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Spatial working memory load impairs manual but not saccadic inhibition of return

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A B S T R A C T

Although spatial working memory has been shown to play a central role in manual IOR (Castel, Pratt, & Craik, 2003), it is so far unclear whether spatial working memory is involved in saccadic IOR. The present study sought to address this question by using a dual task paradigm, in which the participants performed an IOR task while keeping a set of locations in spatial working memory. While manual IOR was eliminated, saccadic IOR was not affected by spatial working memory load. These findings suggest that saccadic IOR does not rely on spatial working memory to process inhibitory tagging.

1. Introduction

An abrupt change of brightness (the cue) in a peripheral location usually facilitates the processing of stimulus (the target) subsequently presented at that location. When the delay between the cue and the target (stimulus onset asynchrony, SOA) becomes longer than 300 ms, however, the early facilitation effect turns into an inhibition effect (Posner & Cohen, 1984; Posner, Rafal, Choate, & Vaughan, 1985). That is, responses to targets at the cued location become slower than to those at the uncued location. The latter effect is now known as inhibition of return (IOR) and has been demonstrated in a wide range of tasks (Klein, 2000; Lupiáñez, Klein, & Bartolomeo, 2006; Lupiáñez, Milan, Tornay, Madrid, & Tudela, 1997).

A central question in IOR concerns the mechanism for maintaining the inhibitory tagging at previously attended locations (Klein & Dukewich, 2006; Klein & Ivanoff, 2005). Many investigators have suggested that spatial working memory (SPWM, Baddeley, 1986; Baddeley, 2003) may be responsible for this mechanism (Castel et al., 2003; Gilchrist & Harvey, 2000; Klein, 1988; Posner & Cohen, 1984). For example, Posner and Cohen (1984) proposed that IOR acts as memory for previously attended location and therefore increases the efficiency of foraging activity by biasing attention away from recently examined locations. Consistent with this notion, IOR can co-occur at several sequentially cued locations and appears to be greatest in the last cued location (Dodd, Castel, & Pratt, 2003; Dodd & Pratt, 2007; Snyder & Kingstone, 2000; Snyder & Kingstone, 2007). Strong evidence for the memory-based hypothesis comes from the finding that IOR was eliminated by concurrent SPWM load but not affected by concurrent verbal WM load (Castel et al., 2003). Collectively, these observations appear to suggest that IOR may recruit SPWM to keep and update inhibitory tagging.

However, IOR is not a unitary process but rather consists of two dissociable components manifesting in different response modalities: a saccadic component in oculomotor tasks and an attentional component in manual tasks. (Hunt & Kingstone, 2003; Sumner, 2006; Sumner, Nachev, Vora, Husain, & Kennard, 2004). For instance, Hunt and Kingstone (2003) have demonstrated a double dissociation between these two components along the line of response modality. When IOR is measured using saccadic responses, it interacted with an effect that is thought to be specifically oculomotor (the fixation–offset effect, FOE) but not with an effect that is known to affect attention (the target luminance effect). In contrast, when IOR is measured using manual responses, it exhibits a reversed effect. That is, it interacted with the target luminance effect instead of the FOE effect. Consistently, S-cone signals, which are invisible to the retinotectal pathways, have been shown to induce robust IOR in the saccade task but not in the manual task (Sumner, 2006; Sumner et al., 2004).

It is so far unclear whether the SPWM based mechanism is also involved in saccadic IOR. In fact, contrary to the involvement of SPWM in manual IOR (Castel et al., 2003), there is some evidence for the absence of interference of SPWM on saccadic IOR. Two recent studies have shown that saccadic IOR in the memory condition is comparable to or larger than that in the no memory condition (Belopolsky & Theeuwes, 2009; Theeuwes, van der Stigchel, & Olivers, 2006). However, because these two studies were primarily interested in the inhibition effect toward the memorized location, the SPWM task was set to share rather than compete for the memory resource with the saccadic IOR task. In Belopolsky and

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Theeuwes study (2009), for instance, the participants were required to make a saccade toward a location kept in memory. That is, the memory cue not only indicated a to-be-remembered location but also served as a peripheral cue to elicit saccadic IOR. Under such circumstances, there is no reason for IOR system to recruit additional SPWM resource to memorize a location already existing in SPWM. This manipulation, thus, precludes any definitive conclusions about whether saccadic IOR depends on SPWM.

