Title: Spatial constraints in saccadic inhibition of return

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ABSTRACT

Despite being one of the most prominent and well-known biases in visual orienting, inhibition of return (IOR), a tendency to avoid recently viewed locations, remains a controversial and poorly understood phenomenon. To investigate the characteristics of IOR, participants made rapid alternating saccades between two targets, return saccades, or produced eye movements that followed an “hourglass” pattern in which the same location was only revisited every fourth eye movement. Saccade dwell times and secondary saccade frequency increased when the eye returned immediately to a previously viewed location. Surprisingly, the higher rate of secondary saccades did not contribute directly to the longer dwell times in the return condition. Saccade precision was equivalent between conditions, but saccade gain was smaller for hourglass saccades. Varying the height and width of the hourglass revealed that the magnitude of inhibition of return depended on the angular separation between subsequent saccades and was not characterized by a constant zone around the targets. Even when the angular difference of hourglass saccades, relative to return saccades, was made as small as 3°, significant differences in dwell times and secondary saccade characteristics were observed. The results further explicate constraints on inhibition of return, reveal novel factors guiding secondary saccade programming, and provide insight into motor and attentional constraints governing the rate of sequential eye movements.

Keywords: IOR, ISR, saccades, saccadic eye movement

1. INTRODUCTION

Exploration of the visual environment requires serial shifts of attention that bring prioritized regions of space onto the fovea. Inhibition of return (IOR), a bias that prevents gaze from continuously returning to the highest priority location, has been proposed as one mechanism to improve the efficiency of this exploratory process. Although this bias has been incorporated into computational accounts of active vision as a fundamental feature of visual scanning (Itti & Koch, 2001), the behavioral underpinning and properties of IOR remain controversial (Berlucchi, 2007; Bays & Husain, 2012; Wilming et al. 2013).

The hypothesis that there is a mechanism to bias attention away from previously viewed locations was originally put forth by Posner & Cohen (1984). The phenomenon was initially described in a study examining how covert shifts of spatial attention influenced speeded responses indicating the location of a stimulus. Prior to the onset of the imperative stimulus, a spatial cue is presented, and the location of this cue either corresponds (valid cue) or does not correspond (invalid cue) with the target location. If the interval between the cue and target is short, reaction time (RT) is faster when the cue is valid compared to when it is invalid. However, if there is an extended interval between the cue and target (e.g. > 225 ms), RT is actually prolonged on valid trials, relative to invalid trials. This reversal, from a facilitatory gain to an inhibitory cost, was assumed to reflect a bias against reorienting attention to recently attended locations. Presumably, attention had shifted to the cued location, but with the extended delay, had returned to the original fixation position prior to the onset of the imperative signal. A substantial body of behavioral and neuroscientific research has accumulated over the past 35 years, elaborating on the sensory and attentional constraints underlying this phenomenon (Posner et al., 1985; Tassinari et al., 1987; Spence & Driver, 1998; Bennett & Pratt, 2001; Dorris et al., 2002; Fecteau, Bell, & Munoz, 2004; Satel et al., 2011).

One influential account makes a case for the importance of oculomotor programming in generating IOR (Rafal, Calabresi, & Brennan, 1989). Hooge & Frens (2000)

demonstrated a form of IOR distinct to the oculomotor system, or what is referred to as inhibition of saccadic return (ISR). Rapid sequences of saccades were used, enabling comparisons between conditions in which the target location had recently been fixated ($n-1$) with conditions in which the target location was relatively novel. Fixation duration, or dwell time, was much longer when the forthcoming eye movement immediately returned to the previously visited location. Indeed, the size of this effect, up to 40%, was much larger than that observed in traditional IOR (typically $< 10\%$). In addition, the zone of inhibition in ISR is limited to only about 4° of visual angle around the target rather than extending to the entire visual field (Bennett & Pratt, 2001), and is eliminated after a single fixation, ~ 300 ms, instead of lasting for up to two seconds (Posner et al., 1985).

