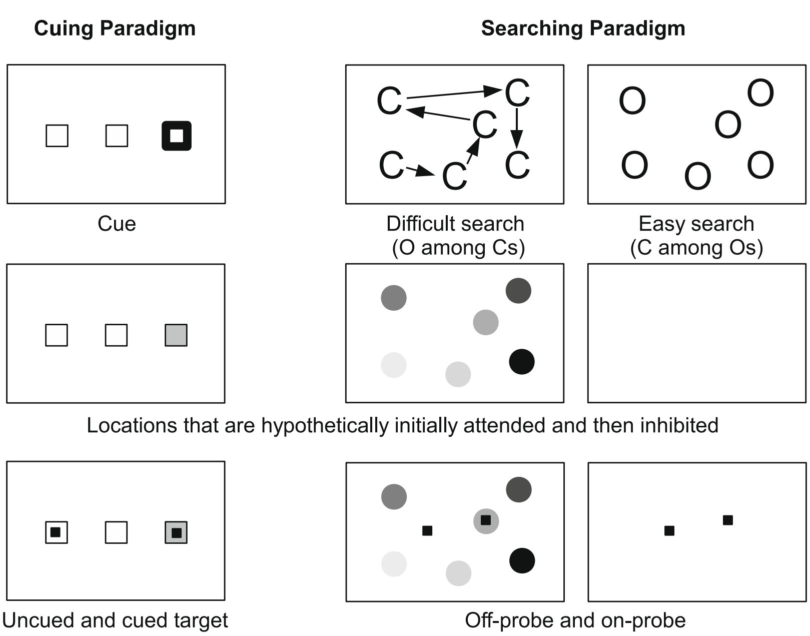

Fig. 1. Two paradigms for studying orienting and IOR. In the cuing paradigm (cf. Posner & Cohen, 1984), orienting and inhibition are generated by a single uninformative peripheral cue, and the IOR effect is defined as the reaction time (RT) difference between targets at cued and uncued locations. In the searching paradigm (cf. Klein, 1988), multiple inhibitory tags are, hypothetically, left in the display at previously inspected locations after a difficult search. This paradigm also includes an easy search (pop-out) task to control non-IOR factors that may contribute to the on-probe cost in the difficult search task. The IOR effect is operationalized as the on-probe cost in the difficult search task minus the on-probe cost in the easy search task. (Target absent trials are illustrated and arrows in the figure denote hypothesized covert shifts of attention.)

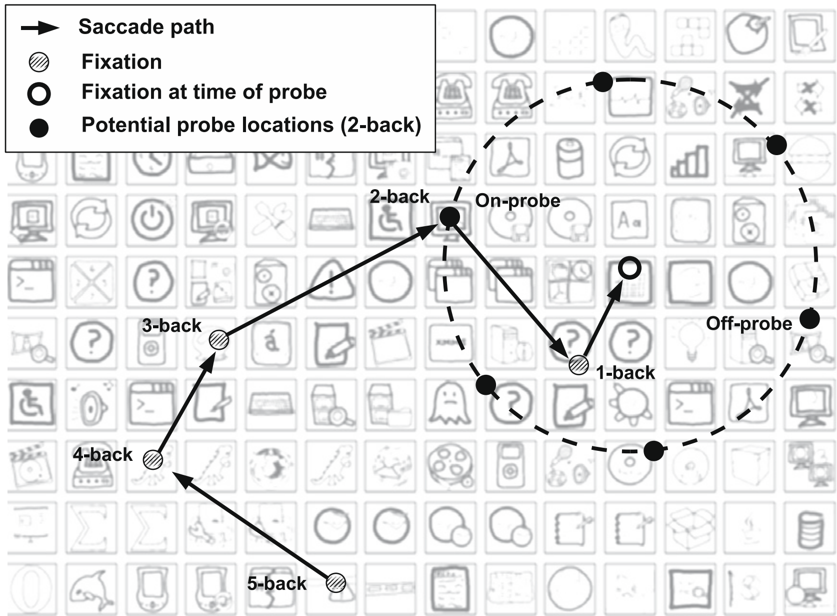

Fig. 2. Overt probe-following-search paradigm (see text for details). Redrawn from Klein and MacInnes (1999).

ited by attention must be inferred based on the assumption that search was serial and self-terminating whereas with the overt paradigm the sequence of inspections can be directly observed by the experimenter.

2. Results and discussion

Whether because most researchers have come to the conclusion that some form of "memory" mechanism is operating in difficult search tasks or because some have advanced the idea of memory-less search, the role of IOR in search has become a hot topic in the field. According to our knowledge, there are 12 published papers that have probed for IOR during or following search. These papers will be reviewed below according to whether they used tasks the same as (or similar to) the covert or the overt probe-following-search paradigm.

2.1. Covert paradigm

The covert probe-following-search paradigm has been fruitfully used to explore the role of IOR in difficult search tasks. As noted above, this paradigm typically includes two search tasks, a difficult (serial) search task and an easy (pop-out) search task (other baseline control tasks were used in a recent study, e.g. Thomas & Lleras, 2009, see Section 3 for a discussion on this issue), with the on-probe cost difference between these two tasks used as a measure of the IOR effect in difficult search. The following variables will be used to describe the findings of the studies included in the present review: task (difficult/easy), target (absent/present), probe (off/on) and display size. Klein's (1988) foraging facilitator proposal predicts that: (a) RTs to on-probes will be longer than RTs to off-probes in the difficult search task; (b) if this difference is also present in the easy task it will be larger for the difficult search task than for the easy search task (an interaction between task and probe).