In the present study, we used a spatial cueing task in conjunction with a competing SPWM task and measured saccade latencies to examine whether holding spatial locations in WM would impair saccadic IOR. Crucially, we manipulated the SPWM so that the location of SPWM was not overlapped with the location of the peripheral cue. Such manipulation enabled us to determine whether SPWM affects saccadic IOR when they compete for limited storage resources. If saccadic IOR needs SPWM to hold the inhibitory tagging (Castel et al., 2003; Dodd et al., 2003; Klein & Dukewich, 2006), saccadic IOR should be impaired when SPWM has been occupied. Alternatively, if saccadic IOR, in analogy to refractory periods after intense neural activity, is merely an aftereffect of attention orienting and does not involve the use of SPWM (Hooge, Over, van Wezel, & Frens, 2005), saccadic IOR should be unaffected by SPWM load.

2. Experiment 1. Spatial working memory on saccadic IOR

2.1. Methods

2.1.1. Participants

Eleven naïve, paid volunteers and the first author participated in Experiment 1. All participants (10 female, 2 male, 23.8 ± 2.6 years) had normal or corrected-to-normal vision and gave written informed consent. The local ethics committee approved this and all the following experiments.

2.1.2. Apparatus

Participants were seated in a dimly lit, sound attenuated room and sat about 57 cm from an 85-Hz CRT monitor (iiyama MA203DT, resolution 1024 × 768) using a chin rest. All stimuli were presented on a black background (1.25 cd/m^2). An IBM compatible Pentium-equipped PC running Experiment-Builder 1.2 controlled stimulus presentation. Eye movements were recorded using an Eyelink II system (500-Hz temporal and 0.05° spatial resolution) set in pupil mode with a saccade threshold of 30.0°/s (Li & Lin, 2002; Rafal, Egly, & Rhodes, 1994; Taylor & Klein, 2000). A standard nine-point grid calibration was performed at the beginning of each block and the calibration was checked at the beginning of each trial. Participants self initiated each trial by pressing a defined button on a gamepad.

2.1.3. Stimuli and procedure

Fig. 1A illustrates the procedure. (1) At the beginning of each trial, a gray fixation dot (45.6 cd/m^2, 0.67° in diameter) was presented in the center of the screen for 800 ms. Participants were instructed to keep their eyes on the fixation dot until a target for the saccade task appeared. (2) Subsequently, an array of SPWM load consisted of four white filled squares or one (87.7 cd/m^2, 0.5° × 0.5°) was presented for 1000 ms. Participants had to remember the locations of the squares till the end of the trial. In 4-WM load trials, four white squares were presented at four of twenty possible locations, with the constraint that four squares always fell in different quadrants. The twenty possible locations were selected from a 5.0° × 5.0° region in the center of the screen. Each location was spaced at least 0.9° from adjacent locations and at least 1.14° from the fixation dot (Fig. 1B). In 1-WM load trials, a white square was randomly presented to the up or down of the central fixation (red locations in Fig. 1B). (3) Then, two empty gray square placeholders (2° × 2.5°, 14.3 cd/m^2) were presented 8° to the left and the right of the fixation dot for 1,000 ms, followed by a peripheral cue (a filled white square, 2.42° × 2.92°) presented on one of the placeholder for 165 ms. (4) After a 165 ms delay, a central cue (a white dot 1.42° in diameter) was presented at the fixation point for 200 ms followed by a 353 ms delay. (5) A white target bar (87.7 cd/m^2, 0.58° × 1.12°) then appeared in one of the two placeholders until the participant made a saccadic response, or 800 ms had elapsed. Participants were asked to move their eyes toward the target as quickly and accurately as possible and were alerted if they start saccade in less than 80 ms or failed to start saccade within 700 ms. (6) Then, an empty square (87.7 cd/m^2, 1.0° × 1.0° with 0.08° thickness) was presented at either a remembered location or an unremembered location. By pressing the "5" or "6" button on the gamepad, the participants made an unspeeded response to indicate whether the probe was presented at one of the memorized locations and received distinct auditory