Hooze and Frens (2000) used constrained sequences of eye movements, controlling the trajectories and terminal locations of the eye movements. Other researchers have followed up on this work with more naturalistic tasks, focusing on visual scanning behavior in free viewing or active search. Some of these experiments have provided evidence for ISR (Bays & Husain, 2012; Luke et al., 2014), while others have questioned its existence (Wilming et al., 2013). Interestingly, the relationship between IOR and ISR has not been considered in these visual scanning studies.

The present study builds upon Hooze & Frens (2000), comparing conditions in which sequential saccades return to the same location (back and forth) or follow an hourglass pattern between four points. The task, voluntary rapid alternating saccades (RAS) between predefined points, combines the ecological validity of visual scanning with the tight experimental control typically observed in cue-target or reaction time experiments. Whereas Hooze and Frens (2000) tested a small number of participants, we tested a large participant pool to get a sense of individual differences on these tasks. More important, we employed experimental manipulations that allowed us to examine how ISR varies with saccade amplitude and movement direction, the dependence of ISR on the angular difference between subsequent saccades, and the role that secondary saccadic eye movements might play in generating the effects.

In Experiment 1, we consider two questions concerning ISR. First, is ISR greater in the periphery relative to the perifoveal visual field. In the cue-target paradigm, IOR is stronger for stimuli presented at more distant eccentricities (Bao & Pöppel, 2007; Lei & Bao 2012; Bao et al., 2013). These findings have been linked to the spatial inhomogeneity of the visual field (Pöppel & Harvey, 1973) and the notion of two independent attentional processing modes (Pöppel, Cramon, & Backmund, 1975), one for perifoveal and another for peripheral stimuli. A finding that ISR is equivalent or decreases at greater eccentricities would further distinguish IOR from ISR and suggest that the underlying constraints might be motor rather than perceptual or attentional. Second, does ISR differ for horizontal and vertical eye movements. Recent work in non-human primates indicates that IOR is weaker, or perhaps even eliminated, for vertical saccades (Tian & Haged, 2015). While horizontal saccades are coded in contralateral brain regions (e.g., superior colliculus, frontal eye fields), vertical stimuli activate lateralized visuo-motor structures simultaneously and this may mediate the neural inhibition proposed to underlie the IOR and ISR phenomenon (Wang et al., 2011). Weaker ISR for vertical saccades may reflect greater residual activation spread across both motor maps.

In Experiment 2, we investigate whether ISR is best characterized as a constant zone around the target (Hooge & Frens, 2000; Bennett & Pratt, 2001) or might instead depend on the angle between subsequent eye movements (Anderson, Yadav, & Carpenter, 2008; Smith & Henderson, 2009; Bays & Husain, 2012). A dependence on angle rather than zone would again suggest ISR is likely driven by motor constraints (**Figure 1**). We also consider whether ISR exists as a phenomenon distinct from saccadic momentum, a linear increase in fixation duration accompanying changes in saccade angle (Smith & Henderson, 2009; Wilming et al., 2013). Return saccades might have the longest fixation durations simply because they represent the largest possible angular difference. A nonlinear increase in inhibition when saccades return to a previously viewed location would provide evidence for an independent ISR mechanism (Luke et al., 2014).

Finally, in both of the experiments we consider what role, if any, secondary fixational saccades play in generating the observed behavioral effects. Because of their ability to reset oscillatory oculomotor processes, micro-saccades required to maintain fixation have been proposed as a mechanism underlying classical inhibitory effects in cue-target IOR studies (Tian, Yoshida, & Hafed, 2016). The time needed to plan these secondary saccades as well as their movement duration may prolong fixation durations and directly contribute to the ISR phenomenon.

2. MATERIALS AND METHODS

2.1 Participants

16 individuals participated in Experiment 1 (two participants were excluded from analysis because of problems with the eye tracker system), and 10 individuals participated in Experiment 2. Participants were undergraduates at the University of California, Berkeley and naive concerning the purpose of the experiment. They participated in the study in exchange for course credit. All participants had normal or corrected to normal vision. The protocol was approved by the IRB at UC Berkeley in accordance with the Declaration of Helsinki.

