Inhibition of Return in Visual Search Does Not Rely on Spatial Working Memory

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ABSTRACT

Inhibition of return (IOR) prevents the immediate reorientation to previously attended locations, such that unattended locations are prioritized. In the current study, we were interested in whether saccadic IOR is affected by the storage of visuospatial information in working memory (WM) during a visual search task. To this end, participants searched a display for a target letter once while holding no, two, or four object locations in their spatial WM. During the search, either a previously inspected or an uninspected item was probed, and the participants were instructed to immediately saccade to this probed item before resuming the search. The results showed that saccadic latencies to previously inspected items were longer than to uninspected items, indicating the presence of IOR during the search. However, this effect was observed regardless of the number of item locations held in the spatial WM. This finding suggests that saccadic IOR does not rely on visuospatial WM in visual search.

KEYWORDS

attention
visual search
eye movements
inhibition of return
spatial working memory

INTRODUCTION

Searching for a book on a bookshelf or for traffic obstacles while driving on the road are only two examples of performing a visual search, that is, a search for one or more target objects among distractors. During visual search, attention is typically directed from one object to another to find the object of interest. Therefore, visual search has become a key paradigm to investigate the attentional processes involved (see e.g., Eckstein, 2011; Wolfe, 2010, 2020). In parallel to attentional processes, the influence of memory processes has also been studied for more than twenty years now (e.g., Gilchrist & Harvey, 2000; Höfler et al., 2014, 2015, 2021; Horowitz & Wolfe, 1998; Hout & Goldinger, 2010; Körner et al., 2018; Kristjánsson, 2000, McCarley et al., 2003; see Shore & Klein, 2000 for an early review).

Within the research on the involvement of memory during search, results on whether and how different types of working memory (WM) are important for visual search are mixed. In such experiments, participants are usually asked to memorize some property of the presented items (e.g., their locations to test for the involvement of spatial WM or their color to test for visual WM) before they perform a visual search task. If the respective WM load impairs search times and/or efficiency, this indicates that visual search processes rely on these WM resources. For instance, Woodman et al. (2001) had participants memorize the colors of no, two, or four items prior to the search and discovered that, whilst such a nonspatial WM load affected the search times in the memory load conditions, search efficiency (i.e., the search rate per additional item in the display) was not impaired. This latter finding indicates that the search process is not affected by visual WM load and hence, that visual search does not rely on visual WM. However, when analyzing participants' eye movements during such a task and splitting up the search processes into a presearch, search, and postsearch phase, Solman et al. (2011) were able to show that a nonspatial WM load also might affect the search process itself—as well as the phases before the search is started and after it is completed, respectively. On the other hand, both Oh and Kim (2004) and Woodman and Luck (2004) showed that visuospatial WM load, that is, memorizing the locations of objects prior to search, affected both search efficiency and performance (see however, Höfler et al., 2021). In addition to the importance

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of spatial WM in visual search, Anderson et al. (2008) showed that verbal WM load also decreased search efficiency, and He and McCarley (2010) demonstrated that even an executive WM load reduced search performance. Taken together, these findings suggest that spatial WM in particular is involved in visual search, whereas nonspatial WM as well as verbal/numeric load do not seem to be as important.