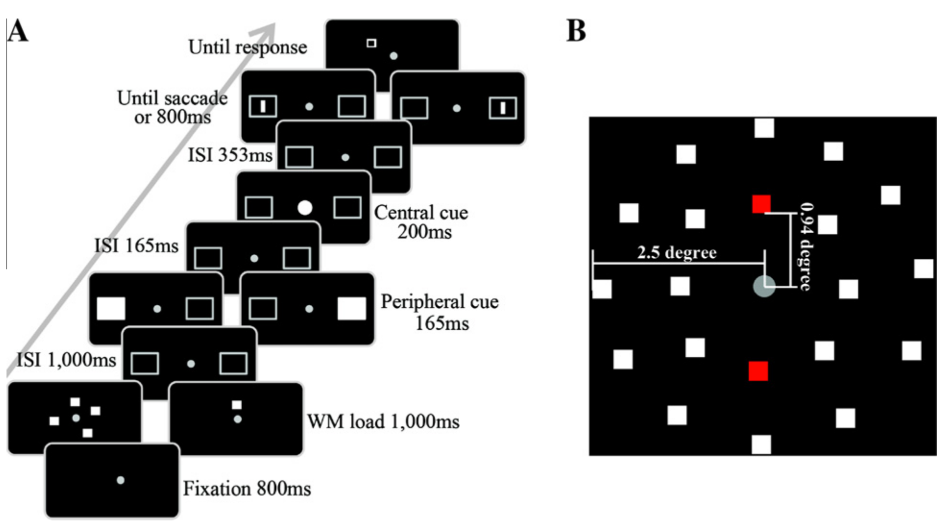

Fig. 1. Stimulus configuration used in the experiment. (A) An illustration of the sequence of the stimuli presented during Experiment 1. (B) The twenty possibility locations used for the spatial working memory task. In 4-WM load trials, the four locations were randomly selected from all of these locations (white and red). In 1-WM load trials, the one location was randomly selected from the two red locations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

feedback for correct and incorrect judgments. The response key mappings were counterbalanced across participants. All participants were told that their performances on these two tasks were equally important.

Given SPWM may bias the attention toward the memorized locations (Awh, Vogel, & Oh, 2006), the arrays of SPWM load in the valid and invalid conditions were counterbalanced across participants. Moreover, in order to rule out the possible influence of the center of mass on attention (Robertson, 2004; Zhou, Chu, Li, & Zhan, 2006), the center of mass of WM items were matched across the valid and invalid conditions and in each conditions the mean of centroids were restricted in 0.1° area around the central fixation.

We did not employ the same paradigm as Castel et al. (2003). In their study, the SPWM load was presented after the cue of the IOR task. As this manipulation would load both the WM coding and WM storage processing on IOR, it is not appropriate to examine the role of SPWM storage (as proposed by memory hypothesis) in IOR. We adapted the procedure by loading the WM items before the cue, which would rule out the possible influence of the memory coding on IOR. This arrangement has been widely used to examine the role of memory in visual search (Oh & Kim, 2004; Woodman & Luck, 2004; Woodman & Luck, 2009; Woodman, Vogel, & Luck, 2001). It has also been used in recent studies to explore the effect of WM load on IOR in dynamic displays and on the time course of IOR (Klein, Castel, & Pratt, 2006; Zhang, Zhang, & Fu, 2007).

2.1.4. Design

The experiment was a two-factor (*cueing* × *WM load*) within-participant design. The factor *cueing* had two levels: valid trials in which the target and cue appeared at the same location, and invalid trials in which they appeared at the opposite locations. The factor *WM load* had two levels: 4-WM load trials with four locations memorized and 1-WM load trials with one location memorized. Saccade latency was defined as the interval between the onset of the target and the initiation of the saccade.

The experiment consisted of five blocks of 240 trials. Each block comprised of six repetitions of factorial combination of two possible cue locations, two possible target locations, and two types of WM load (4-WM and 1-WM load). All trials within each block were presented randomly. Prior to the experimental trials, a block of 48 trials was presented for practice. The total duration of the experiment was approximately 80 min with time for breaks between the blocks.

2.1.5. Data analysis

There are two types of errors in the saccade task: the fixation error in which the participants failed to maintain fixation within 2° of the fixation spot during the cue-target interval; and the saccade error in which the saccade was not started within 2° of the central fixation or was not terminated within the 3° of the target location. These two types of error trials and trials with incorrect responses in WM task were excluded from the saccade latency analysis. For each condition of each subject, correct RTs were submitted to a non-recursive outlier elimination procedure with moving criterion (Van Selst & Jolicoeur, 1994). Those outliers constitute 2.2% of the trials. For each participant, mean saccade latencies and mean error percentages were entered into a repeated measures analysis of variance (ANOVA) with factors of *cueing* (valid and invalid) and *WM load* (4-WM and 1-WM load).

