

Inhibition of return functions within but not across searches

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Abstract Inhibition of return (IOR) facilitates visual search by discouraging the reinspection of recently processed items. We investigated whether IOR operates across two consecutive searches of the same display for different targets. In Experiment 1, we demonstrated that IOR is present within each of the two searches. In Experiment 2, we found no evidence for IOR across searches. In Experiment 3, we showed that IOR is present across the two searches when the first search is interrupted, suggesting that the completion of the search is what causes the resetting of IOR. We concluded that IOR is a partially flexible process that can be reset when the task completes, but not necessarily when it changes. When resetting occurs, this flexibility ensures that the inhibition of previously visited locations does not interfere with the new search.

Keywords Visual search · Inhibition of return · Attention · Eye movements

The search for a target among distractor objects is an important everyday behavior. For example, we search for a book on the bookshelf, a pencil on the desk, or a familiar face in a crowd. A controversial topic in this area has been the extent to which memory processes support visual search (see, e.g., Gilchrist & Harvey, 2000; Horowitz & Wolfe, 1998; Peterson, Kramer, Wang, Irwin, & McCarley, 2001; Shore & Klein, 2000) and the properties of any proposed memory system involved (e.g., Beck, Peterson, & Vomela,

2006; Dickinson & Zelinsky, 2005; Körner & Gilchrist, 2008; Williams, Henderson, & Zacks, 2005). Several suggestions have been made as to how memory can support visual search. For instance, previous research has demonstrated that recently inspected items are actively remembered (e.g., Hollingworth, 2004; Zelinsky & Loschky, 2005). Such active remembering may support search by providing a code for which items are at what locations, and so guide the search process to new locations where the target might be found. In support of this idea, there is evidence that participants are less likely to reinspect previously attended items (McCarley, Wang, Kramer, Irwin, & Peterson, 2003) and are thus more likely to search through noninspected objects. However, it is also possible that previously visited locations are avoided because these locations are actively inhibited, and that this inhibition either reduces the probability that recent locations will be revisited and/or slows down motor responses to those locations. This process of inhibiting recently inspected items has been called *inhibition of return* (IOR). IOR was first reported by Posner and Cohen (1984) in the context of a paradigm used to investigate attentional processes. In their experiment, Posner and Cohen presented an uninformative cue that was followed by a target at the same or a different position. They found a facilitation effect for targets presented within 200 ms after the cue at the same position (cf. Posner, 1980). However, when the cue–target interval increased, this facilitation effect turned into an inhibition effect: Manual responses were now slower to a target at the cued position than to one at the noncued position.

The function of IOR in visual search was first proposed by Klein (1988; see also Klein, 2000). In Klein (1988), a probe was presented after participants had searched through a display. The position of this probe either had or had not been occupied before by an item in the search display. Klein (1988) found that it took longer to respond to a probe at a previously occupied position than to a probe at a

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previously empty position. This supported the idea that locations become inhibited as a result of the visual search process. One limitation of this study was that there was no direct measure of the allocation of attention during search (e.g., Wang & Klein, 2010); that is, it was not clear whether an item had indeed been inspected during the preceding search. To address this limitation, Klein and McInnes (1999) had participants perform a visual search while the participants' eye movements were recorded. Eye movements provide a more direct measure of where attention has been allocated in search, particularly when the discrimination task is difficult (see Findlay & Gilchrist, 2003). For Klein and McInnes, participants performed an extremely demanding "Where's Waldo" search task. During this search task and after a variable number of fixations, a probe was presented and participants were instructed to interrupt search and to saccade to this probe. Saccadic response times were longer to probes presented at a previously fixated location than to probes at a new location. Exactly this result would be expected if IOR operated during visual search: Due to IOR, recently inspected (old) items were inhibited during search, and hence, noninspected (new) items were preferred. Klein and McInnes suggested that IOR acts as a "foraging facilitator" in visual search (but see Smith & Henderson, 2011, who recently challenged this assumption).

Dodd, Van der Stigchel, and Hollingworth (2009) investigated whether IOR is a general characteristic of visual behavior or whether it is specific to visual search. When various visual tasks (namely, free viewing, memorizing a scene, and making a pleasantness judgment) were compared, IOR was only observed in the context of visual search. For the other conditions, even a *facilitation* of return was observed.

In recent years, the effect of IOR in visual search has been investigated intensively. A number of groups have questioned whether IOR is functional in influencing return probability during visual search (e.g., Hooge, Over, vanWenzel, & Frens, 2005; Smith & Henderson, 2009), while others have produced evidence for its effect in search and suggested that it may have an influence on up to the five most recently inspected items (Snyder & Kingstone, 2000), and that these effects may be graded, with the most recently fixated items having more inhibition (Boot, McCarley, Kramer, & Peterson, 2004). Wang, Zhang, and Klein (2010) suggested that IOR operates in static or slower dynamic search, whereas they did not observe it in faster, dynamic search. Farrell, Ludwig, Ellis, and Gilchrist (2010) manipulated the probability that participants would be required to return to a previously visited location, and they found that the IOR effect was modulated by this manipulation. Hence, environmental statistics affect IOR, suggesting that the system is flexible in adapting to changes in our environment. Finally, when the display was removed at the time the probe was presented, IOR did not occur (Klein &

McInnes, 1999; Müller & von Mühlenen, 2000; Takeda & Yagi, 2000), suggesting that the maintenance of IOR relies on the presence of the objects in the display. The assumption that IOR is object- rather than location-based was also supported by evidence that IOR operated during search even when the stimuli in the search display were moving (e.g., Ogawa, Takeda, & Yagi, 2002).

By taking these findings together, IOR has been shown to be an important process underlying visual search. The literature reviewed here suggests that IOR may be present across multiple prior locations and may vary depending on such factors as task, likelihood of return, and the difficulty of visual processing. IOR may even reset when the stimuli are removed. Thus, there is considerable support for the idea that IOR is a mechanism that adapts to the needs of the organism as well as to the environment in a very flexible manner.