A further factor that has been shown to influence search behavior is inhibition of return (IOR). It was first demonstrated in the mid-1980s using spatial cueing paradigms in which an uninformative peripheral cue was followed by a target presented either at the same (valid) or the opposite (invalid) side of that cue (Posner & Cohen, 1984; Posner et al., 1985). When the target was presented within about 250 ms after the cue, responses were faster for valid than for invalid trials due to attentional capture of the cued side. However, this effect changed for targets presented later than about 250–300 ms after the cue: In this case, responses to invalid targets were faster than to valid targets, suggesting that valid target positions were inhibited after the initial capture (see Lupiáñez et al., 2006; Klein, 2000, for reviews). A few years later, Klein (1988) showed for the first time that inhibitory tagging (i.e., IOR) is also involved during serial visual search. That is, participants needed longer to respond to a probe presented at a location previously occupied by a search item compared to a probe presented at a previously empty location, indicating that attended distractors were tagged and inhibited. Moreover, using eye tracking, Klein and MacInnes (1999; see also Wang & Klein, 2010, for a review) proposed that IOR facilitates foraging in visual search by discouraging the reinspection of previously inspected items, thus directing searches to heretofore uninspected items. Since then, IOR in visual search has not only been investigated in various laboratory settings (e.g., MacInnes & Klein, 2003; Höfler et al., 2011; Höfler et al., 2019; Thomas & Lleras, 2009), but also in virtual environments (e.g., Thomas et al., 2006). However, it is still unclear whether such an oculomotor IOR during visual search is based on the same process observed during the original cueing paradigms without eye movements (see e.g., Berlucchi, 2006; Dukewich & Klein, 2015, for discussions).

There is a large amount of research addressing the question of whether and how IOR is related or linked to WM. Typically, cueing paradigms are used to answer this important question. That is, one or more item locations (in case of spatial WM) or other features of the items such as their color (in case of visual WM) have to be memorized prior the presentation of the peripheral cue that is followed by the target. The rationale of introducing such a secondary task is that if IOR relies on the specific type of WM, the respective WM load should affect the magnitude of IOR because there are not enough resources left for inhibition processes. For instance, Castel et al. (2003) examined the effect of verbal (numeric) and spatial WM load on IOR. To this end, they had participants perform various secondary tasks during the interval between the cue and the target (i.e., monitoring odd digits, adding digits, or remembering the directionality/orientation of arrows or objects). Their results showed that only the spatial WM tasks reduced IOR but not the verbal WM task, suggesting that IOR relies only on the former WM system. However, when Theeuwes et al. (2006) had participants memorize the location of a dot before the task, they found no evidence that spatial WM load affected IOR. Zhang and Zhang (2011) had participants respond to the target either via button press (manual response) or via a saccade while holding either one or four item locations in WM. Their findings showed that only the manual IOR, but not saccadic IOR, was affected by such a spatial memory load. Finally, Shen et al. (2021) varied the response modality in a cueing paradigm with a concurrent spatial WM memory task (holding one or five item locations in WM) and had participants make either a manual localization response or a manual or saccadic detection response to the target. They found almost the opposite pattern to Zhang and Zhang (2011), namely, that the amount of IOR was not affected by WM load for manual responses, but only when saccadic responses were required. Overall, the findings regarding the influence of WM on IOR are inconclusive and the question also remains whether and how such a possible impact would apply to a visual search task.

In the current study, we were interested in whether and to what extent IOR during visual search is affected by either a low or high spatial WM load. To this end, we had participants search for a target letter in a display while being asked to hold no, two, or four item locations in memory. During the search, an inspected or noninspected item was probed in the search display, and participants' saccadic responses to this probe were recorded via an eyetracker. If spatial WM is linked to an attentional process such as IOR, we expected IOR to be impaired or even disappear in the low and high load conditions compared to the no load condition.

METHOD

Participants

We tested 18 participants (13 females, 5 males). They were on average 25.7 years old (*SD* = 3.9; 18–35 years) and had normal or corrected-to-normal vision. All gave informed consent. The experiment was approved by the ethics committee of the University of Graz.

Measures

The participants had to search once in a 15-letter display. The target was present on half of the trials. During the search, one of the items was probed. The probe was presented at a position that was previously fixated (old probe) or not (new probe). There were three memory conditions: Before the search started, no, two, or four squares were presented around the central fixation cross (no load, low load, and high load condition) and participants were asked to memorize the locations of these squares. After the search ended, a test display was presented. This test display resembled the memory display in half of the trials. In the other half of the trials, one of the squares had changed its location. All factors were varied within-subject. In order to test IOR in relation to the different load conditions, saccadic latencies (i.e., the time from the probe onset to the start of the respective saccade to the probe) were measured.