2.2. Results

2.2.1. Saccade latencies

Left panel of Fig. 2 shows the mean saccade latencies for correct trials as a function of *WM load* and *cueing*. As expected, there was a significant main effect of cueing, $F(1, 11) = 14.88$, $p < 0.01$, demonstrating significant saccadic IOR effect. Participants responded faster to invalid targets (184 ms) than to valid targets (209 ms). There was also a significant main effect of *WM load*, $F(1, 11) = 8.53$, $p < 0.05$, suggesting faster responses for 4-WM load trials (189 ms) than for 1-WM load trials (204 ms). However, no significant interaction of *WM load* and *cueing* was found, $F(1, 11) = 0.12$, $p = 0.73$. The magnitudes of saccadic IOR were 23 and 26 ms for 1-WM and 4-WM load conditions respectively.

2.2.2. Saccade and WM error rates

Saccade and WM error rates for each condition are displayed in Table 1. The ANOVA of the WM error rates revealed a significant main effect of *WM load*, $F(1, 10) = 258.14$, $p < .0001$. The error rates were higher in the 4-WM load condition (27.85%) than in the 1-WM load condition (4.17%). Neither the main effect of *cueing* nor the interaction of *WM load* and *cueing* was significant (both $F < 1$). The ANOVA of saccade error rates revealed no significant results.

2.3. Discussion of Experiment 1

The main purpose of Experiment 1 was to determine whether the saccade IOR also needed SPWM to keep the previous attended locations. In particular, we tested whether full loaded SPWM would impair saccadic IOR. In Experiment 1, subjects were slower to make a saccade toward the target presented at cued locations regardless of the SPWM load. The saccadic IOR was robust, even when the SPWM capacity was exhausted by four SPWM loads. These results contrast the results reported by Castel et al. (2003)

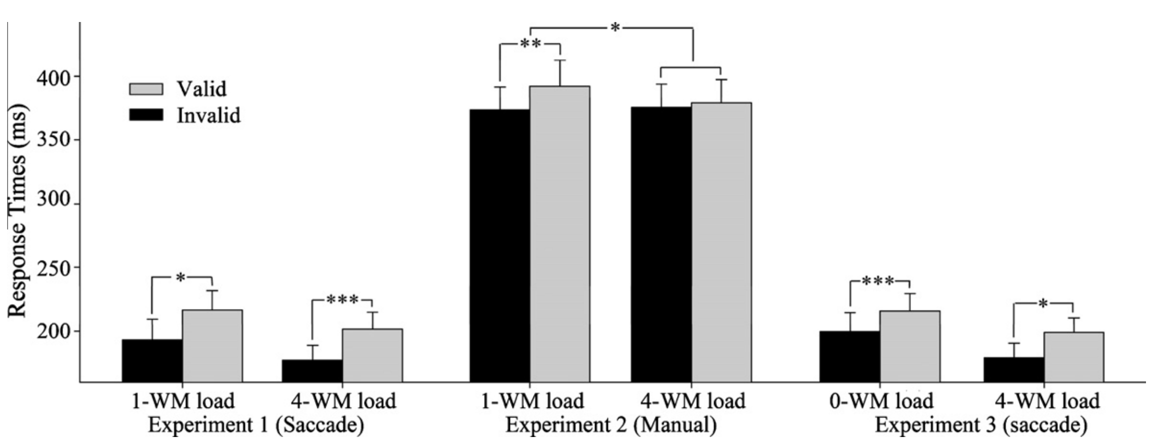

Fig. 2. Mean of correct saccade latencies (±SEM) as a function of *cueing* and *WM load*. $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

Table 1
Percentage errors (%) for fixation (FI), saccades (SA) and working memory (WM) as a function of *cueing* and *WM load* in Experiments 1–3. In Experiment 2, the SA indicates error responses in the IOR task.

		Experiment 1		Experiment 2		Experiment 3	
	Cuing	1-Load	4-Load	1-Load	4-Load	0-Load	4-Load
FI	Invalid	0.69	1.11	0.0	0.0	1.53	1.53
	Valid	1.53	2.08	0.13	0.13	1.81	2.22
SA	Invalid	7.78	6.11	1.67	1.79	4.86	6.11
	Valid	7.50	8.06	0.77	1.28	8.75	6.94
WM	Invalid	4.44	28.19	3.97	22.69	–	25.14
	Valid	3.89	27.50	4.23	25.64	–	26.67

who found no presence of manual IOR when SPWM load was introduced.