The vast majority of research in visual search has required participants to search a display for a target until the target is found, then to subsequently search a new display for a new target, and so on. However, when we search for objects in the real world, the environment is quite stable, and we often carry out repeated searches in the same environment. For instance, we may search for a pen on the desk first and then for an eraser on the same desk. Although this kind of repeated search is ubiquitous, it has drawn very little attention. Among the few who have investigated this kind of search, Wolfe and colleagues (e.g., Kunar, Flusberg, & Wolfe, 2008; Wolfe, Klempen, & Dahlen, 2000) were interested in whether memory processes supported repeated visual search. In their studies, search performance did not increase, even if participants searched the same display hundreds of times. Though Wolfe and colleagues were not able to find long-term memory effects, this does not exclude the possibility that short-term memory supports repeated search. This was investigated by Körner and Gilchrist (2007), who had participants search the same 10-letter display consecutively for two different targets and found that response times were faster in the second than in the first search, suggesting that participants benefited from the first search when they searched the same display again. The researchers showed that this benefit came as a result of finding those target items faster in the second search that had been inspected more recently during the previous search. This finding that recently inspected items facilitate a subsequent search is quite surprising if we assume that IOR should inhibit such recently inspected items. This assumption would imply that IOR functions across two searches - a possibility that Körner and Gilchrist (2007) did not investigate.

In visual search, IOR has been exclusively investigated within single-trial searches; that is, a new search display was presented with each trial. One question, then, is how IOR functions in repeated searches of the same display. Takeda (2007) was interested in whether distractor-

inhibitory processes carried over across searches in more conventional single-trial search. His results suggested that there is some amount of such intertrial inhibition, though again, he did not measure overt shifts of attention in his study. In general, there are three possibilities for how IOR could operate when a display has to be searched repeatedly. (1) IOR acts consistently across both searches and is unaffected by the switch to the second search. In this case, in the second search there should be a bias away from items that were fixated in the first search. (2) In repeated search, IOR is modulated, or even functionally absent, throughout the task because it would disrupt the second search by inhibiting locations that now might contain the target. (3) IOR is present within each search but is reset at the end of the first search. Thus, possible target locations in the second search that were previously fixated in the first search are no longer inhibited. As a consequence, in the subsequent search, search could be guided to any object, without attentional bias.

In this study, we investigated how IOR functions in the context of repeated visual search. Participants had to search the same letter display twice. In [Experiment 1](#), we investigated whether IOR functions within each of two consecutive searches. In [Experiment 2](#), we addressed the question of whether IOR also operates across two searches. Finally, in [Experiment 3](#), we investigated whether or not the first search must be completed in order for IOR to operate at the start of the second search.

Experiment 1

The purpose of [Experiment 1](#) was to investigate whether IOR is present in repeated visual search. To this end, one item was probed in each of two consecutive searches. Participants were instructed to saccade to this item as quickly as possible and to resume search after their response to the probe. The probed item was either an item that had been recently fixated (*old probe*) or had not been fixated at all (*new probe*). IOR was revealed by longer saccadic latencies when participants had to saccade to old probes, as compared to saccades to new probes, in each of the two consecutive searches. In addition, we investigated the extent to which the strength of IOR varied with the number of fixations that occurred between the times the location was fixated and subsequently probed.

Method

Design Participants had to search in a display with 15 letters twice consecutively for two different target letters. The target was either present (P) or absent (A) on each of the two searches (creating search conditions AA, PA, AP, and PP). During each search, one item was probed. The

probe was presented randomly when at least five but not more than nine items were fixated. There were two probe types: The probe either had recently been fixated (old probe) or had not been fixated (new probe). When an old probe was presented, the probed item was one of the last one to four items that had been fixated. All manipulations were made within subjects. Saccadic latencies were used as the main dependent variable. The saccadic latency was defined as the time between the onset of the probe and the start of the corresponding saccade to the probe.

Participants A total of 16 participants (9 women) were recruited for this experiment. All of them were naïve as to the goal of the study. They were paid either €25 or received class credit. They were 24.6 years old on average ($SD = 3.8$; range, 20–35 years). All participants had normal or corrected-to-normal vision (contact lenses) and gave informed consent.

Apparatus An EyeLink II eyetracking system (SR Research, Ontario, Canada) was used to collect the data. Eye movements were recorded at a sampling rate of 500 Hz. Data were collected from the eye that produced the better spatial resolution (typically better than 0.31°). Displays were presented on a 21-in. CRT monitor with a resolution of $1,152 \times 864$ pixels and a refresh rate of 75 Hz. The viewing distance was approximately 63 cm, and a chinrest was used to minimize head movements. The velocity threshold for saccade detection was set to $35^\circ/s$, the acceleration threshold to $9,500^\circ/s^2$. Subsequent fixations of the same item were collapsed online into one item fixation. A game pad was used for collecting manual responses.

Stimuli For each trial, 15 upper case letters were sampled randomly from a set of 17 letters (A, E, F, G, H, I, K, L, M, O, P, R, S, T, U, V, and Z). These letters were presented in the display. The two remaining letters not presented in the display were used as the targets, in the case of target-absent searches. The stimuli were presented in Arial font (bold) on the computer screen. Each letter was surrounded by a circular line 0.18° in thickness. The circle made the item a clear saccade target and minimized its identifiability in peripheral vision (see Bouma, 1970). Moreover, in a pilot experiment we demonstrated that letter identification did not reliably differ from chance when fixation was more than 3° away from these stimuli. Each letter subtended 0.32° ; the diameter of an item (letter and circle) was 0.9° . The stimuli were presented in white on a black background. The letters were placed on the intersections of an imaginary 6×6 grid, with a grid cell size of 3.6° . The letter position deviated randomly from the intersection within $\pm 0.23^\circ$ in both the horizontal and vertical directions. The viewing angle of the whole display subtended $21.6^\circ \times 21.6^\circ$.