2.1.1. The IOR effect and the importance of maintaining the scene

Whereas Klein (1988) reported a significant IOR effect in his two experiments, a significant interaction between task (easy/hard) and probe condition (on/off), this finding was quickly not replicated by Wolfe and Pokorny (1990) and a few years later Klein himself (cf. Klein & Taylor, 1994) wondered if his original finding was a fluke when, in three experiments, Klein failed to replicate the IOR following search effect. In their study of object and environmental coding of IOR (using a cue–target paradigm with moving objects), Tipper, Weaver, Jerreat, and Burak (1994) endorsed the foraging facilitator proposal while trying to explain the Wolfe and Pokorny (1990) non-replication of Klein (1988). They noted that "If inhibition is associated with objects... then the removal of the objects will remove the object-based inhibition... a more sensitive technique would keep visible the objects toward which attention was directed previously." (pp. 495–496). In 2000, two papers (Müller & von Mühlenen, 2000; Takeda & Yagi, 2000) were published using the covert probe-following-search method. Demonstrating the wisdom of Tipper's advice, in both studies, IOR following search was observed when the array remained visible when the probe was presented, whereas it was absent when the array was removed.

The literature on this question is summarized in Fig. 3. Here it can be seen that IOR effect was not significant in 10 experiments (labeled on the left side of the figure) in which, except for Müller and von Mühlenen (2000, Exp. 3), the display was turned off before the presentation of the probes. The exceptional study is informative because, as the authors noted, the search array might have been used by participants to predict "on" probes, thereby reducing on-probe RT and obscuring IOR if it were present. When the bias was eliminated (Exp. 4) IOR was significant. Significant IOR effects were obtained in 10 experiments (labeled on the right side of the figure) in which, except for Klein (1988) and Thomas and Lleras (2009), the display remained visible when the probes were presented. Klein and MacInnes (1999), whose overt probe-following-search experiments demonstrated a similar effect of maintaining versus removing the scene, speculated that in the exceptional experiments by Klein (1988) a high luminance setting and relatively slow decay rate of the oscilloscope phosphor may have allowed the scene to remain, albeit at reduced luminance, even after it had been turned off. In Thomas and Lleras (2009), an interrupted search task was used. In this paradigm, as first reported by Lleras, Rensink, and Enns (2005), the search array is repeatedly displayed for 100 ms and then turned off for 900 ms until the search response is made. This exceptional finding (IOR despite removal of

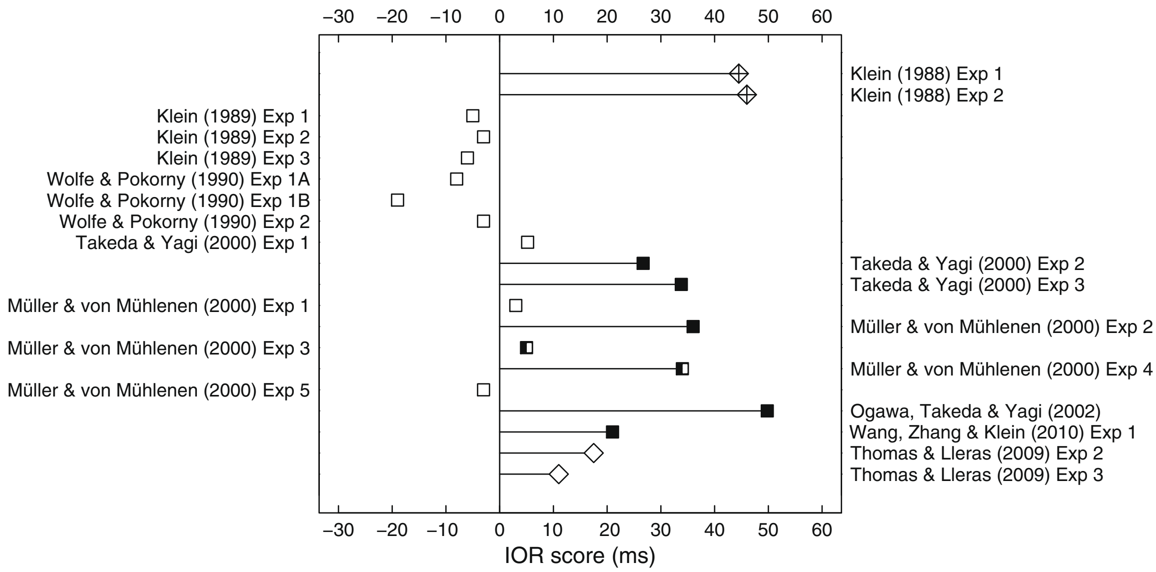

Fig. 3. IOR effect (positive scores represent IOR) in the covert probe-following-search paradigm and the importance of maintaining the search display. Filled symbols denote experiments in which the search display was maintained when probes were presented, open symbols denote experiments in which the search display was turned off when probes were presented. Symbols that are neither open nor closed represent ambiguous cases (see text). Solid lines in the figure are used to indicate that a significant IOR effect was reported by the authors. Only the IOR scores on target absent trials are shown here because all items in the display are supposed to be inspected on target absent trials and therefore, by hypothesis, on-probes would be always presented at a previously inspected, and hence inhibited, location (see next section).

the search array) can be explained if, under the conditions of interrupted search, the mental representation containing the tags is not immediately terminated when the search response is made, an idea put forward by Thomas and Lleras (2009) and discussed briefly below.