Stimuli and Apparatus

The search display consisted of 15 letters randomly selected from 16 letters ("A," "E," "F," "G," "H," "K," "L," "M," "O," "P," "R," "S," "T," "U," "X," and "Z") for each trial (see Figure 1). In the target-absent trials, the remaining letter not presented on the display was the search target. In target-present trials, the search target was randomly chosen from all letters in the display. The letters were each arranged in the center (± 0.23 ° jitter in each direction) of 15 different grid cells randomly selected from an invisible 6 × 6 grid (21.6 ° × 21.6 °); the size of each grid cell was 3.6 °. In order to prevent the letters from being recognized from the periphery, they were surrounded by a ring which was 0.18 ° thick. The size of an item (letter + ring) was 0.9 °.

The memory display consisted of no, two, or four squares presented randomly in order around a central fixation cross, within the inner 4 × 4 grid cells of the 6 × 6 grid. The size of each square was 0.6 °. In the test display (after the search was completed), one of the squares changed position on half of the trials (see below). All stimuli were displayed in light gray (RGB: 130,130,130) on a black background. The size of the fixation cross presented at the center of the screen was 0.4 °. The resolution of the display was 1152 × 864; the refresh rate was 80 Hz. We used an Eyelink 2 (SR Research, Canada) in order to track participants' eye movements.

Procedure

Each trial started with a fixation cross/drift correction presented in the center of the screen. After the fixation was registered by the experimenter via keyboard, the memory display (1,000 ms) was presented. During the memory display, either no, two, or four squares were displayed within the inner 4 × 4 grid cells of the 6 × 6 grid, representing the no load, low load, and high load conditions, respectively. The memory display was followed by a brief drift correction for the eye tracker. Thereafter, the search display was presented, and a target letter was simultaneously announced using speakers positioned to the left and right of the monitor. The participants were instructed to search for this target and press the right trigger on a gamepad when the target was present and the left trigger when the target was absent. Critically, in most trials, one of the items in the display was probed during search such that the surrounding ring of the item turned into a red square (twice the size of the ring). In order to make the probe even more salient, the probed item flickered (i.e., the probe was on for 50 ms, then off for 50 ms and then on again). The participants' task was to immediately saccade to this probe when it was recognized and then continue the search. The probe disappeared when the probe was fixated (using a minimal distance criterion) within the first three fixations after probe onset or when more than 500 ms had passed. After pressing the button, a test display (low and high load conditions) or a fixation cross (no load condition) was presented. The test display presented the same number of squares as before the search. On half of the trials, one of the squares was in a different location than before the search. Participants were asked to decide whether the test display was the same as before (right trigger on the game pad) or different (left trigger). If there was no response within 5,000 ms, the display was deleted, and a new trial started. In the memory condition with no squares, a fixation cross was presented for 1,000 ms.

Each participant completed four blocks of 70 trials each for each memory condition. Six trials per block were catch trials in which no probe was presented. Each memory condition was tested on a separate day. The order of the memory conditions was counterbalanced across participants. The probe condition (old/new) and target presence (present/absent) was varied within each block.

RESULTS

For the analysis, we used JAMOVI 1.6.23.0 (The jamovi project, 2021). We collected a total of 15,120 trials (18 participants × 840 trials). Eight trials were lost due to technical errors. Data of one participant