Procedure At the beginning of each trial, a fixation disc was presented to allow for drift correction (see Fig. 1). Participants were instructed to fixate this disc. When the fixation was registered, the trial was started by the experimenter. A placeholder display was presented for 500 ms that was identical to the search display, except that each letter was replaced by the hash symbol (#). After that, the search display was presented, and simultaneously, the first target letter was announced through the loudspeakers. When the target was present in the display, it was chosen randomly from among all of the items. When it was absent, it was one of the two items that were not presented in the display. Participants had to search for this target letter and give a manual “target present” or “target absent” response. During the search, one item was probed by changing its surrounding ring into a square whose line width was 0.36° . This probe was triggered when the end of a critical saccade was registered. The critical saccade was chosen randomly when at least five and maximally nine items had been fixated during the search. The probe was selected as follows: It was chosen either from the items that had been fixated within the last one to four item fixations (old probe) or from the items that had not been fixated at all (new probe). Further, it appeared at the location of the item whose Euclidean distance from fixation at probe onset was closest to 10.8° . If no item fit these criteria, a randomly

chosen item was probed, and these trials were not included in the analysis. The probed item turned back to normal when the saccade landed either within an imaginary 3° square around the item or when the probe was not fixated within three fixations after probe onset. Participants were instructed to saccade to the probed item and then to resume search. With the first manual search response, a new target letter was announced, and participants started the second search in the same display. As in the first search, an item was probed randomly between the fifth to ninth fixated items. Again, it had either been fixated within the previous four fixations during the second search or had not been fixated before. Participants were instructed to saccade to it and then to resume search. After the second manual response, the display was cleared and a new trial started.

Participants performed 8 practice trials before the first experimental block. They were instructed to search as quickly and accurately as possible. They were instructed to press the right trigger on the game pad if the target was present and the left trigger if the target was absent. Critically, they were told to interrupt search and to saccade to the probed item as soon as the probe appeared. Each participant completed eight blocks with 64 trials each. The eight blocks were divided in two sessions of four blocks administered on different days. Each of the two sessions

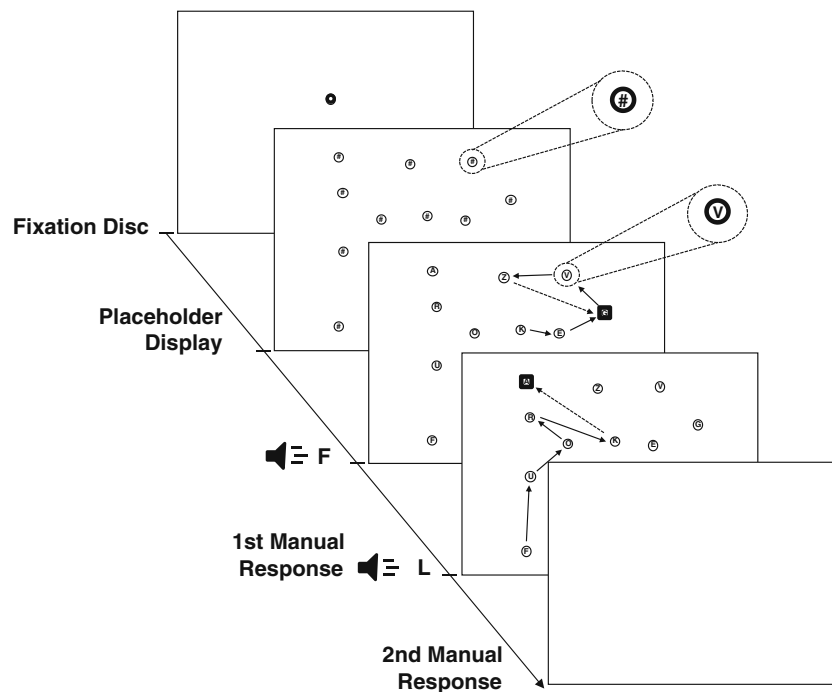


Fig. 1 Experiment 1: Sequence of events in a trial. Participants had to search twice in the same display. Arrows represent example scan paths during search. During each search, one item was probed (i.e., the outer ring turned into a square). Participants were asked to saccade to the probe immediately (dashed arrow) and afterward to resume search.

The probe either had been fixated during search (old probe, as presented here in the first search) or had not (new probe, as presented here in the second search). Note that in the experiments, the stimuli were actually presented in white on a black background

lasted approximately 90 min.; in total, the data from 8,192 pairs of searches were collected.

Results and discussion

We reanalyzed offline the online-collected data in all experiments to recheck the validity of the probe selection. Data from 2 trials were lost due to technical problems. There were 55 trials in which the probe was chosen at random because no suitable probe was found (see the Procedure section above). Furthermore, 4 first searches and 81 second searches were removed because offline analysis of the probe selection did not match the online analysis. The main reason for these mismatches was that the probe had not been fixated within the four most recent fixations. The error rate was 2.7% in the first search (individual range, 0.4% to 5.7%) and 3.9% in the second search (1.2% to 10.1%). Because error rates were generally low in all experiments presented here and quite typical for such a repeated visual search task (e.g., Körner & Gilchrist, 2007), they will not be analyzed further.

In 1,404 first searches and 1,500 second searches, the participants found the target and responded manually before the probe was supposed to be delivered. In 4,671 first searches and 4,637 second searches, participants did not fixate the probe with the first saccade (using a minimal distance criterion). All of these trials were excluded. Thus, 2,052 first searches and 1,912 second searches were available for analysis. The substantial reduction of the data reflects the participants' difficulty in interrupting search and responding to the probe and is typical for such experiments (e.g., Boot et al., 2004; Klein & McInnes, 1999).

Saccadic latencies Saccadic latencies were analyzed with respect to probe type (old vs. new probe) and search (first vs. second search). Averaged across individual medians, the saccadic latencies for first searches were 247 ms ($SD = 30$) for old probes and 227 ms ($SD = 33$) for new probes (see Fig. 2). For second searches, the latencies were 251 ms ($SD = 33$) for old probes and 232 ms ($SD = 30$) for new probes. A 2×2 ANOVA with Probe Type (old vs. new) and Search (first vs. second search) as factors showed a reliable effect of probe type, $F(1, 15) = 19.67$, $p < .001$, $\eta_p^2 = .57$, but no effect of search, $F(1, 15) = 2.28$, $p = .15$. The interaction was also not significant, $F(1, 15) = 0.79$, $p = .78$. Thus, saccadic latencies to recently fixated items were on average 20 ms (first search, $SD = 17$) and 19 ms (second search, $SD = 17$) longer than latencies to items that had not been fixated before. Because longer latencies were observed in both searches, it can be assumed that IOR was present in both searches to the same extent.