Although there are a few exceptions, the dissociation illustrated in Fig. 3 suggests, in accordance with the suggestion of Tipper et al. (1994), that the IOR effect observed by most scholars in difficult search tasks is coded in object- or scene-based coordinates such that, normally, when the scene in which the tags have been placed is removed the tags are removed with the scene. This object-IOR conclusion was strongly supported by the observation by Ogawa, Takeda, and Yagi (2002), of an IOR effect even when the to-be-searched items moved smoothly around in the display.

These findings while supporting an object- or scene-coding component, do not rule out a contribution from location-based IOR in difficult search. When the items in the display remained visible, not only the identity but also the location information is available. Studies in the cue–target IOR literature suggest that IOR can be associated additively with both object- and location-based components (Leek, Reppa, & Tipper, 2003). In Müller and von Mühlenen's (2000) Exp. 4, the target-defining features in the display were either removed (4a) or not removed (4b). When these two experiments were analyzed together, a significant IOR effect was observed that did not interact with the partial-removal of display elements. This finding is methodologically important. It suggests that it is not necessary to leave the search scene entirely intact: leaving "markers" behind where each inspected object had been was sufficient to see evidence of IOR. The theoretical implication of this finding, however, is not clear: It is consistent with a role for location-coding, so long as relevant locations are marked, but it is also consistent with the possibility that the IOR is coded in a "sketchy" representation of the scene. The fact that IOR effects were observed in interrupted search tasks (Thomas & Lleras, 2009) is consistent with the latter explanation. Perhaps participants get so good at maintaining their representation of the search array during the 900 ms periods when the array is not displayed and the target has not yet been found that the mental representation of the search array, inhibitory tags and all, is simply maintained briefly after the target is found even though the display is terminated once again.

2.1.2. The IOR effect and search target presence vs absence

On the assumption that difficult search is accomplished by a serial, self-terminating strategy, on target absent trials all the items are inspected whereas, on average only half of the items are inspected on a target present trial, and the actual number of inspected items will vary greatly from trial to trial. When combined with the finding that IOR is relatively long lasting (cf. Samuel & Kat, 2003), Klein (1988) inferred that the IOR effect following target absent trials should be about twice as large as that on target present trials. Although only one experiment (Müller & von Mühlenen, 2000, Exp. 4) reported a significant 3-way interaction between task, probe and target, viewed as a whole, the IOR scores of the 10 experiments that found significant IOR, agree with Klein's suggestion. Statistical analysis (of the data reported in Table 1 from these 10 experiments) reveals that IOR scores for target absent trials (31.88 ms) is larger than and roughly twice as large as that for target present trials (16.73 ms), $t(9) = 3.38$, $p < 0.01$.

The amount of IOR measured with the subtraction logic, and its dependence on set size and target presence versus absence, depends on the decay rate of IOR (Müller & von Mühlenen, 2000) and whether the number of inhibitory tags is limited. To the extent that inhibitory tags decay before the search is completed, only the undecayed tags would be left in the display when the probe is presented. With a display size that is twice the number of available inhibitory tags or larger, the number of useful inhibitory tags would be the same for both the target absent and target present trials and there should be no larger IOR effect observed on target absent than on target present trials. However, the near 2:1 ratio of the IOR effects for target absent and present trials should hold true with relatively small display sizes, like those which have been used so far in this literature (16 and under).

2.1.3. The IOR effect and search display size

As for the effect of search display size on the IOR effect, the available findings are mixed. Klein (1988) reported significant IOR effects independent of display size (2, 6, and 10), Takeda and

Table 1
Summary of the covert probe-following-search literature.

Source	Sample	Task characteristics			IOR score	
		Task	Exp	Display	Target-absent	Target-present
Klein (1988)	Exp. 1: $n = 14$ Exp. 2: $n = 5$	Gap task and line task Display size: 2, 6, 10	Exp. 1* Exp. 2*	Off?[a] Off?	44.5 46	22.5 28
Klein (1989)[b]	Exp. 1: $n = 9$ Exp. 2: $n = 13$ Exp. 3: $n = 10$	Gap task/line task? Display size: 2, 6, 10	Exp. 1 Exp. 2 Exp. 3	Off Off Off	−5 −3 −6	– – –
Wolfe and Pokorny (1990)	Exp. 1A: $n = 10$ Exp. 1B: $n = 10$ Exp. 2: $n = 10$	Line task (Exp. 1) Letter task (Exp. 2) Display size: 5, 10, 20[c]	Exp. 1A Exp. 1B Exp. 2	Off Off Off	−8 −19 −3	−7 8 3
Takeda and Yagi (2000)	Exp. 1: $n = 20$ Exp. 2: $n = 19$ Exp. 3: $n = 20$	Line task (Exp. 1) Gap task (Exp. 2 and 3) Display size: 4, 8	Exp. 1 Exp. 2* Exp. 3*	Off On On	5.2 26.65 33.8	−2.8 11.2 19.5
Müller and von Mühlenen (2000)	Exp. 1 & 2: $n = 10$ Exp. 3a: $n = 10$ Exp. 3b: $n = 10$ Exp. 4a: $n = 10$ Exp. 4b: $n = 10$ Exp. 5: $n = 10$	Square task Display size: 2, 6, 10 (6 and 10 in Exp. 4 and 5)[d]	Exp. 1 Exp. 2* Exp. 3ab Exp. 4ab* Exp. 5	Off On On On Off	3 36 5 34 −3	−18 5 5 14 6
Ogawa et al. (2002)	$n = 12$	Square task (items moving) Display size: 4, 8	Exp. 1*	On	49.75	13.9
Wang, Zhang, and Klein (2010)	Exp. 1: $n = 20$	Letter task Display size: 6, 12	Exp. 1*	On	21	10
Thomas and Lleras (2009)	Exp. 2A: $n = 16$ Exp. 2B: $n = 16$ Exp. 3: $n = 16$	Letter task (interrupted search)[e] Display size: 8, 16 (16 in Exp. 3 and 4)	Exp. 2* Exp. 3*	Off Off	17.5 11.1	20.2 23