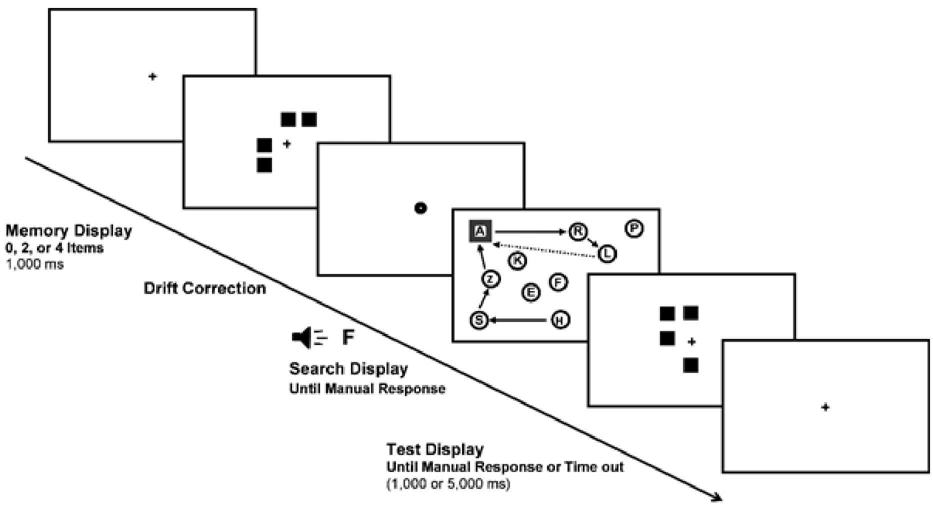

FIGURE 1.

The procedure in a high-load trial with an old probe. In general, participants memorized zero, two, or four item locations before they searched through a display of 15 letters for a target letter. During the search, either a recently inspected or noninspected item was probed. Participants were asked to saccade to the probe immediately and then to continue the search. After a manual response, a test display was presented which was either the same or different to the memory display.

was excluded due to high error rate in the visual search task (> 20%). However, the error rate in the search task was low for the remaining 17 participants and did not vary between memory conditions (no load: *M* = 5.0%, *SD* = 4.0; low load: *M* = 5.8 %, *SD* = 3.3; high load: *M* = 5.5%, *SD* = 2.7; $F < 1$). However, as expected, the error rate of the memory task was higher in the high load condition (*M* = 20.9%, *SD* = 7.6) than in the low load condition (*M* = 17.6%, *SD* = 7.8; $t[16] = 2.50$, $p = .024$).

For the analysis of the response times in the search task, response times greater than 15,000 ms (and 7 invalid trials with response times smaller than 0) were excluded from this analysis (0.28% of the trials). Mean response times in the search task (averaged across individual means) were *M* = 4,992 ms (*SD* = 834), *M* = 5,197 ms (*SD* = 1,063) and *M* = 5,150 ms (*SD* = 861) for the no load, low-load, and high-load conditions, respectively. We fitted a generalized linear mixed model (GLMM) using a gamma distribution with the identity function. We treated the memory-load condition (no load, low load, high load) as a fixed factor and participants as a random factor. The result of the model can be seen in Table 1. Response times were significantly higher for both the high load and the low load condition than for the no load condition. In addition, a post hoc analysis (Bonferroni-corrected) showed that response times were slightly shorter in the high load compared to the low load condition, $p < .001$. Nevertheless, the results indicated that the WM load successfully affected the search performance.

For the analysis of whether IOR is affected by spatial WM load, only saccadic latencies for which the probed item was inspected immediately after probe onset and were greater than 50 ms were included in the analysis. This was the case for 2,243 old probes and 1,706 new probes. The mean saccadic latencies (averaged across individual means) for old and new probes depending on the three load conditions are shown in Figure 2. Overall, saccadic latencies were longer to old probes (M_{no}= 248 ms, SD_{no} = 25; M_{low} = 244 ms, SD_{low} = 32; M_{high} = 240 ms, SD_{high} = 23) than to new probes (M_{no} = 231 ms, SD_{no} = 33; M_{low} = 227 ms, SD_{low} = 31; M_{high} = 224 ms, SD_{high} = 29) regardless of load condition. For deeper analysis, we used the same GLMM as described above with saccadic latencies as the dependent variable. The model output can be seen in Table 2. The results showed that saccadic latencies in the low and high load conditions were significantly faster than in the no load condition. However, there was no such a difference in saccadic latencies between the low and high load condition ($p = 1$). Crucially, saccadic latencies to old probes were longer than to new probes and this was regardless of WM load, as indicated by the nonsignificant interactions. This suggests that spatial WM did not affect IOR.