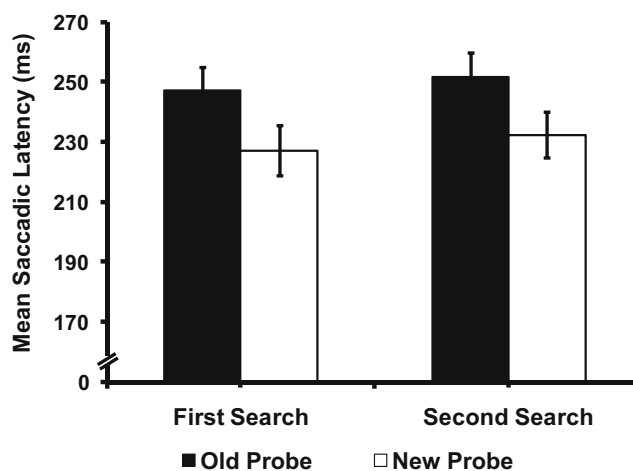


Fig. 2 Mean of the individual median saccadic latencies for old and new probes presented in the first search and the second search. Error bars represent standard errors

Next, we investigated whether IOR varied with respect to probe recency. Although IOR may affect search for as long as several seconds (Klein, 2000), it is possible that saccadic latencies differ with respect to items that had been fixated just before or items that had been inspected a few fixations ago (e.g., Boot et al., 2004). Therefore, we analyzed saccadic latencies to old probes according to their recency (e.g., a probe recency of 1 means that the item was the penultimate item fixated before it was probed) for each search (see Table 1). A 2×4 repeated measures ANOVA with Search (first vs. second search) and Probe Recency (1–4) as factors showed a main effect of neither search, $F(1, 15) = 0.58$, $p = .46$, nor probe recency, $F(3, 45) = 0.73$, $p = .54$. The interaction was also not significant, $F(3, 45) = 1.06$, $p = .38$. Hence, saccadic latencies to old items did not differ with respect to probe recency over the range studied here, in both searches. These results demonstrated that at least the last four fixated items during each of the two consecutive searches were affected by IOR.

Although we have shown that IOR affects search while it is ongoing, it is still unclear whether IOR also acts *across* two consecutive searches. If this is the case, recently inspected items (of the first search) should be inhibited at the start of the second search. We tested this assumption in [Experiment 2](#).

Experiment 2

As in [Experiment 1](#), participants had to search the same display twice. A probe was once again presented twice during each trial. The first probe was presented within the first search. This served as a control condition, and we expected to replicate the effect found in [Experiment 1](#). To

Table 1 Mean saccadic latencies (in milliseconds) and number of cases (N) for the four most recently fixated probe locations (probe recency) and for new probes, as a function of search condition

Experiment		Old Probe Recency				New Probe
		1	2	3	4	
1	1st search	241 (38)	252 (26)	255 (31)	248 (35)	227 (33)
	N	167	250	316	302	1,021
	2nd search	253 (44)	253 (32)	252 (31)	248 (49)	232 (30)
	N	202	324	302	157	932
2	Within search	227 (16)	234 (21)	229 (15)	230 (25)	213 (17)
	N	173	374	418	236	939
	Across searches	194 (24)	185 (8)	181 (13)	187 (11)	188 (10)
	N	40	237	99	141	1,020
3	Interrupted search	220 (30)	210 (18)	207 (14)	212 (19)	201 (16)
	N	59	277	405	413	1,460
	Completed search	206 (18)	204 (11)	204 (14)	205 (14)	205 (15)
	N	71	328	208	279	1,146

See the text of the respective experiments for detailed information. Standard deviations are presented in parentheses.

test the role of IOR across searches, we presented the second probe immediately at the beginning of the second search (see the Apparatus, Stimuli, and Procedure section below). The probed item was either recently fixated during the first search (i.e., within the last one to four items) or not fixated at all. If IOR also acts across two consecutive searches, we would expect saccadic latencies to old probes to be longer than latencies to new probes.

Method

Design As in [Experiment 1](#), participants had to search the same display of 15 letters twice for different target letters. The target was present in half of the searches, resulting in four search conditions (AA, AP, PA, and PP). Two letters were probed in each trial: The first probe (the *within probe*) was presented when five items had been fixated in the first search; the second probe (the *across probe*) was presented immediately at the beginning of the second search. The within probe either was one of the items that had been fixated one to four items back (*old-probe within*) or had not been fixated so far (*new-probe within*). The across probe was either one of the items that had been fixated one to four items back during the first search (*old-probe across*) or an item that had not been fixated during the first search (*new-probe across*). Note that for across probes, only trials on which the target was present in the first search (i.e., search conditions PA and PP) are of interest, because only in those trials were there uninspected items left after the first search that could be used as new probes. When the target was absent in the first search (search conditions AA and AP),

only old probes were available. In addition, we included two types of catch trials to reduce the strong expectation that the probe in the second search would be presented with the first fixation (see Apparatus, Stimuli, and Procedure below). Saccadic latencies to the probed item were again used as the main dependent variable. Manual responses were measured with respect to the search task.

Participants A group of 8 participants (6 women) took part in this experiment. All of them were naïve as to the goal of the study and gave informed consent. They were 24.4 years old, on average ($SD = 2.8$; range, 20–29 years) and were paid €50. All participants had normal or corrected-to-normal vision (contact lenses).

Apparatus, stimuli, and procedure The apparatus and stimuli were the same as in [Experiment 1](#), except that at probe onset the circle that surrounded the probed letter changed into a red square with a line width of 0.36° and flickered from red (50 ms) to white (50 ms) and back to red. We changed the cue to a stronger visual transient in order to increase the number of trials available for analysis.

At the beginning of each trial, a fixation disc was presented randomly at a position where a letter would appear in the search display. The placeholder display was then presented for 500 ms, followed by the search display. Simultaneously with the onset of the search display, a target letter was announced through the loudspeakers. Participants had to search for this target letter. During search, at the start of the fixation of the fifth item, the surrounding circle of one of the four most recently fixated items changed into a probe (within probe). The item changed its color from red to

white and back to red. Participants were instructed to saccade to this item immediately and then to continue search. The probe disappeared when the following saccade landed within an imaginary square region of 3° around the center of the item, or the following three saccades did *not* land in this region, or the item was not fixated within 1,000 ms.