Notes: *Significant IOR effect was reported. Line task: participants were asked to search for O among Qs in the hard search task and to search for Q among Os in the easy (pop-out) search task. Gap task: participants were asked to search for O among Cs in the hard search task and to search for C among Os in the easy search task. Letter task: participants were asked to search for T among Ls in the hard search task and to search for a salient feature among Ls. Square task: in the hard search task, the target is a square with the First quadrant segmented and the distractors were squares with one of the other three quadrants segmented. In the pop-out search task, the target was rotate 45° and the distractors were the same as the hard search task.

[a] In Klein (1988), stimuli were presented on a Tektronix 604 oscilloscope with p31 phosphor in a dark room, these conditions may have been optimal for visible persistence of the search display after it was "turned off" (Klein & MacInnes, 1999).

[b] Unpublished data, cited in Klein and Taylor (1994). Whether the three experiments used the gap task or the line task or both was not specified in Klein and Taylor (1994).

[c] The search task and probe-following-search task were assigned to 2 different sessions and only display size 10 was tested in the probe-following-search task. Probes were presented in 75% trials in Exp. 1A, in 50% trials in Exp. 1B.

[d] The display was partially on (target-defining item elements were removed) when probing in Exp. 3a and 4a. To ensure that every location was probed equally, 36 on-probe trials and 84 off-probe trials were presented in experiment 4 & 5 when the display size was 6. In Exp. 2, significant IOR effect was found only on target absent trials in large set size conditions.

[e] Search display was repeatedly turned-on for 100 ms and turned off for 900 ms. Only the data of Exp. 2 and 3 are presented here because no specially designed baseline condition was used in Exp. 1 and 4. In Exp. 2, a baseline was provided by a passive-viewing task (Exp. 2B). Because a yoked design was used it's questionable whether to use the subtraction method to calculate IOR effect, since the baseline condition (Exp. 2B) produced near zero on-probe cost, the on-probe costs of the search task (Exp. 2A) are reported. In Exp. 3, participants searched arrays in which half of the display items were in a non-target color that could be ignored. RT to probes presented at these supposed to be ignored locations were no greater than to probes in empty locations and consequently will be used as baseline for the IOR scores reported.

Yagi (2000) found no IOR difference between display size 4 and 8 (p. 931), Müller and von Mühlenen (2000) found clear IOR effect for set size 6 and 10 but not for display size 4 (p. 1600, footnote). Thomas and Lleras (2009, Exp. 2) found no display size (8 and 16) effect on IOR, and similar results were obtained in Wang, Zhang, and Klein (2010, Exp. 1) with display size 6 and 12. These findings, together with the logic discussed in the previous section, suggests that the optimum display size for exploring IOR in difficult search might be about 6–16. However, because of some methodological issues concerning display size (see Section 3), further studies with carefully designed display conditions are recommended.

2.1.4. Time course of IOR in search

In the covert paradigm, probes are almost always delivered shortly after the search response, in other words after the termination of searching. While the IOR that has been consistently observed at this time demonstrate the presence of IOR immediately after search, it is only by assumption that IOR was present and guiding search earlier, during the search episode. Although probes during search can and have been used in the overt paradigm (see the "Overt paradigm" section), we are only aware of one experiment, using the covert paradigm, that explored how IOR evolves (time course) during a search episode. In that experiment (Exp. 4 from Thomas & Lleras, 2009) the interrupted search paradigm (see p. 1248) was used and probes were presented 900 ms after the first, second or third display of the search array. After the first display responses were faster to on-probes than to off-probes, a facilitation effect that might reflect the allocation of attention to all array items as part of the process of building up a representation of the array that could guide search. For subsequent probes, which were presented before the search task had completed, on-probe RT was slower than off-probe RT. This crossover from facilitation to inhibition during search provides clear evidence that IOR actually tags inspected items (locations) as the foraging process evolves.

2.2. Overt paradigm

There are three noticeable methodological advantages of the overt probe-following-search paradigm. First, with participant's eye-movements or other searching behavior monitored, researchers can "see" clearly which items had been inspected, thus guaranteeing the possibility of presenting on-probes at previously inspected locations. Second, with the 1-back, 2-back,...*n*-back conditions, one could tap into the capacity (life) of inhibitory tags in difficult search tasks, much as Snyder and Kingstone (2000) did in their sequential cuing task. Last, but not least, to the extent that we can assume that the on- and off-probe locations are equivalently stimulated, no other baseline control condition (such as the easy search in the covert paradigm) is required. The overt probe-following-search literature is summarized in Table 2.

2.2.1. The IOR effect and the importance of maintaining the scene

For the overt probe-following-search paradigm, the IOR foraging proposal predicts that SRT (or RT) will be longer to probes at previously fixed locations than to probes at equivalent new locations. This prediction has been consistently supported by studies using this method (Dodd, Van der Stigchel, & Hollingworth, 2009; Klein & MacInnes, 1999; MacInnes & Klein, 2003; Thomas et al., 2006). As shown in Table 2, significant IOR effects were observed in the 1-back, 2-back, and, when tested by Dodd et al. (2009), 4-back conditions.