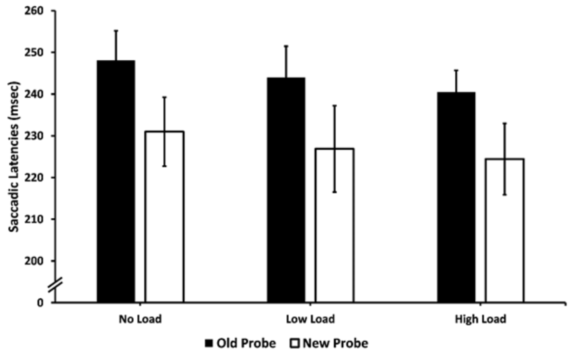

FIGURE 2.
Mean saccadic latencies to old versus new probes depending on the load conditions. Standard errors represent the 95% CIs (Cousineau, 2005; Morey, 2008).

DISCUSSION

In the current paper, we were interested in whether and how a spatial WM load affects saccadic IOR during a visual search. To this end, we had participants memorize no, two, or four item locations before a subsequent visual search task. During this visual search, we tested for IOR by probing either a previously inspected or a noninspected item. In line with previous results, we showed that IOR was active during search because saccadic latencies to recently inspected items were longer than to noninspected items. However, the results also indicated that, although spatial WM load decreased search performance, the magnitude of IOR was not affected by the concurrent memory load. This finding suggests that saccadic IOR and spatial WM do not rely on the same resources.

One might assume that, in the current experiment, saccadic IOR was not affected by the concurrent WM load because keeping two- or four-item locations in WM might not have filled it to its capacity and hence, there were enough resources left for inhibition processes. However, the spatial WM load (whether low or high) mattered for search times, suggesting that the spatial WM load was effective.

TABLE 1.
Generalized Linear Mixed-Model Analysis for Search Response Times

			95% CI			
	Estimate	*SE*	Lower	Upper	*z*	*p*
Fixed effects						
Intercept (= grand mean)	5150	3.05	5144	5156	1686.7	< .001
Low load–no load	214	2.98	208	220	71.8	< .001
High load–no load	159	2.00	155	163	79.3	< .001
Random effects	Variance	*SD*				
Participants (intercept)	127664.67	357.30				
Participants (low load)	99019.68	314.67				
Participants (high load)	72674.71	269.58				

TABLE 2.
Generalized Linear Mixed-Model Analysis for Saccadic Latencies

			95% CI			
	Estimate	*SE*	Lower	Upper	*z*	*p*
Fixed effects						
Intercept (= grand mean)	238.52	4.88	228.96	248.09	48.885	< .001
Low load–no load	−5.13	2.06	−9.16	−1.09	−2.488	0.013
High load–no load	−8.65	3.89	−16.28	−1.02	−2.223	0.026
New probe–old probe	−16.25	3.34	−22.79	−9.71	−4.872	< .001
Low load–no load × new probe–old probe	−2.44	5.00	−12.25	7.36	−0.488	0.625
High load–no load × new probe–old probe	−2.18	3.94	−9.90	5.54	−0.554	0.580
Random effects	Variance	*SD*				
Participants						
Intercept	123.94	11.13				
Low load	3.25	1.80				
High load	101.14	10.06				
New probe	64.88	8.05				
Low load × new probe	247.10	15.72				
High load × new probe	85.20	9.23				

Furthermore, the error rates in the memory task were reliably higher in the high load condition than in the low load condition, suggesting that the high load task was more difficult. Nevertheless, in future research, it would be desirable to also include a range of load conditions that clearly exceed WM capacity in order to see in greater detail whether and how spatial WM load might affect saccadic IOR.