With the participants' first manual response, the announcement of the second target was triggered and the second search started. When the first saccade was registered in the second search, a probe was presented immediately at the end of this saccade (i.e., at the start of the subsequent fixation). The probed item had either been fixated one to four fixations back *in the first search* or had not been previously fixated (across probe). Note that this was only possible when a target had been present in the first search, because usually not all items would be inspected in that case. If the first search was a target-absent search, any inspected item from the first search could be chosen as a probe. Such trials were not used for the across-probe analysis. The participants were instructed to saccade to the probe immediately and then to continue search. Furthermore, we included catch trials. In eight trials per block, the probe in the second search was presented when the end of the saccade to the fifth fixated item was registered (as in Search 1); in six further trials, no probe occurred at all in either search. These catch trials were not analyzed. After the second manual response, the display was cleared and a new trial started.

Participants performed 8 practice trials before the start of the first block. They completed 16 blocks with 70 trials each (14 of which were catch trials). The 16 blocks were divided into four sessions of 4 blocks each, with each session on a different day. Each of the 4 sessions lasted approximately 90 min. All in all, data were collected from a total of 8,960 trials, 8,192 within-probe (first) searches, and 2,688 across-probe (second) searches.

Results and discussion

Data from 11 trials were lost due to technical problems. We eliminated the catch trials (767 within-probe searches, 1,791 across-probe searches) and all trials on which the probe was chosen randomly in either of the searches because no suitable probe was found (815 trials). Nine within-probe searches and 155 across-probe searches had to be removed because offline analysis of the probe selection did not match the online analysis.

In 877 within-probe searches and 8 across-probe searches, the participants found the target and responded manually before the probe was supposed to be delivered. Furthermore, in 5,206 within-probe searches and 1,486 across-probe searches, participants did not fixate the probe with the first saccade. All of these trials were excluded.

Thus, 2,156 trials of within-probe searches and 1,537 trials of across-probe searches were available for analysis.

Saccadic latencies We averaged individual medians with respect to probe time (within vs. across) and probe type (old vs. new). For within probes, the saccadic latencies were 230 ms ($SD = 15$; old probe) and 213 ms ($SD = 17$; new probe) (see Fig. 3, left). The across-probe latencies were 186 ms ($SD = 7$; old probe) and 188 ms ($SD = 9$; new probe) (see Fig. 3, right). A 2×2 ANOVA with Probe Time (within vs. across) and Probe Type (old vs. new) as factors showed reliable effects of probe time, $F(1, 7) = 29.71$, $p < .01$, $\eta_p^2 = .81$, and probe type, $F(1, 7) = 16.02$, $p < .01$, $\eta_p^2 = .70$. The interaction was also significant, $F(1, 7) = 8.91$, $p < .05$, $\eta_p^2 = .56$. Planned post-hoc comparisons (t tests) showed that, for within probes, saccadic latencies to old probes were on average 17 ms ($SD = 10$) longer than those to new probes, $t(7) = 4.73$, $p < .01$, $\eta_p^2 = .76$. There was no reliable difference between the latencies to old and new probes in the across-probe condition, $t < 1$ ($M = 1$ ms, $SD = 10$), suggesting that there was no IOR in this condition.

It is possible, however, that IOR was present for the most recently fixated item in the across-probe condition but not for items fixated three or four fixations back. Therefore, we investigated whether saccadic latencies to old items differed with respect to probe recency (see Table 1). A 2×4 repeated measures ANOVA with Probe Time (within vs. across probe) and Probe Recency (1–4) as factors showed a significant main effect of probe time, $F(1, 7) = 43.55$, $p < .001$, $\eta_p^2 = .86$. There was no effect of probe recency, $F(2.0, 14.2) = 0.50$, $p = .62$ (Greenhouse–Geisser corrected). Also, the interaction was not significant, $F(3, 21) = 0.93$, $p = .44$. Hence, saccadic latencies to old items did not vary with probe recency for either probe time. This shows that the effects were not driven simply by a single location.

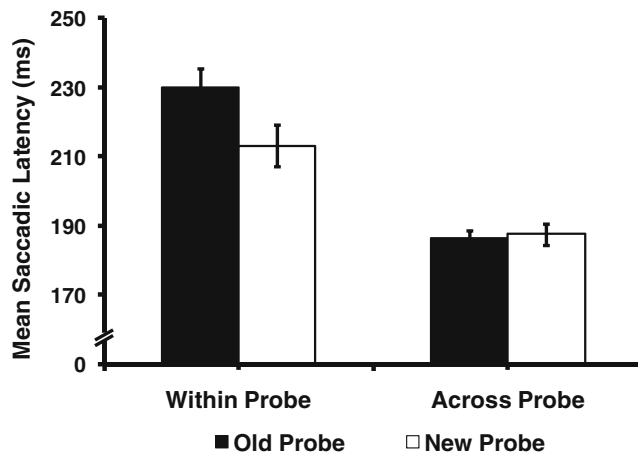


Fig. 3 Mean of the individual median saccadic latencies for old and new probes when the probe was presented within a search or across two searches. Error bars represent standard errors

Another possibility for the absence of IOR across searches could be that the time interval between probe onset and the preceding fixation of the probed item differed for within and across probes. For across probes, fixation durations might have been longer because participants had to press a button at the end of the first search, whereas for within probes, no such manual response had to be produced. Thus, IOR in the across-probe condition might have been absent because the time interval between the last fixation of an item before probe onset was longer than the respective time interval in the within-probe condition. To rule out this possibility, we analyzed the time interval between probe onset and the preceding fixation of the respective items for both probe times. For within probes, the time interval (averaged across individual medians) was 708 ms ($SD = 23$); for across probes, the time interval was 671 ms ($SD = 108$). The difference was not significant, $t(7) = 1.01$, $p = .35$. Thus, the absence of IOR for across probes cannot be attributed to a longer time interval between fixation of the probed item and the probe onset.