Encouraged by the findings in the covert search literature, (Klein & MacInnes, 1999; MacInnes & Klein, 2003) tested whether the IOR effect would be observed when the scene was removed or remained visible. An IOR effect, as indicated by slower SRT to on-probes, was not observed if the scene was removed before presenting the probes, but was observed if the scene remained visible. These findings, which were found both with probes that were presented during search (Klein & MacInnes, 1999) and probes presented after searching had paused (MacInnes & Klein, 2003), are consistent with findings in the covert probe-following-search literature, supporting the conclusion that IOR in search is scene- or object-based.

2.2.2. Life of the IOR effect

Using probes that interrupted search, Klein and MacInnes (1999) found evidence of IOR in the 1-back and 2-back conditions; MacInnes and Klein (2003) extended this finding to probes presented when searching had paused. Significant IOR effect was observed in the 2-back condition of a virtual reality study by Thomas et al. (2006). Unlike other search tasks, this is a very slow search task, it takes about 1700 ms for participants to explore each item. Consequently, the finding of an IOR effect in the 2-back condition suggests a tag-duration of at least 3400 ms. In a recent study, Dodd et al. (2009) found clear IOR in both their 2- and 4-back conditions. These findings suggest that at least 2–4 previously inspected locations could be tagged with behaviorally measurable IOR. Based on the fact that on average, inter-saccade time interval is 254 ms in the experiment reported by Dodd et al. (2009), we could postulate that IOR in difficult occulomotor search tasks lasts for at least 1000 ms.

2.2.3. Nature of the tasks

A wide range of search tasks and probe methods have been used in the overt probing literature. Search displays and targets have included searching for Waldo in pictures from Martin Handford's books (Klein & MacInnes, 1999; MacInnes & Klein, 2003), searching for camouflaged letters in computer-generated natural scenes (Dodd et al., 2009) and for hidden fruits in a virtual 3-D environment (Thomas et al., 2006). Although saccadic response to the probes have been most commonly used (Dodd et al., 2009; Klein & MacInnes, 1999; MacInnes & Klein, 2003), manual responses have also been also explored (e.g. Thomas et al., 2006). Typically the probes have been presented during search – essentially interrupting it, but in MacInnes and Klein (2003) participants were instructed to look for something interesting and to stop there. Thus, instead of presenting probes in the midst of searching, in this study probes were only delivered after the searching temporarily ceased. Delayed probe response time for probes presented at previously fixated locations has been consistently observed in this literature despite this rich methodological variation. We believe that the robustness of the finding of IOR in the face of these methodological variations provides strong evidence in favor of the foraging facilitator proposal.

3. General discussion

A mechanism that biases attention away from previously inspected objects (locations) is ecologically important for human beings living in a world of complex visual stimuli. Without such a mechanism, one might go back to inspect the most salient location (object) over and over again. As summarized in the previous sections, the foraging facilitator proposal of IOR is consistently supported by evidence from studies using both the covert and overt probe-following-search paradigms. Although these two paradigms provide useful tools for exploring IOR effect in difficult search, there are a few methodological and conceptual issues that need to be addressed in further studies.

3.1. Methodological issues

3.1.1. Search array as cue

Search array as a cue to where the probes might be presented is a factor that could obscure the IOR effect in difficult search. In the typical probe-following-search paradigm 50% of the probes are

Table 2
Summary of the overt probe-following-search literature.

Source	Sample	Task characteristics		IOR score[a]				
		Task	Display	1-Back	2-Back	3-Back	4-Back	6-Back
Klein and MacInnes (1999)[b]	Exp. 1: $n = 8$	Where's Waldo?	On	20*	57*	–	–	–
	Exp. 2: $n = 6$		Off	12	−6	–	–	–
MacInnes and Klein (2003)	$n = 12$	Where's Waldo?	On	47*	–	–	–	–
			Off	6	–	–	–	–
Thomas et al. (2006)	$n = 16$	Fruit search[c]	On	25&	22*	12	–	–
Dodd et al. (2009)	$n = 12$	Scene search	On	–	70*	–	82*	2

Notes: *Significant IOR effect was observed. &Marginally significant IOR effect was observed. Where's Waldo? Participants were asked to search for a man (Waldo) who is hidden in a variety of dense and colorful environments. Fruit search: participant's task was to search for a pear hidden under an array of leaves in a virtual reality environment. Scene search: participants were asked to search for two small letters (N or Z) embedded in computer-generated natural scenes.

[a] The IOR effects of Klein and MacInnes (1999) and MacInnes and Klein (2003) reported in this table are calculated from the probe RTs in the 0° (on-probe) and 180° (off-probe) conditions. IOR effects in Thomas et al. (2006) are calculated from Fig. 3 of their paper.

[b] The 1-back condition was used in Exp 1, and 2-back condition was used in Exp 2.

[c] Unlike other overt studies reported here, a manual response (button press) was required to the probe.

on-probes and 50% are off-probes. Therefore, when the display size is smaller than one half of the possible locations for presenting search items, each location occupied by these items will be more likely to be probed than each empty location. Although Klein's method of using the on–off difference from easy search as a baseline "to control for most other factors" includes this one, it is possible that the degree to which a participant's information processing system picks up the probabilistic information about probe locations that might be provided by the search array will increase to the extent that this array is attended, which will be greater when the search is difficult. In order to solve this problem, Müller and von Mühlenen (2000, Exp. 4) added a sufficient number of off-probe trials to guarantee that all locations were equally probed. With this manipulation, a significant IOR effect and an interaction between this effect and target (absent/present) were observed. However, this manipulation also introduces another potential problem, that is, this manipulation might adjust participant's expectancy for on-probes versus off-probes, perhaps making their responses to expected probes faster. An alternative strategy would be to select set size and display parameters in which the number of on and off-probe locations is equated. To our knowledge this has not yet been done.