As our main motivation is to determine whether the same mechanism for maintaining inhibitory tagging underlines the saccadic and the manual IOR, it is necessary to use the same paradigm to compare the influence of SPWM on IOR in both tasks. However, the SPWM task in Experiment 1 was different from that in Castel et al. (2003). While the SPWM load was presented during the IOR task in their study, the SPWM load was added before the IOR task in the present study. This difference made it hard to compare those two studies. Given this reason and the pitfall of the procedure in Castel et al. (2003), we replicated their results by using the same SPWM load task as in Experiment 1 but with manual localization responses for the IOR task.

3. Experiment 2. SPWM on manual IOR

3.1. Methods

3.1.1. Participants

Eleven new naïve students and the first author participated in Experiment 2 (mean age of 22.4 ± 3.1 years, five male, seven female). All had normal or corrected-to-normal vision. One of them was replaced due to significant facilitation in both the 1-WM and 4-WM load conditions (38 and 16 ms for 1-WM and 4-WM load conditions respectively).

3.1.2. Apparatus, stimuli, and procedure

The stimuli and procedure were identical to Experiment 1, except that the participants had to make a manual localization rather than a saccadic response to the target of the IOR task. That is, the participants were required to discriminate at which location the target appeared by pressing the "5" and the "6" key on the gamepad for left and right respectively.

3.1.3. Data analysis

Error trials in both tasks and trials in which the participants failed to keep fixation were excluded from the saccade latency analysis. For each condition of each subject, correct RTs were submitted to a non-recursive outlier elimination procedure with moving criterion (Van Selst & Jolicoeur, 1994). Those outliers constitute 2.9% of the trials. For each participant, mean RT and error percentages were submitted into a repeated measures analysis of variance (ANOVA) with factors of *cueing* (valid and invalid) and *WM load* (1-WM and 4-WM load).

3.2. Results

The RTs mean for correct trials as a function of *WM load* and *cueing* was shown in the central panel of Fig. 2. For the RT analysis, the main effect of *cueing* was significant, $F(1, 11) = 6.99$, $p < 0.05$, with faster responses for invalid (375 ms) trials than for valid trials (386 ms). Moreover, the interaction of *WM load* and *cueing* was significant, $F(1, 11) = 7.488$, $p < 0.05$, indicating that the IOR effect was greater in the l-WM load condition (19 ms) than in the 4-WM load condition (4 ms). There was no significant main effect of *WM load*, $F < 1$.

The analysis of WM errors yielded a significant main effect of *WM load*, $F(1, 11) = 82.16$, $p < 0.001$, indicating that the WM performance was significantly better in 1-WM load trials than in 4-WM load trials. Neither the main effect of *cueing* [$F(1, 11) = 2.48$, $p = 0.14$] nor the interaction of *WM load* and *cueing* [$F(1, 11) = 1.43$, $p = 0.29$] reached significance. The analysis of IOR error and fixation error revealed no significant result.

3.3. Discussion of Experiment 2

Experiment 2 replicated the results of Castel et al. (2003) that maintaining concurrent SPWM load decreased the IOR effect in a manual task. When SPWM was occupied by four locations, the IOR in the manual task was abolished. This pattern of results was quite different from the pattern observed in Experiment 1, in which we found a robust saccadic IOR in the 4-WM load condition. This pattern was further confirmed by a three-way mixed ANOVA on RTs with *cueing* and *WM load* as within-subject factors and with *response model* (saccade vs. manual) as a between-subject factor. The RT results revealed a significant triple-interaction [$F(1, 22) = 4.45$, $p < 0.05$], suggesting that SPWM load impaired only manual IOR not saccadic IOR. Most importantly, this effect was not due to different priorities assigned to the WM task, as the main effect of *response mode* on WM errors was far from statistical significance [$F(1, 22) < 1$, $p = 0.448$]. Taken together, these results suggested that the saccadic IOR, different from the manual IOR, did not rely on SPWM to maintain the inhibitory tagging.