2.2 Visual Stimuli and Presentation

Visual stimuli were generated using Matlab Software and presented on a gamma-corrected 21" CRT monitor with a refresh rate of 100 Hz at a viewing distance of 57 cm. The display resolution was set to 1,024 x 768. Experimental trials and communication with the eye tracker were controlled using Psychtoolbox in Matlab.

The visual saccade targets were black circles, with a diameter of 1° and a luminance of 7.4 cd/m², presented on a uniform gray background (72.2 cd/m²). There were either two stimulus locations, for return saccades, or four stimulus locations arranged in a rectangle,

for the hourglass condition. The fixation target, a black cross, was presented at the center of the screen.

2.3 Task Design and Procedure

In each trial, the task was to make 10 primary saccades as quickly as possible, either back and forth between two targets (5 cycles) or in an hourglass pattern (2.5 cycles) between four stimulus locations arranged in a rectangle (**Figure 1**). Each trial terminated once 10 primary saccades were detected by the online software algorithm.

Participants were instructed to complete the sequence as quickly as possible. Each trial started with the participant fixating a black cross presented on a gray background in the center of the screen. After a randomly determined interval (0.5-1.5s) the fixation target disappeared and the saccade targets were presented. If a blink was detected during the saccade sequence, the trials was immediately repeated. Participants received auditory feedback (a short beep) at the end of a successful trial.

In Experiment 1 the visual saccade targets were either 5° or 15° apart, arranged along the vertical or horizontal axis. In the hourglass condition, the two adjacent targets were separated by 4°. The factorial combination of distance (5,15), direction (H,V), and shape (return, hourglass) yielded eight conditions. A block consisted of 40 trials with the condition for each trial selected at random, subject to the constraint that there were 5 trials of each of the 8 conditions within a block. Participants completed 4 blocks of the experiment, yielding, in total, roughly 200 eye movements per condition.

In Experiment 2, we increased the number of distances and hourglass target separations to better specify constraints on ISR. Fourteen conditions were created by using selected combinations of three horizontal distances (5°, 10°, or 20°) and five hourglass heights (0.5°, 1°, 2°, 4°, or 8°). The pseudo-factorial design was structured to manipulate the area and angular difference between target locations for hourglass saccades, asking how these influenced the strength of ISR (**Figure 4**). Participants completed four blocks of 70 trials

each, with a short break after 35 trials. The condition was randomly determined for each trial subject to the constraint that each condition was tested 5 times in each block. As in Experiment 1, the total set included roughly 200 eye movements per condition.

Figure 1. Experimental methodology and conditions in Experiment 1. Participants made rapid alternating saccades (RAS) with an amplitude of 5° or 15° of visual angle in the horizontal or vertical direction (not shown), either alternating between two points or moving in an hour glass pattern. The separation of the sides of the hour glass was held constant at 4°, resulting in an angular change, relative to return saccades, of 39° for 5° saccades and 15° for 15° saccades.

2.4 Eye Movement Recording and Analyses

Participants viewed the stimuli binocularly and head position was stabilized with a combined head and chin rest. Eye movements were recorded from the right eye using a desktop mounted SR Research Ltd. EyeLink 1000 eyetracker with a sampling rate of 1000 Hz.

We recorded with the "pupil-CR" (Corneal Reflection) mode to compensate for small head movements. The centroid mode was used to track the center of the thresholded pupil. Although changes in pupil size can lead to systematic deviations in the reported

gaze position (Ivanov & Blanche, 2011; Hooge, Holmqvist, & Nyström, 2016; Nyström, Hooge, & Andersson, 2016), we did not correct for pupil-size related artifacts, since dynamics should be similar across the different conditions. The average accuracy of the Eyelink 1000 system is 0.25-0.50° of visual angle. To calibrate and validate gaze position tracking, two nine-point grids were presented at the beginning of the experiment. During calibration, we used the Eyelink interface to verify that the average tracking error was < 0.5° for each participant.