In our experiments, we tried to control for the Euclidean distance between the last fixated item and the probed item (see the Procedure section of Exp. 1). However, a post-hoc analysis of that distance showed that, for across probes, distances for old probes ($M = 7.0^\circ$, $SD = 0.7$) were significantly shorter than those for new probes ($M = 10.3^\circ$, $SD = 0.1$), $t(7) = 13.32$, $p < .001$, $\eta_p^2 = .96$. This was not the case for old and new probes ($M = 10.1^\circ$, $SD = 1.1$, and $M = 10.4^\circ$, $SD = 0.1$, respectively) in within-probe searches, $t < 1$. Although variation of distance in this range should not have affected saccadic latency (see Kalesnykas & Hallett, 1994), it is important to show that the presence or absence of IOR does not depend on distance. We therefore performed an analysis for across probes after selectively eliminating trials (56.5%) in such a way that the distances no longer differed for the old and the new probes. Not surprisingly, saccadic latencies for old probes ($M = 188$ ms, $SD = 6$) still did not differ from those for new probes ($M = 184$ ms, $SD = 6$), $t(7) = 1.21$, $p = .27$. Thus, Euclidean distance between the fixated item and the probed item did not affect saccadic latencies in our paradigm.

Another factor that might affect the magnitude of IOR is the angular distance between the direction of the latest saccade at probe onset and the direction from the fixated location to the probe (see, e.g., Klein & McInnes, 1999). An analysis of such distances in our data showed that across probes (old probe, $M = 28^\circ$, $SD = 4$; new probe, $M = 75^\circ$, $SD = 10$) did indeed have greater angular distances than within probes (old probe, $M = 46^\circ$, $SD = 7$; new probe, $M = 89^\circ$, $SD = 7$). Thus, IOR might have been deleted in the across-probe condition simply because of this difference in angular distances. If this was the case, we would expect IOR also to be eliminated in the within-probe condition if

trials with angular distances $\leq 10^\circ$ (which distances should have a substantial impact on IOR) were excluded. A saccadic latency analysis showed, however, that IOR still occurred for within-probe searches with this restricted angular range (old probe, $M = 230$ ms, $SD = 18$; new probe, $M = 214$ ms, $SD = 18$). Hence, we conclude that angular distance did not affect the presence of IOR in our paradigm.

Results for the within-probe searches replicated the finding of Experiment 1 that it takes longer to saccade to old than to new probes: IOR is present within the search. For the across-probe searches, we found no difference in saccadic latencies with respect to old and new probes. Thus, we cannot conclude that recently inspected items of a previous search are inhibited at the start of a subsequent search. Somewhat unexpectedly, there was also a significant main effect of probe time. Mean saccadic latencies for within probes were about 30 ms longer than latencies for across probes. However, note that this difference might be explained by the fact that probe onset occurred in two quite different phases of the search process. There is evidence that saccades are sometimes programmed in advance (McPeck, Skavenski, & Nakayama, 2000; Nuthmann, Smith, Engbert, & Henderson, 2010). Therefore, when a probe onset occurs during search, such programming of subsequent saccades has to be interrupted in order to saccade to the probe. In contrast, at the beginning of the second search, participants might have postponed the programming of the subsequent saccades, anticipating a probe in most of the trials.

The results of Experiment 2 suggest that, although IOR operates *while* search is ongoing, it is not functioning when one search has terminated and the next is about to begin. Why are there differences with respect to the involvement of IOR within and across searches? Usually, within search, the behavioral goal is to find the target as quickly and accurately as possible. In this case, inhibition facilitates search because noninspected items are preferred. When search has finished, there is no need to inhibit recently inspected items anymore, because the search was successfully completed and the behavioral goal has been accomplished by deciding whether or not a target was present. If this interpretation is correct, IOR may still function if a previous search is terminated unsuccessfully—that is, before the participant is able to make that decision. We tested this possibility in Experiment 3.

Experiment 3

Method

Design As in Experiment 1 and 2, participants had to search the same display twice for different target letters. There were

again four search conditions (AA, AP, PA, and PP). A single probe was presented in each trial, immediately at the beginning of the second search. The first search was either completed by the participant's buttonpress (*completed search*) or interrupted by announcing a new target letter through the loudspeaker when five to nine items had been fixated (*interrupted search*; see Apparatus, Stimuli, and Procedure below). Again, the probe had either been fixated recently during Search 1 or had not been fixated (*old probe* vs. *new probe*). Saccadic latencies to the probed item were the main dependent variable; manual response times were measured with respect to the visual search task.

Participants A total of 12 participants (8 women) took part in this experiment. All were naïve as to the goal of the study and gave informed consent. They were 25.3 years old, on average ($SD = 5.2$; range, 21–40 years) and were paid €50. All participants had normal or corrected-to-normal vision (contact lenses).

Apparatus, stimuli, and procedure At the beginning of each trial, a fixation disc was presented randomly at a position where a letter would appear in the search display. Afterward, the placeholder display was presented for 500 ms, followed by the search display. Simultaneously with search display onset, a target letter was announced through the loudspeakers. When the target was present in Search 1, search lasted until the manual response. With the manual response, a new target letter was announced, and participants started the second search. As in Experiment 2, with the end of the first saccade in the second search, an item was probed. This item either had been fixated one to four fixations back in the first search or had not been fixated at all during the first search. Participants were instructed to saccade to this item immediately and then to continue search. The probed item turned back to normal when the saccade landed within an imaginary square region 3° around the item, or when the following three fixations after probe onset did not fall into this region, or when the item was not fixated within 1,000 ms. When the target was absent in Search 1, the search was interrupted by announcing a new target letter through the loudspeakers randomly when at least five and at most nine items had been fixated. Again, a probe was presented after registering the end of the first saccade in the second search. The probe either had or had not been recently fixated during the first search. Furthermore, 16 catch trials per block were included in which either the probe onset in the second search was preceded by a target-absent search in the first search (i.e., participants finished the first search) or no probe onset occurred at all during the trial. These catch trials were inserted to avoid learning effects and were not analyzed further. After the second manual response, the display was cleared and a new trial started.

Participants performed 8 practice trials before the first experimental block. They completed 16 blocks with 72 trials each. The 16 blocks were spread across four sessions of 4 blocks each. Each session was conducted on a different day. A session lasted approximately 90 min. In total, data from 13,824 trials were collected (5,376 searches for each [of the two] search conditions, plus catch trials).