4. Experiment 3. SPWM on saccadic IOR with 0- and 4-WM load

The results in Experiments 1 and 2 provided evidence for the idea that saccadic and manual IOR might depend on distinct mechanisms to keep the inhibitory tagging. Many researchers, however, usually included a condition in which the participants were required to ignore the memory items as a baseline condition to evaluate the effect of WM load. As such a condition involved no memory load, it might be a more appropriate baseline for assessing the effect of WM on saccadic IOR. Besides, such a manipulation would amplify the difference in WM load from 3 (4 − 1) to 4 (4 − 0) items and therefore increase the chance to find a possible effect of SPWM on saccadic IOR. Hence, in Experiment 3 we replicated Experiment 1 with one key difference: the 1-WM load condition was replaced with the ignore condition (the 0-WM load condition).

4.1. Methods

4.1.1. Participants

Thirteen new naïve students participated in Experiment 3 (mean age of 22.6 ± 2.5 years; 4 male, 9 female). All had normal or corrected-to-normal vision. One of them was excluded from analysis due to facilitation in both the 0-WM and 4-WM load conditions (10 and 5 ms for 0-WM and 4-WM load conditions respectively).

4.1.2. Apparatus, stimuli, and procedure

The stimuli and procedure were identical to Experiment 1, apart from the followings. First, the 1-WM load condition in Experiment 1 was replaced with a 0-WM load condition. In Experiment 2, the 0-WM and the 4-WM load conditions adopted the same stimuli and procedure but with different instructions. Participants were instructed to remember the locations of squares in the 4-WM load condition while ignoring the squares in the 0-WM load condition. There were 120 arrays of WM load stimuli; each of them was presented twice, once for the 4-WM load condition and once for the 0-WM load condition. Second, the experiment consisted of six blocks of 40 trials each rather than five blocks of 48 trials each.

The WM load was manipulated between blocks. The order of the blocks was counterbalanced across participants. Each participant completed two practice blocks of 24 trials for each WM condition before the experiment session.

4.1.3. Data analysis

The outlier, error definition and data analysis procedure were identical to Experiment 1. The RTs outlier procedure excluded 2.5% of the trials.

4.2. Results

The right panel of Fig. 2 shows the RT results. The RT analysis revealed a significant main effect of *cueing*, $F(1, 11) = 17.95$, $p < .001$, indicating faster saccades for invalid trials ($M = 189$ ms) than those for valid trials ($M = 208$ ms). The main effect of *WM load* was significant, $F(1, 11) = 5.08$, $p = .046$, suggesting faster saccades under the 4-WM load condition compared to the 0-WM load condition. This effect might imply that the memory items caused a more diffuse attention window in the memory condition than they did in the ignored condition. However, this biasing effect on saccade latency is not consistently revealed in our pilot experiment in which slightly different SPWM parameters from the current study have been used (the four item was randomly selected from twelve instead of sixteen locations). Hence, it is not clear how much weight can be put on it. The interaction of *cueing* and *WM load* was not significant ($F < 1$). The magnitude of saccadic IOR was 16 and 20 ms for the 0-WM load and 4-WM load conditions respectively.

The mean error rates of each error type as a function of cueing and WM load are shown in Table 1. The saccadic error analysis revealed a significant main effect of *cueing*, $F(1, 11) = 16.16$, $p < 0.01$, suggesting more saccadic errors for valid trials (7.8%) than for invalid trials (5.5%). Neither the main effect of *WM load* [$F(1, 11) = 2.54$, $p < 0.139$] nor the interaction between *WM load* and *cueing* ($F < 1$) reached significance. All other effects on saccade error failed to reach significance. A paired-samples p test revealed no significant effect of *cueing* on WM error rates, $t(11) < 1$.

4.3. Discussion of Experiment 3

In Experiment 3, the same memory array was presented in the zero and four SPWM conditions. Participants were required to keep the memory array in 4-WM load blocks and ignore it in 0-WM load blocks. This provided a better baseline condition to evaluate the effect of SPWM load on saccadic IOR.

The results of Experiment 3 were similar to those of Experiment 1. Participants were slower to move eyes toward target stimuli presented at cued locations, which is the saccadic IOR effect. Most importantly, this effect did not vary with the increasing of the SPWM loads. The magnitude of saccadic IOR was comparable in the 0-load (16 ms) and 4-load conditions (20 ms).

5. General discussion

Although models of IOR have proposed that spatial working memory is critical for keeping the inhibitory tagging, only manual IOR has been examined. In the current study, we tested whether saccadic IOR also relies on SPWM to hold the inhibitory tagging. We addressed this question by using a dual task procedure in which subjects were required to remember a set of spatial locations while performing a saccadic IOR task. If SPWM was critical for saccadic IOR, saccadic IOR should be reduced or eliminated when four SPWM items occupied SPWM.