Velocity was computed using a 9-sample moving filter. Saccade onset was detected as the first time point at which both velocity exceeded 22 °/s and acceleration exceeded 4000 °/s. When velocity and acceleration fell below these thresholds, the end of the saccade was registered. These criteria were used to identify primary and secondary saccades. Saccade dwell time was calculated by subtracting the onset of a primary saccade from the offset of the immediately preceding primary saccade. As such, this measure included the duration of any accompanying secondary saccades. To calculate saccade gain, we divided saccade amplitude by the target amplitude for each location. Endpoint scatter, or precision, was determined by calculating the covariance matrix for each location. We used the sum of the variance in the two orthogonal directions, the mean squared distance from the mean (van Beers, Haggard, & Wolpert, 2004), as our measure of precision.

Saccade parameters were compared statistically between conditions using a repeated measures ANOVA in SPSS. When the assumption of sphericity was violated, appropriate corrections were used. Post-hoc comparisons were made with Bonferroni corrected p-values.

Figure 2. Dependent variables for the RAS task. Each trial consisted of 10 successive saccades. From the time series, measures were derived for dwell duration, saccade gain, endpoint precision, and secondary saccade frequency, amplitude, and latency.

2.5 Exclusion Criteria

Analysis of the eye movement data was performed with customized scripts written in Matlab. To guarantee the accuracy of our recordings, we visually inspected the saccade traces to ensure the robustness of our coded exclusion criteria. The first saccade in each trial was excluded from the analysis. Outliers within each trial were removed from the data set. These included primary saccades with amplitudes $< 3^\circ$, saccade durations > 130 ms, dwell times < 50 ms or > 800 ms, and saccades whose landing or starting position was greater than 3° from the target, or were outside of the screen coordinates. Only the first secondary saccade within a single fixation was included for further analysis given that additional “secondary” saccades were rare. Secondary saccades were defined as eye movements occurring > 20 ms after the primary saccade ended, with an amplitude $< 20\%$ of the target amplitude, and a duration between 8 and 50 ms. On an individual basis, we also rejected saccades in which the values on any measure were outside of 3 SDs for that participant. These exclusion criteria resulted in $\sim 9\%$ of all registered saccades being excluded in Exp. 1 and $\sim 8\%$ of registered saccades being excluded in Exp. 2.

3. RESULTS

Our core measure of inhibition of saccadic return (ISR) was dwell time. This measure, as well as those related to secondary saccades, varied with the movement context. In the report of the results from Experiment 1, we focus on how ISR varied with the direction and amplitude of the saccades. In Experiment 2, we consider whether ISR was dependent on the zone around the target, the angular difference between subsequent saccades, or a combination of these factors.

3.1 Experiment 1: Amplitude and Direction

Participants performed the RAS task, moving their eyes as quickly as possible between targets separated by 5° or 15°, either along the horizontal or vertical axis. The targets were arranged to either require return movements between two targets, or movements in an hourglass pattern between four targets (**Figure 3**). For the latter, the separation between adjacent hourglass targets was 4°, based on previous research indicating that this separation was sufficient to abolish ISR (Hooge & Frens, 2000).

A repeated measures factorial ANOVA was used to test for effects of amplitude (5,15), direction (horizontal, vertical), and condition (return, hourglass). In terms of dwell time, there was a main effect of condition, ($F(1,13) = 128.80, p < .001$). Dwell times were shorter in the hourglass condition compared to the return condition, verifying that the latter produces robust ISR. There was also a main effect of amplitude, with participants taking longer to complete sequential saccades at 5° than at 15° ($F(1,13) = 69.07, p < .001$), but no effect of direction ($F(1,13) = 2.43, p = .143$). Two 2-way interactions were significant: The release from inhibition was larger for horizontal movements compared to vertical movements, ($F(1,13) = 7.66, p = .016$), and was greater for the 5° saccades than for 15° saccades, ($F(1,13) = 10.56, p = .006$). The 3-way interaction was not significant, ($F(1,13) = 0.02, p = .899$).