3.1.2. Search display size

Because of the limited capacity and duration of inhibitory tags in search (as suggested by the findings of Dodd et al. (2009) and Snyder & Kingstone (2000), the display sizes used in the covert probe-following-search paradigm have been relatively small (ranging from 2 to 16). Given a hypothesized capacity of five inhibitory tags, as suggested by the findings of Snyder and Kingstone (2000), when the display size increases from 5 to 20, on target absent trials, the probability of an on-probe being presented at a location with no (or a very weak) inhibitory tag will increase from 0 to 0.75. As a result, as set size increases it is likely that the on-minus off-probe RT difference (measured IOR) would be obscured.

Furthermore, previous studies in the IOR literature show clear evidence that, although the IOR effect around a cued location decreases with distance from the cued location, a large area around a cued location could be inhibited (Bennett & Pratt, 2001; Klein et al., 2005; Maylor & Hockey, 1985). This is another reason for preferring small display sizes in the covert probe-following-search paradigm. When a large display size is used, the display becomes crowded, and given the relatively broad gradient of inhibition around an attended location, if a large number of locations were inhibited, inhibition might spread over the entire array thereby minimizing differences between on and off-probes.

3.1.3. Baselines

In the covert probe-following-search paradigm, an easy (pop-out) search task has been used as a baseline condition to control (all) possible factors that might obscure the on–off-probe difference as a measure of IOR. However, this baseline condition is not the only possible control condition. We believe that it is valuable to explore and use other baseline control conditions. Similar findings obtained using different baselines will gain in credibility; while changes in the pattern of results when different baselines are used would be challenging and would point to the need for further research.

One promising task that could be used as the baseline condition in the covert paradigm is a passive-viewing task, recently reported by Müller, von Mühlenen, and Geyer (2007) in a search study that adopted a logic similar to Klein (1988). In the passive-viewing task, the display array was presented for an amount of time comparable to that in the search condition. Participant's task was to simply "look at the display" and respond to the probes (on or off). Another way to approach this problem is to redesign the covert probe-following-search paradigm to adopt the rationale behind the overt probe-following-search paradigm. To do so, one has to make sure that some display items are searched while others are not, so that on and off probes are both presented at distractor locations (with similar bottom-up salience) while, by hypothesis, on-probes are presented at inspected locations while off-probes are presented at uninspected locations.

Both methods were used in a recent paper by Thomas and Lleras (2009). In their Experiment 2, to validate the IOR effects observed in the search task (Exp. 2A), a passive-viewing task (Exp. 2B) was used as a baseline condition (with exposure durations based on Exp. 2A's search duration data). In their Experiment 3, participants were asked to search for a target among distractors of one color while ignoring distractors of a different color (with color assignment counterbalanced across participants). Probes were delivered either at the locations of attended or unattended distractors or empty location. Their finding of no RT difference between probes at empty location and probes on unattended distractors provides some assurance that this is a reasonable method.

3.1.4. Types of probe

The rationale behind the probe-following-search paradigms is straight forward: if inhibitory tags are left at previously inspected locations then information processing at these locations would be hindered. In the Posner cuing paradigm, the cuing effect was caused by the cue (Stimulus 1) and revealed by a target (Stimulus 2). In the same vein, to reveal the information processing cost caused by the hypothesized inhibitory tags, a probe is presented during or following the search. The standard task used to "probe" for the hypothesized inhibitory tags has typically involved visual transients: participants are instructed to detect a probe target's onset (see Thomas et al. (2006), for an exception). Such probes, added to the search display, are new objects which may capture attention reflexively. Although such stimuli are typically used as targets in the cuing paradigm in which IOR was discovered and fruitfully explored (see Klein, 2000, for a review), and have obviously been sensitive to previous orienting (as illustrated in this review) it is valuable to explore different probes that are not new objects (such as offsets, rotations and isoluminant color changes). To our knowledge, there is one study (Thomas et al., 2006, who used a flickering stimulus with a 16 Hz luminance fluctuation) that did not use onsets as probes and, like the most of the studies we have reviewed, this study found evidence for IOR. We would like to see more such studies, as the generality and possible boundary conditions of the hypothetical inhibitory tags could be illuminated by varying the type of probe.

It should be noted that probing is not the only method that has been used to reveal inhibitory tags in visual search. Klein and MacInnes (1999) observed that the freely-made saccades were biased away from the previous one or two fixated locations and they subsequently showed that this bias was likely caused by IOR rather than the reverse (MacInnes & Klein, 2003).

3.2. Does IOR really guide orienting in new directions?

The finding of inhibitory tags during, and in the aftermath of search provides strong evidence for the proposal that IOR encourages novelty-seeking as proposed by Posner and Cohen (1984) and that it acts as the foraging facilitator proposed by Klein (1988). Yet, two questions have emerged from several recent papers (for a more detailed discussion of these studies, see Klein & Hilchey, in press) the answers to which may qualify this proposed role:

(1) If IOR is discouraging reinspections then why are refixations "so frequent"?

(2) Does IOR operate only in search – which is explicitly a foraging situation – or is it present whenever covert or overt attention is oriented, regardless of the context?