In line with previous studies of IOR, larger cueing costs were obtained across two saccadic experiments. Saccades toward the target were on average about 20 ms slower when the target and the peripheral cue appeared at the same location than when they appeared at different locations. The most striking finding was that the saccadic IOR elicited by the peripheral cue was not modulated by SPWM load. We found a roughly equal magnitude of saccadic IOR in high (four) and low (zero or one) SPWM load conditions (see Fig. 2). This pattern differed from the pattern observed in the manual task, in which IOR was eliminated by four WM loads (Experiment 2). The finding that concurrent SPWM load has no effect on saccadic IOR suggests that saccadic IOR essentially does not rely on SPWM to process the inhibitory tagging.

An alternative explanation for the null effect of SPWM load on saccadic IOR may be that the memory items used in 4-WM load trials did not fill SPWM to capacity. The residual SPWM capacity, therefore, can be available to hold the inhibitory tagging for the saccadic IOR. Several lines of evidence, however, excluded this explanation. First, the memory accuracy was far from the ceiling (see Table 1), suggesting that SPWM capacity was indeed overloaded in 4-WM load trials (Bays & Husain, 2008; Cowan, 2001; Cowan & Rouder, 2009; Zhang & Luck, 2008).Besides and most importantly, in Experiment 2, we employed the same WM task as Experiment 1. If SPWM were not overloaded by four locations, the manual IOR should be unaffected. We observed, however, that manual IOR was abolished in the 4-WM load condition. Thus, it seems unlikely that such an explanation could account for the null interaction between SPWM load and saccadic IOR.

If SPWM is not involved in saccadic IOR to hold the inhibitory tagging, then what are the likely mechanisms? There are three possible mechanisms. The first is implicit memory. After all, the peripheral cue was irrelevant to the target; there is no reason to recruit an intended and active system (Baddeley 1986; Baddeley 2003) to maintain this irrelevant information. Thus the implicit memory, an unintended and passive system, may be a reasonable candidate for keeping this information. The second possible mechanism may be the spatial indexing as suggested by Wright and Ward (2008). The spatial indexing is a non-attentional system that can hold the information of four or five spatial locations during visual processing (Pylyshyn, 2007). Those properties make it a possible candidate in saccadic IOR to hold the inhibitory tagging. The third possibility may be that saccadic IOR just reflects a simple low-level visual neural habituation (Dukewich & Boehnke, 2008; see a review in Dukewich, 2009) or a mechanism analogous to refractory periods after intense neural activity (Hooge et al., 2005) rather than a memory-based effect. Further studies may rest on the combination of the implicit memory and the IOR task to examine these possibilities.

The results presented here have important implications for memory-based manual IOR hypothesis (Castel et al., 2003; Klein & Dukewich, 2006; Posner & Cohen, 1984). Castel et al. (2003) found that manual IOR was abolished by concurrent performance of a SPWM task, suggesting an involvement of SPWM in manual IOR. However, as we mentioned before, the paradigm used in Castel et al. (2003) may confound the effect of WM coding with the effect of WM storage on manual IOR. That is, the lack of IOR in Castel et al. (2003) may be due to an influence of WM coding rather than WM storage on IOR. In the current study, we ruled out this confounding factor by loading SPWM before the presence of the peripheral cue and found that manual IOR was abolished by maintaining four SPWM loads in mind. Thus, the results of Experiment 2 provide new evidence for the memory-based manual IOR hypothesis. However, one may argue that the abolished IOR in Experiment 2 may be due to a depletion of spatial attentional resources.[1] That is, the lack of IOR in 4-WM load condition may result from the competition of the spatial attentional resources rather than the storage sources of SPWM. If it were the case, reduced saccadic IOR would be expected under the 4-WM load condition, as spatial attention has been demonstrated to be involved in both the manual and saccadic IOR (Souto & Kerzel, 2009a). In contrast, a robust saccadic IOR was found under the 4-WM load condition (Experiments 1 and 3). Therefore, it is unlikely that such an explanation could account for the absence of manual IOR under the 4-WM load condition.