Figure 3. Mean dwell duration (left) and magnitude of inhibition of saccadic return, ISR (right), in the horizontal (A) and vertical (B) directions for saccades of different amplitudes in Experiment 1. Colored points represent individual participants. Error bars represent within-participant 95% confidence interval.

We next examined the characteristics of secondary saccades (**Table 2**). Our measure of dwell time included the duration of any accompanying secondary saccadic eye movements. As a result, an increase in the frequency of secondary saccades might directly prolong dwell times. Secondary saccades may also prolong dwell times by resetting oculomotor processes or because of the additional time needed for their planning and programming.

The characteristics of secondary saccades are thought to depend of the target error of the primary saccade. Primary saccade precision was worse for larger amplitude saccades, ($F(1,13) = 70.56$, $p < 0.001$), but similar for the two primary axis, ($F(1,13) = 2.97$, $p = 0.108$), and conditions, ($F(1,13) = 3.46$, $p = 0.086$). Hourglass saccades did, however, gain ($F(1,13) = 36.04$, $p < 0.001$), larger undershoot. These results would suggest that the frequency of secondary saccades should be greater for larger amplitude movements and in the hourglass conditions.

Consistent with this prediction, secondary saccades were more common when the eye movements spanned 15°, ($F(1,13) = 6.96$, $p = 0.020$). However, despite the greater

undershoot for primary hourglass saccades, secondary saccades were more frequent in the return conditions ($F(1,13) = 23.64, p < 0.001$). The effect of saccade direction on saccade frequency was not significant, ($F(1,13) = 1.31, P = 0.273$). The only significant interaction was between condition and amplitude, ($F(1,13) = 6.36, p = 0.026$), with the reduction in secondary saccade frequency most pronounced in the hourglass condition for the large amplitude movements.

Secondary saccade latency was shorter for vertical saccades ($F(1,13) = 10.70, p = 0.006$) and for 15° saccades ($F(1,13) = 6.57, p = 0.024$), but did not differ between return and hourglass conditions ($F(1,13) = 0.24, p = 0.632$). The amplitude of the secondary saccade was larger in the hourglass condition compared to the return condition, ($F(1,13) = 18.88, p < 0.001$), likely in response to the larger saccade undershoot for hourglass saccades. Secondary saccade amplitude did not differ between direction, ($F(1,13) = 0.49, p = 0.494$), or amplitude ($F(1,13) = 1.51, p = 0.241$).

Amplitude (Condition)	Mean (SD) of Parameters					
	Dwell (ms)	Gain (%)	Precision (°)	Secondary Frequency (%)	Secondary Latency (ms)	Secondary Amplitude (°)
Horizontal						
5° (Repeat)	404 (83)	94 (6)	0.58 (0.24)	16 (7)	219 (46)	0.95 (0.32)
5° (Hourglass)	325 (91)	87 (7)	0.68 (0.31)	12 (9)	194 (39)	1.55 (0.69)
15° (Repeat)	365 (98)	93 (3)	0.89 (0.26)	25 (13)	191 (35)	1.20 (0.30)
15° (Hourglass)	304 (93)	89 (5)	1.17 (0.36)	15 (15)	202 (67)	1.35 (0.56)
Vertical						
5° (Repeat)	385 (97)	97 (13)	0.80 (0.43)	21 (11)	180 (46)	0.91 (0.20)
5° (Hourglass)	322 (86)	91 (9)	0.87 (0.65)	12 (9)	182 (32)	1.32 (0.55)
15° (Repeat)	340 (102)	94 (7)	1.17 (0.32)	28 (16)	162 (30)	1.21 (0.28)
15° (Hourglass)	296 (96)	92 (7)	1.19 (0.50)	16 (12)	172 (38)	1.32 (0.41)

Table 1. Average dwell times, primary saccade gain and precision, and secondary saccade frequency, latency, and amplitude in Experiment 1.