Results and discussion

Data from 43 of the trials were lost due to technical problems. We eliminated 3,061 catch trials and 1,101 trials in which the probe was chosen randomly because no suitable item was found. A total of 326 (completed search) and 363 (interrupted search) trials had to be removed because offline analysis of the probe selection did not match the online analysis.

In 18 trials of the completed- and interrupted-search conditions, the participants found the target and responded manually before the probe was delivered. In 2,234 trials (completed search) and 2,128 trials (interrupted search), participants did not fixate the probe with the first saccade. All of these trials were excluded. Thus, 2,032 trials for the completed-search condition and 2,614 trials for the interrupted-search condition were analyzed.

Saccadic latencies Averaged across individual medians, the saccadic latencies were 209 ms ($SD = 15$) to old probes and 201 ms ($SD = 16$) to new probes (see Fig. 4, left) in the interrupted-search condition. In the completed-search condition, the saccadic latencies were 205 ms ($SD = 9$) to old probes and 205 ms ($SD = 15$) to

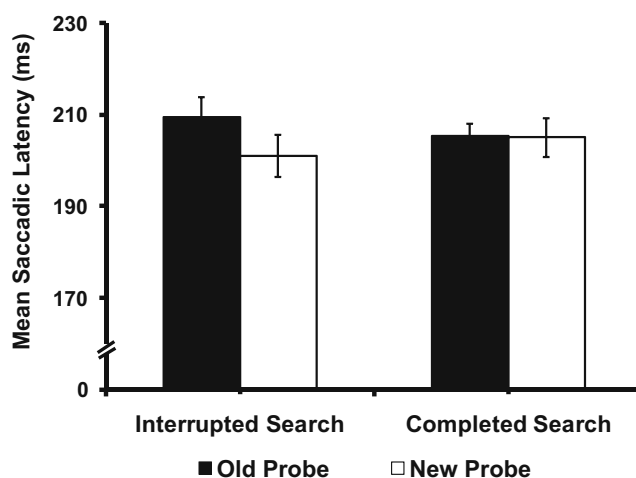


Fig. 4 Mean of the individual median saccadic latencies for old and new probes when the first search was interrupted or completed. Error bars represent standard errors

new probes (see Fig. 4, right). A 2×2 ANOVA with Probe Type (old vs. new) and First-Search Condition (interrupted vs. completed) as factors showed a reliable effect of probe type, $F(1, 11) = 5.52$, $p < .05$, $\eta_p^2 = .33$, but no effect of first-search condition, $F(1, 11) = 0.0$, $p = 1.00$. The interaction was significant, $F(1, 11) = 7.08$, $p < .05$, $\eta_p^2 = .39$. Planned post-hoc comparisons (t tests) showed that, in the interrupted-search condition, saccadic latencies to old probes were on average 8 ms ($SD = 7$) longer than those to new probes, $t(11) = 4.31$, $p < .01$, $\eta_p^2 = .63$. In the completed-search condition, latencies did not differ ($SD = 1$), $t(11) = 0.12$, $p = .91$. This provides some support for IOR being present in the interrupted-search but absent in the completed-search condition.

In addition, results from the saccadic-latency analysis were not driven by a difference in saccadic latencies between the most recent four positions (see Table 1): A 2×4 repeated measures ANOVA of old-probe latencies with First-Search Condition (interrupted vs. completed search) and Probe Recency (1–4) as factors showed neither a significant main effect of first-search condition, $F(1, 11) = 4.19$, $p = .07$, nor an effect of probe recency, $F(3, 33) = 1.77$, $p = .17$. Also, the interaction was not significant, $F(1.9, 21.2) = 0.75$, $p = .48$ (Greenhouse–Geisser corrected). Hence, saccadic latencies to old items did not differ with respect to probe recency for the two search conditions.

To summarize, if search was completed, we found no effect of IOR, replicating the corresponding result from [Experiment 2](#). However, when participants could not finish search (interrupted-search condition) our results suggest that IOR did act across searches.

General discussion

The aim of this article was to investigate whether and how IOR functions in a context of repeated visual search. In particular, we were interested in whether IOR not only operates within a single search but also acts across two consecutive searches of the same display. In [Experiment 1](#), we demonstrated that IOR acts within each of the two searches. Recently inspected items were inhibited during search: Longer mean saccadic latencies were observed when a recently inspected item was probed than when a noninspected item was probed. In [Experiment 2](#), we investigated whether IOR also operates across two searches. Saccadic latencies to old items did not differ from latencies to new items when the probe was presented at the beginning of the second search. This indicates that IOR does not act across the two searches. Based on this result, we assumed that the completion of the first search might reset the inhibition of recently inspected items. We

tested this assumption in [Experiment 3](#). In this experiment, the first search was either completed by the participant him- or herself or was externally interrupted before completion by presenting the target of the second search. Again, recently inspected items of the first search or new items were probed. As in [Experiment 2](#), saccadic latencies to old and new probes did not differ when participants were allowed to complete the first search. However, when the first search was not completed, saccadic latencies to old probes were again longer than those to new probes. In this case of noncompletion, IOR seems to function across two consecutive searches.

The results of [Experiment 2](#) and [3](#) suggested that IOR does not act across two searches. When the first search is completed, IOR seems to be reset. Hence, the end of the first search seems to be a crucial moment for the maintenance of IOR. There are three events that mark the transition between the first search and the next, and any of them could be a candidate for the processes that resets IOR: (1) the end of the search, determined by the participant's decision, (2) the subsequent manual response (buttonpress), and (3) the processes involved in setting up and beginning the execution of the second search. First, search only ends when the participant has either found the target or come to the conclusion that the target is not present in the display. The end of the search is driven internally in both cases; that is, the participant him- or herself decides when to end the search. This decision process may drive the resetting of IOR. Our data are consistent with this possibility.

Second, IOR might function up to the time when the participant decides to finish the search but resets when the button (as a manual activity) is pressed. Note that in [Experiment 3](#), when the participant was not allowed to complete the search, he or she was also not forced to press a button. Hence, we cannot rule out the possibility that either the end of the search itself or the buttonpress (or both) are responsible for resetting IOR after the first search. This should be addressed in further experiments in which, for instance, an irrelevant manual response has to be made before the probe is presented.