To our knowledge, most of the studies that investigated a possible relationship between IOR and spatial WM used cueing paradigms instead of visual search to address this important question. Comparing the findings of such experiments with our results is thus rather difficult and should only be made with caution (see e.g., Dukewich & Klein, 2015, for a discussion). Nevertheless, at first glance, our findings are in line with the findings of Zhang and Zhang (2011), but different to those of Shen et al. (2021). Zhang and Zhang had participants maintain up to four item locations in spatial WM before performing the cueing task and also showed that—in contrast to manual IOR—saccadic IOR was not influenced by such a WM load. In contrast, Shen et al. found evidence that an increased WM load reduced saccadic—but not manual—IOR significantly. However, in their high load condition, participants had to memorize five item locations instead of the four-location load used in the current experiment. This five-location load in Shen et al. might have exceeded WM capacity and hence might have led to the interference with—but still not to the extinction of—IOR. Therefore, at least for saccadic IOR, the findings of Shen et al. might not be seen as a contradiction to our results and those of Zhang and Zhang.

Zhang and Zhang (2011) postulated three rather passive mechanisms that could explain why saccadic IOR was maintained although spatial WM was absent: (a) As the peripheral cue used in their experiments was irrelevant for the target, implicit memory might have kept the information, (b) spatial indexing as a nonattentional system was used to hold up to four or five locations (see Pylyshyn, 2007; Wright & Ward, 2008), or (c) that IOR might be a "simple, low-level visual neural habituation" (p. 151). However, a further possibility might be that there is an interplay of saccadic IOR and spatial WM that supports the respective visual task rather flexibly. For instance, previous research has indicated that both IOR and WM enhance visual search performance by using the information gained from previously inspected items. However, while IOR ensures that attention is guided to new information in the visual environment (e.g., Höfler et al., 2011; Höfler et al., 2019; Klein & MacInnes, 1999; MacInnes & Klein, 2003; see Wang & Klein, 2010 for a review), spatial WM might also be used to store information about which items should be inspected immediately again when this is necessary for completing the task (e.g., Höfler et al. 2015). The case in which spatial WM and IOR work simultaneously to guide search to noninspected items might be the standard if a stable display has to be searched once for a target, as both processes ensure that the search task can be fulfilled in the best possible way. Accordingly, when the display is not stable, then neither WM nor IOR should be observed, which has been repeatedly demonstrated (Christ et al., 2002; Wang et al., 2010). However, if the same display is searched repeatedly and spatial memory (besides object memory) of previously inspected items can be used to guide search back in case one of the items becomes a target in a subsequent search (Körner & Gilchrist, 2007; Hout & Goldinger, 2010; Höfler et al., 2014, 2015), IOR should become inactive, as it would hinder the immediate reinspection of the items. Indeed, there is evidence that, in a repeated visual search task, saccadic IOR is absent after the first of two consecutive searches was completed (Höfler et al., 2011; see also Höfler et al., 2019) but remains active if the search is only briefly interrupted (Höfler et al., 2011; Thomas & Lleras, 2009). Furthermore, findings from Dodd et al. (2009; see also Smith & Henderson, 2009) also suggest that IOR strongly depends on the visual task. They had participants perform either a visual search, a memorization task, a pleasantness rating, or a free viewing task in a scene. Their results showed that IOR was active in the visual search task only, whereas there was even a facilitation effect for previously inspected locations in all the other tasks. That is, if a task such as visual search benefits from inhibiting recently inspected items, then IOR seems to be present; if not, IOR seems to be absent.

Taken together, we provided first evidence that the findings from previous cueing paradigms on the question of the relationship between saccadic IOR and spatial WM (e.g., Zhang & Zhang, 2011; Shen et al., 2021) can be generalized to visual search. In line with these results, we showed that saccadic latencies to recently inspected items were longer than to noninspected items, reflecting the involvement of IOR. However, this effect was regardless of any accompanying WM load, suggesting that saccadic IOR can be observed in the absence of spatial WM.

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DATA AVAILABILITY

Data of this study are available from the corresponding author (MH) on request.

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