To directly assess the effect of secondary saccades on dwell times, we extracted and compared dwell durations before and after primary saccades that were accompanied by a secondary saccade (**Table 2**). Previous studies have suggested that secondary saccade occurrence can lead to significant prolongation of saccade dwell times (Wu, Kwon, & Kowler, 2010). We replicated this result, observing that dwell times were longer both before and after the primary saccade (before: $M = +18\text{ms}$, $SD = 17$), ($t(13) = 3.93$, $P = 0.002$; (after: $M = +104\text{ms}$, $SD = 34\text{ms}$), ($t(13) = 11.46$, $p < 0.001$).

Because secondary saccades were more frequent in the return than hourglass conditions, the prolongation of saccade dwell times associated with secondary saccades may have contributed to the longer dwell times (i.e., greater ISR) in the return conditions. To test this hypothesis, we examined the extent to which secondary saccades prolonged our measure of dwell time. This was calculated as the difference in duration between dwells that did or did not contain secondary saccades, multiplied by the frequency of secondary saccade occurrence. Interestingly, secondary saccades in the hourglass condition, which had a lower frequency of occurrence, prolonged dwell times by a greater duration than in the return condition ($F(1,13) = 18.32$, $p = 0.001$). As a result, despite the greater frequency of secondary saccades in the return condition, the contribution that secondary saccades made to overall dwell times in the two conditions were equivalent (**Table 2**).

Amplitude (Condition)	Mean (SD) of Parameters			
	Dwell Before (ms)	Dwell After (ms)	Dwell Before Contribution (ms)	Dwell After Contribution (ms)
<hr/> Horizontal <hr/>				
5° (Return)	+ 5 (37)	+ 89 (83)	+ 1 (6)	+ 15 (9)
5° (Hourglass)	+ 26 (69)	+ 157 (91)	+ 4 (8)	+ 18 (13)
15° (Return)	+ 21 (38)	+ 97 (98)	+ 4 (9)	+ 22 (10)
15° (Hourglass)	+ 60 (76)	+ 124 (93)	+ 7 (8)	+ 18 (15)
<hr/> Vertical <hr/>				
5° (Return)	+ 4 (27)	+ 62 (97)	+ 2 (7)	+ 14 (13)
5° (Hourglass)	- 8 (39)	+ 127 (86)	- 1 (4)	+ 15 (10)
15° (Return)	+ 21 (18)	+ 75 (102)	+ 6 (6)	+ 22 (19)
15° (Hourglass)	+ 16 (45)	+ 98 (96)	+ 2 (7)	+ 14 (10)

Table 2. Change in dwell duration for fixations either preceding or during the occurrence of secondary saccades in Experiment 1. Contribution represents change in overall dwell duration as a result of fixations that were associated with secondary saccades.

3.2 Experiment 2: Zone vs. Angle

One of the key findings in Experiment 1 was that the release from inhibition was greater for hourglass movements that required 5° saccades compared to those that required 15° saccades. Superficially, this observation accords with what has been observed in cue-target studies of IOR, with multiple studies showing that IOR increases with target eccentricity (Bao & Pöppel, 2007; Bao et al., 2013). However, by using a constant distance of 4° between the two targets forming the base of the hourglass, we introduced a confound in that the small amplitude condition also produced a greater angular separation between successive movements to a given side (**Figure 1**). Hooze & Frens (2000) characterized the spatial properties of ISR in terms of an inhibited zone surrounding the target. Although the zone was a constant 4° for both the 5° and 15° saccades in Experiment 1, the angular difference between subsequent movements, relative to a return movement was larger for 5° saccades, 39°, compared to the 15° saccades, 15°.

To examine this issue, we focused on horizontal eye movements in Experiment 2, manipulating the width and height of the hourglass. We selected conditions that allowed us to examine the effects of zone and angle, without the two variables being confounded (**Figure 4**). For one analysis, we focused on conditions in which the horizontal distance was varied and the vertical distance was constant. Here the zone is held constant and the angle of the hourglass changes. For the other analysis, the width and height were varied to create a constant hourglass angle, while the size of the zone varied. ISR strength was calculated by taking the difference between return and hourglass conditions for each amplitude. This allowed us to control for the independent influence of saccade amplitude on dwell times. Taken together, these two analyses provide two assessments of the impact of zone and angle on ISR (see predictions in **Figure 4a,b**).