Third, it is also possible that the announcement of the second target through the loudspeaker and the start of the second search contributed to the reset of IOR. This suggestion can be ruled out by the results of [Experiment 3](#). In this experiment, the subsequent searches started the same way in both (completed- and interrupted-search) conditions: A new search target was announced. Thus, the start of the second search was effected in the same way in both conditions. Nevertheless, in [Experiment 3](#), IOR decreased to 8 ms (from about 20 ms in Exps. 1 and 2). Although comparisons of the absolute magnitude of effects between experiments are somewhat problematic, this might suggest that the start of the second search somehow

affected IOR, even if IOR was not reset. To address the question what factors are responsible for modulation of the magnitude of IOR, further experimentation is necessary. For instance, the first search could be interrupted by a target announcement without changing the behavioral goal (i.e., the same target has to be searched in the second search). Another possibility is that the completion of the oculomotor program associated with the first search itself activates the switch in task. Perhaps IOR was not reset in the interrupted-search condition because this program had not terminated yet, such that participants had actually not started the second search.

As it stands, the evidence from the experiments presented here suggests that the processes associated with the end of the first search, rather than the preparation for the subsequent search, are what allow IOR to be reset across searches. [Experiment 1](#) showed that saccadic latencies to old probes were reliably longer than latencies to new probes. This finding is in line with previous research regarding the involvement of IOR in visual search. Inhibition of recently fixated items results in search processes being guided to noninspected items, because reinspection of old items is discouraged (see, e.g., Klein, 1988). In this sense, IOR may act as a “foraging facilitator” in visual search. Furthermore, our results show that at least the four most recently fixated items were inhibited, which has also been demonstrated in previous research (e.g., Snyder & Kingstone, 2000). However, in all three experiments we found that inhibition did not differ within the last four fixations. This differs from results reported by Boot et al. (2004). One explanation for this difference is that Boot et al. presented only three stimuli at the same time in the display. Furthermore, in their study, the display did not remain stable during search. With every eye movement made by the participant, one of the already-inspected items was removed and a new item was presented, either at an already-inspected position or at a position where no item had been presented before (see also McCarley et al., 2003, for a similar procedure). Another possibility is that controlling the distance of the probe location in our experiments led to the lack of variation in latencies with respect to probe recency. To our knowledge, an effect of recency is typically reported for experiments without such systematic control of distance.

Körner and Gilchrist (2007) investigated the extent to which search benefited from previous exposure to the display in the first search. They demonstrated that the time necessary to find a target letter in the second search depended on when that letter was last fixated in the previous search and that this fixation recency effect lasted for about four fixations. They argued that these results provide evidence for a limited-capacity short-term memory store operating in visual search that stores both the identity and the location of a limited number of items. Such a short-

term memory system could facilitate search. However, if IOR was acting in addition to drive fixations away from recently fixated items, these two processes would act against each other and reduce the benefits in search efficiency that would be delivered by the short-term memory process alone. The absence of such an IOR effect across searches suggests that the size of the short-term memory effects reported by Körner and Gilchrist (2007) were not modulated by a concurrent IOR effect, but also suggests one good functional reason for resetting IOR at the end of a search: Such resetting allows the search process to benefit fully from the information held in short-term memory.

During search, IOR acts as a facilitator, because the search process is discouraged from revisiting already-processed items. However, outside the laboratory, we often search the same environment a number of times for different targets. In this context, it is adaptive to have IOR as a flexible process that can reset so that inhibition in the old search does not linger to affect the new search process. However, IOR appears to be only partially flexible, in that interruption of a search, as occurred in [Experiment 3](#), does not appear to reset IOR. Following the argument set out above, it would make more sense for IOR to be reset when a task switch occurs, for whatever reason. One speculation is that when a task is externally interrupted in this manner, the attentional system assumes that the interrupted task may be returned to, and so does not reset IOR. Evidence for such an effect was shown by Thomas and Lleras (2009). They demonstrated that interrupting search for a short delay does not affect IOR, even when the display was deleted during the delay. Rather, when the participants were allowed to resume their search after the delay, inhibition processes were maintained.

Some evidence from previous research has shown that IOR operates even if a probe is presented after search has finished (e.g., Klein, 1988; Müller & von Mühlénen, 2000; Takeda & Yagi, 2000). It would seem that this research contradicts our findings. However, it may be that the resetting of IOR requires the completion of the old search as well as the start of a new one. Such a new search was not present in these studies. In addition, there were some methodological differences from our experiments: Those studies used manual response times as a measure for IOR, comparing responses to on-probes (in a location previously occupied by an item during search) and off-probes (in a location not occupied by an item). Although we do not question the validity of that measure, analyzing eye movements instead might provide a deeper insight into the processes involved (see also Wang & Klein, 2010). For instance, analyzing manual responses typically allows for differentiating between on-probes or off-probes, whereas only the analysis of eye movements can reveal whether or not an item has been fixated. Furthermore, analyzing eye

movements before probe onset also ensures that only recently inspected items are probed, which is important if we assume that the capacity of IOR is limited to about five items (Snyder & Kingstone, 2000).

We have shown that the resetting of IOR is not only driven by an external change in the environment (e.g., the removal of the display, as in Klein & McInnes, 1999) but can be a result of an internal process, in this case the completion of the previous task. The results add to a growing body of evidence that suggests that IOR is a flexible process that can respond to both task demands and the properties of the environment to facilitate ongoing visual exploration and cognition. For instance, Dodd et al. (2009) found IOR only in the context of visual search, not in the context of other visual tasks (such as free viewing, memorizing a scene, or making a pleasantness judgment), and they suggested that IOR is not a general characteristic of visual attention but rather task specific: IOR functions only in tasks in which the performance benefits from a bias toward new items. This is the case in visual search.

Farrell et al. (2010) showed that an overall IOR could be eliminated when the likelihood of reinspecting a previously inspected item increased, suggesting that IOR adapts quite flexibly when the statistics of the environment are changing. Our findings suggest that IOR can only be observed within search, not across two consecutive searches when the same display has to be searched again. This is further evidence for the flexibility of our visual system.

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