3.2.1. Refixation rates

Whereas some studies of oculomotor behavior during searching (e.g. Hooge, Over, van Wezel, & Frens, 2005) have claimed to have observed a higher than chance frequency of refixations (saccades that return fixation to an array or scene element that had previously been fixated), others using the same type of task (Gilchrist & Harvey, 2000; Peterson, Kramer, Wang, Irwin, & McCarley, 2001), have reported the opposite finding. Putting aside methodological differences that might account for different claims, when drawing conclusions from data about the probability of refixations in search, we must be mindful of the critical issue of deciding what is the chance frequency of refixation. Before any orienting has taken place and, hence, before inhibitory tags have been laid down, bottom-up salience and top-down strategies (such as attentional guidance based on known features of the target) create a non-uniform activation map in the representation that guides orienting. In the absence of IOR (or a voluntary strategy that uses a fixed sequence of inspections as is common in reading), regions that are fixated are – because of their activation levels in this map – more likely to be refixated than other regions in the array (cf. Itti & Koch, 2001). In this context, IOR should decrease the likelihood of a refixation relative to the original probability of fixation (an appropriate baseline). Unfortunately, this ''baseline'' probability is not easy to establish and in our view (see Klein & Hilchey, in press) efforts to do so have so far been unsuccessful.

3.2.2. Context sensitivity

As noted in the ''overt paradigm'' section, Dodd et al. (2009) found IOR when participants were asked to search a scene. Using the same search scenes, when they exposed different participants to three other non-search tasks (memorizing, pleasantness-rating or free-viewing) they found, instead, facilitation. This finding implicates IOR distinctly as a mechanism specific to the ''search'' context. In this light, ''foraging'' may simply be a mental set that activates the tagging system.

With a similar scene memorization task, Smith and Henderson (2009) examined freely-made saccades and onset probes were presented at one-back and two-back locations. Unlike the studies reviewed in this paper, participants were instructed to ignore these probes which nevertheless sometimes generated oculomotor capture. Taken together, the onset-directed saccades in the one- and two-back conditions were initiated with longer fixation durations than when the onsets were presented at equi-eccentric new locations (Smith, personal communication). This finding of IOR in response to probes using a memorization task is in contrast to what one might expect if IOR operated specifically in the context of search (Dodd et al., 2009). To resolve this inconsistency, further study is needed.

4. Summary

Based on the evidence reviewed in the previous sections, we come to the following conclusions: (a) critically, observation of IOR in a variety of human foraging tasks provides robust supporting evidence for the foraging facilitator proposal of IOR; (b) the IOR effect in difficult search is coded in object- or scene- based coordinates; (c) the duration of IOR in difficult search is at least 1000 ms or four previously inspected items (locations). In concluding this review, we would like to put forward a few methodological suggestions to researchers who are interested in using these two paradigms to explore the role of IOR in search.

First, because IOR in search is coded in object- or scene-based coordinates, IOR is removed when the scene is removed, investigators interested in IOR in search should keep the search array (or scene) present when probing for IOR or otherwise encourage participants to briefly maintain the representation of the scene (as in Thomas & Lleras, 2009).

Second, in the covert paradigm, keep the set size relatively small (as has been done so far) because (a) due to the gradient around an inhibited location, inhibition may spread too broadly across the array; (b) if the number of inhibitory tags is limited (Snyder & Kingstone, 2000), measured IOR will begin to decrease as set size increases, as the probability of the probe ''finding'' an inhibitory tag will decrease.

Third, in the overt paradigm, when the probe is presented during search (as in Klein & MacInnes, 1999), on-probes in the 1-back condition always require a saccade in the direction opposite to the previous saccade, so it is unclear whether the IOR effect in the 1-back condition is contaminated by low-level oculomotor compatibility effect (but see Hooge & Frens, 2000). Because of this potential methodological problem, probing immediately after searching has ceased (as in MacInnes & Klein, 2003) and/or probing at ''older'' locations than 1-back should be considered.

Acknowledgments

We are grateful to two anonymous reviewers and Matthew Hilchey for their constructive advice on an earlier version. The collaboration presented here was supported by a scholarship and travel grant from China Scholarship Council to Zhiguo Wang and a Natural Sciences and Engineering Research Council of Canada Discovery Grant to Raymond M. Klein.

References

Bennett, P., & Pratt, J. (2001). The spatial distribution of inhibition of return. *Psychological Science, 12*(1), 76–80. doi:10.1111/1467-9280.00313.

Dodd, M. D., Van der Stigchel, S., & Hollingworth, A. (2009). Novelty is not always the best policy: Inhibition of return and facilitation of return as a function of visual task. *Psychological Science, 20*(3), 333–339. doi:10.1111/j.1467-9280.2009.02294.x.

Gilchrist, I., & Harvey, M. (2000). Refixation frequency and memory mechanisms in visual search. *Current Biology, 10*(19), 1209–1212. doi:10.1016/S0960-9822(00)00729-6.

Hooge, I., & Frens, M. (2000). Inhibition of saccade return (ISR): Spatio-temporal properties of saccade programming. *Vision Research, 40*(24), 3415–3426. doi:10.1016/S0042-6989(00)00184-X.

Hooge, I. T., Over, E. A., van Wezel, R. J., & Frens, M. A. (2005). Inhibition of return is not a foraging facilitator in saccadic search and free viewing. *Vision Research, 45*(14), 1901–1908. doi:10.1016/j.visres.2005.01.030.