For each analysis, we performed a two-way repeated measures ANOVA on the dwell time data. When a constant zone was considered (**Figure 4a**), the factors were zone (1°, 2°) and amplitude (5°, 10°, 20°), where changes in amplitude necessarily correspond to changes in angle. Although the results (**Figure 4c**) appear to show that dwell time varied when the amplitude/angle changed, neither the effects of amplitude ($F(2,18) = 2.26, p = 0.133$), nor zone ($F(1,9) = 3.47, p = 0.096$) were significant. The interaction term was not significant, ($F(4,18) = 2.01, p = 0.164$).

For the second analysis, we held the angle constant (**Figure 4b**) and considered main effects of changes in angle (6°, 11°, 22°) and changes in amplitude (5°, 10°, 20°). Here, changes in amplitude correspond to changes in zone. A significant effect (**Figure 4d**) occurred for changes in angle ($F(2,18) = 26.50, p < 0.001$), but not for changes in amplitude/zone ($F(2,18) = 0.75, p = 0.488$). The interaction term was not significant, ($F(4,18) = 0.67, p = 0.618$). Taken together, the two analyses clearly show that ISR strength depended on the subsequent angle between saccades and not on the zone around the targets.

Figure 4. Conditions, predictions, and results for Experiment 2. Participants made horizontal RAS of 5°, 10°, or 20°. The vertical separation of the hour glass varied between 0.5° and 8°. This allowed us to independently isolate the influence of zone and angular difference between subsequent saccades across different amplitudes. (A) Variation in amplitude while holding the vertical distance (zone) constant between the sides of the hour glass. A constant zone of 2° is shown for illustrative purposes. Predictions for ISR for the amplitude and zone hypotheses. (B) Variation in distance between sides of the hourglass while holding amplitude constant (11° shown), with predictions for the amplitude and zone hypotheses. (C) Experimental results when zone was constant either at 0.5°, 1°, 2°, or 4°. (D) Results when the angle was held constant either at 6°, 11°, or 22°. All tested combinations and results are listed in Table 3.

Figure 4. Conditions, predictions, and results for Experiment 2. Participants made horizontal RAS of 5°, 10°, or 20°. The vertical separation of the hourglass varied between 0.5° and 8°. This allowed us to independently isolate the influence of zone and angular difference between subsequent saccades across different amplitudes. (A) Variation in amplitude while holding the vertical distance (zone) constant between the sides of the hourglass. A constant zone of 2° is shown for illustrative purposes. Predictions for ISR for the amplitude and zone hypotheses. (B) Variation in distance between sides of the hourglass while holding amplitude constant (11° shown), with predictions for the amplitude and zone hypotheses. (C) Experimental results when zone was constant either at 0.5°, 1°, 2°, or 4°. (D) Results when the angle was held constant either at 6°, 11°, or 22°. All tested combinations and results are listed in Table 3.

The features of secondary saccades on the other hand, depended primarily on saccade amplitude and condition (return vs. hourglass), and did not show differences depending on equivalent zones or angles (**Table 3**). Because of this, we averaged the secondary saccade characteristics for hourglass saccades at each amplitude and conducted a two-

way repeated measures ANOVA (amplitude, condition) (**Figure 5**). Replicating Experiment 1, there was a main effect on secondary saccade frequency for amplitude ($F(2,18) = 41.19, p < 0.001$) and condition ($F(2,18) = 11.71, p = 0.008$), with no significant interaction ($F(2,18) = 1.18, p = 0.328$). Secondary saccade latency was reduced for larger amplitude saccades ($F(2,18) = 20.26, p < 0.001$) but showed no differences between the return and hourglass conditions ($F(2,18) = 0.56, p = 0.457$). Secondary saccade amplitude was greater for larger amplitude saccades ($F(2,18) = 30.55, p < 0.001$) and in the hourglass condition ($F(2,18) = 5.38, p = 0.046$).