It should be noted here that although the result of Experimental 2 appears consistent with the notion that manual IOR recruits SPWM to maintain and update the inhibitory tagging, it does not necessarily mean manual IOR exclusively rely on SPWM. Indeed, there is some evidence suggesting the possible involvement of non-WM mechanisms in manual IOR. Two recent studies have found that a subliminal cue that cannot be reached by WM system is able to evoke a significant IOR effect (Bauer, Cheadle, Parton, Muller, & Usher, 2009; Ivanoff & Klein, 2003). Clearly, further studies are needed to determine the scope and boundary of the role of SPWM on manual IOR.

While this paper was written, we received a paper on a similar subject (Vivas, Liaromati, Masoura, & Chatzikallia, 2010). By manipulating when to present the SPWM items, Vivas et al. (2010) demonstrated that concurrent SPWM task disrupted manual IOR but only when SPWM items were loaded after the peripheral cue. When SPWM items were presented before the peripheral cue, there was no reducing of manual IOR. At first glance, this finding seems to contradict with the abolished manual IOR in Experiment 2. It should be noted here, however, that there is a crucial difference between the task used in the current study and the task used by Vivas et al. (2010). While we adopted a widely used SPWM task (e.g. Oh & Kim, 2004; Woodman & Luck, 2004), Vivas et al. (2010) used a non-typical SPWM task introduced by Castel et al. (2003). Specifically the WM task used by Vivas et al. (2010) consisted of three successively presented items, each composed of two adjacent colored circles (red and green) arranged horizontal. This type of task is not very hard, as the participants were required to remember only the relative location of the colored circles. Further, because there are only two possibilities in each SPWM item (red-left or green-left), the participants may simplify the task into a simple verbal and/or visual WM task (e.g. ABA, A and B for red-left and green-left respectively) or even a one-item memory task if the participants realize that there are only six types of WM load array (ABA, ABB, AAB, BAA, BAB, or BBA). In agreement with this, the overall accuracy for the WM task is around 85% in Vivas et al. (2010) and about 93% in Castel et al. (2003) (in Vivas et al., 86%, 88% and 81% for Experiments 1–3 respectively; in Castel et al., 96% and 91% for Experiments 2 and 5 respectively), which is higher than about 75% in the current study. Thus, it is possible that the SPWM load used by Vivas et al. (2010) would not be heavy enough to exhaust the storage resource of SPWM and thereby disrupt the manual IOR.

One may argue that the inconsistent findings between Vivas et al.'s (2010) and the present study (Experimental 2) are instead due to the different ways of presenting the WM load.[2] In Vivas et al.'s (2010) study, the WM items were presented sequentially at the center and therefore cause no shifts of attention to the periphery. In contrast, in the present study, WM items were presented simultaneously and scattered at four locations. This arrangement might involve shifts of attention to the periphery, and thus reduced manual IOR. However, it should be noted here that although the WM items were scattered, their locations were placed around the central fixation (one in each quadrant). Most importantly, even the WM items might have bias attention toward the periphery; it should be the same between the valid and invalid conditions because the WM loads were well balanced between these two conditions. Given manual IOR is independent of endogenous orienting of attention (Berger, Henik, & Rafal, 2005; Berlucchi, Chelazzi, & Tassinari, 2000; Chica & Lupiáñez, 2009; Lupiáñez et al., 2004), it is unlikely that the balanced shifting of attention would systematically abolish the manual IOR effect.

The findings presented here also have important implications for the theory of IOR. Although, the view that attention appeared to segregate saccadic IOR from manual IOR (Hunt & Kingstone, 2003) has been questioned by a recent study showing an involvement of attention in saccadic IOR (Souto & Kerzel, 2009a), a growing body of evidence has demonstrated that saccadic IOR differs from manual IOR in many properties, such as the reference frame or its processing pathway (Abrams & Pratt, 2000; Souto & Kerzel, 2009b; Sumner et al., 2004). The present results provided further evidence for this dissociation by showing that saccadic and manual IOR may differ in how to maintain the inhibitory tagging in previous attended locations.

In summary, unlike manual IOR, saccadic IOR does not rely on spatial working memory to maintain the inhibitory tagging. While manual IOR was abolished by SPWM load, saccadic IOR survived even when the SPWM resources were occupied by four items.

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[1] An anonymous reviewer of our former manuscript in which we presented the data of three pilot experiments pointed out this possibility. In the pilot experiments, we used slightly different SPWM parameters from the current study and found a similar result as the current study. That is we found a reduced manual but robust saccadic IOR under four SPWM load condition.

[2] Thanks for an anonymous reviewer pointed this possibility out.

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