Horowitz, T., & Wolfe, J. (2003). Memory for rejected distractors in visual search? *Visual Cognition, 10*(3), 257–298. doi:10.1080/13506280143000005.

Itti, L., & Koch, C. (2001). Computational modelling of visual attention. *Nature Reviews Neuroscience, 2*(3), 194–203. doi:10.1038/35058500.

Klein, R. (1988). Inhibitory tagging system facilitates visual search. *Nature, 334*(6181), 430–431. doi:10.1038/334430a0.

Klein, R. M. (1989). *Inhibitory tagging in visual search: Three failures to replicate*. Unpublished raw data.

Klein, R. (2000). Inhibition of return. *Trends in Cognitive Sciences, 4*(4), 138–147. doi:10.1016/S1364-6613(00)01452-2.

Klein, R. M., & Hilchey, M. (in press). Oculomotor inhibition of return. In S. Liversedge, I. Gilchrist, & S. Everling (Eds.), *The oxford handbook of eye movements*. Oxford: Oxford University Press.

Klein, R. M., Christie, J., & Morris, E. (2005). Vector averaging of inhibition of return. *Psychonomic Bulletin & Review, 12*(2), 295–300. doi:10.3758/PBR.16.2.238.

Klein, R. M., & MacInnes, J. W. (1999). Inhibition of return is a foraging facilitator in visual search. *Psychological Science, 10*(4), 346–352. doi:10.1111/1467-9280.00166.

Klein, R. M., & Taylor, T. L. (1994). Categories of cognitive inhibition with reference to attention. In D. Dagenbach & T. H. Carr (Eds.), *Inhibitory processes in attention, memory & language* (pp. 113–150). New York: Academic Press.

Leek, E., Reppa, I., & Tipper, S. (2003). Inhibition of return for objects and locations in static displays. *Perception & Psychophysics, 65*(3), 388–395.

Lleras, A., Rensink, R., & Enns, J. (2005). Rapid resumption of interrupted visual search: New insights on the interaction between vision and memory. *Psychological Science, 16*(9), 684–688. doi:10.1111/j.1467-9280.2005.01596.x.

MacInnes, J. W., & Klein, R. M. (2003). Inhibition of return biases orienting during the search of complex scenes. *The Scientific World Journal, 3*, 75–86. doi:10.1100/tsw.2003.03.

Maylor, E. A., & Hockey, R. (1985). Inhibitory component of externally controlled covert orienting in visual space. *Journal of Experimental Psychology: Human Perception and Performance, 11*(6), 777–787.

Müller, H. J., & von Mühlenen, A. (2000). Probing distractor inhibition in visual search: Inhibition of return. *Journal of Experimental Psychology: Human Perception and Performance, 26*(5), 1591–1605.

Müller, H. J., von Mühlenen, A., & Geyer, T. (2007). Top-down inhibition of search distractors in parallel visual search. *Perception & Psychophysics, 69*(8), 1373–1388.

Ogawa, H., Takeda, Y., & Yagi, A. (2002). Inhibitory tagging on randomly moving objects. *Psychological Science, 13*(2), 125–129.

Peterson, M. S., Kramer, A. F., Wang, R. F., Irwin, D. E., & McCarley, J. S. (2001). Visual search has memory. *Psychological Science, 12*(4), 287–292. doi:10.1111/1467-9280.00353.

Posner, M. I., & Cohen, Y. (1984). Components of visual orienting. In H. Bouma & D. G. Bouwhuis (Eds.). *Attention and performance* (Vol. 10, pp. 531–556). Hillsdale, NJ: Erlbaum.

Samuel, A., & Kat, D. (2003). Inhibition of return: A graphical meta-analysis of its time course and an empirical test of its temporal and spatial properties. *Psychonomic Bulletin & Review, 10*(4), 897–906.

Shore, D., & Klein, R. (2000). On the manifestations of memory in visual search. *Spatial Vision, 14*(1), 59–75.

Smith, T. J., & Henderson, J. M. (2009). Facilitation of return during scene viewing. *Visual Cognition, 17*(6), 1083–1108. doi:10.1080/13506280802678557.

Snyder, J., & Kingstone, A. (2000). Inhibition of return and visual search: How many separate loci are inhibited? *Perception & Psychophysics, 62*(3), 452–458.

Takeda, Y., & Yagi, A. (2000). Inhibitory tagging in visual search can be found if search stimuli remain visible. *Perception & Psychophysics, 62*(5), 927–934.

Thomas, L., Ambinder, M., Hsieh, B., Levinthal, B., Crowell, J., Irwin, D., et al. (2006). Fruitful visual search: Inhibition of return in a virtual foraging task. *Psychonomic Bulletin & Review, 13*(5), 891–895.

Thomas, L., & Lleras, A. (2009). Inhibitory tagging in an interrupted visual search. *Attention, Perception & Psychophysics, 71*(6), 1241–1250. doi:10.3758/APP.71.6.1241.

Tipper, S. P., Weaver, B., Jerreat, L. M., & Burak, A. L. (1994). Object-based and environment-based inhibition of return of visual attention. *Journal of Experimental Psychology: Human Perception and Performance, 20*(3), 478–499.

Wang, Z., Zhang, K., & Klein, R. M. (2010). Inhibition of return in static but not necessarily in dynamic search. *Attention Perception & Psychophysics*, *72*(1), in press.

Wolfe, J. M., & Pokorny, C. W. (1990). Inhibitory tagging in visual search: A failure to replicate. *Perception & Psychophysics, 48*(4), 357–362.