Figure 5. Secondary saccade frequency, latency, and amplitude in Experiment 2. Hour glass values reflect the average of the different conditions for the respective amplitudes detailed in Table 3.

Amplitude/ Zone/ Angle	Mean (SD) of Parameters			
	Dwell (ms)	Secondary Frequency (%)	Secondary Latency (ms)	Secondary Amplitude (°)
5° / 0° / 0°	420 (76)	25 (15)	201 (22)	0.78 (0.20)
5° / 0.5° / 6°	375 (91)	23 (16)	205 (21)	0.91 (0.34)
5° / 1° / 11°	369 (87)	18 (13)	208 (25)	0.98 (0.40)
5° / 2° / 22°	356 (91)	18 (14)	203 (28)	1.09 (0.46)
10° / 0° / 0°	395 (69)	33 (13)	199 (25)	0.84 (0.18)
10° / 0.5° / 3°	356 (90)	26 (20)	193 (17)	0.83 (0.21)
10° / 1° / 6°	353 (93)	25 (17)	197 (24)	0.86 (0.21)
10° / 2° / 11°	343 (98)	25 (21)	199 (32)	0.94 (0.26)
10° / 4° / 22°	342 (99)	25 (20)	190 (29)	0.94 (0.28)
20° / 0° / 0°	381 (65)	47 (16)	181 (27)	1.11 (0.17)
20° / 1° / 3°	338 (87)	37 (24)	177 (29)	1.13 (0.21)
20° / 2° / 6°	338 (88)	38 (24)	174 (28)	1.14 (0.19)
20° / 4° / 11°	330 (88)	36 (26)	171 (30)	1.21 (0.24)
20° / 8° / 22°	319 (92)	37 (25)	164 (28)	1.29 (0.25)

Table 3. Average dwell times and secondary saccade frequency, latency, and amplitude in Experiment 2.

4. DISCUSSION

The two experiments revealed that the magnitude of inhibition of saccadic return, ISR, is dependent on three factors: 1) Whether or not the saccade returns exactly to the previously viewed location; 2) The size of the angular change between subsequent eye movements, and 3) Whether the eye movements are made primarily along the horizontal or vertical axis.

In Experiment 1, we compared eye movements that went back and forth between two targets and eye movements that followed an hourglass pattern, varying the length of the hourglass while holding the width constant. Robust ISR was observed in all conditions,

with longer dwell times for the return configurations compared to the hourglass configurations. Moreover, the release from inhibition was larger for horizontal saccades compared to vertical saccades ($\sim 22\%$ vs $\sim 17\%$) and decreased with saccade amplitude (5° : 18% , 15° : 15%).

Experiment 2 allowed us to ask if the effect of amplitude depended on the angular difference between subsequent saccades to a given side, or varied as a function of an inhibitory zone around the targets. The results showed that changes in dwell time were equivalent across different saccade amplitudes when the angles were equated. This dependence on angle held despite the fact that the dwell times themselves were inversely correlated with saccade amplitude. Moreover, the difference in dwell times between return and hourglass saccades was much larger than the differences between saccades of varying angular difference. The specificity for exact return locations provides evidence for an ISR mechanism distinct from that associated with saccadic momentum, where there is a roughly linear increase in fixation duration as the saccade angle changes.

The experiments also highlight important constraints on secondary saccades. The frequency of secondary saccades not only increased with saccade amplitude, but were also greater in the return condition compared to the hourglass condition. Nonetheless, several lines of evidence suggest that secondary saccade occurrence, while perhaps related to ISR, was not a principle driver of the observed effects on dwell times in the return condition. Although greater in frequency, secondary saccades in the return condition prolonged dwell times by a smaller duration than secondary saccades in the hourglass conditions. Multiplying secondary saccade frequency by the amount of prolongation revealed that the contribution of secondary saccades to dwell times was roughly equal between the return and hourglass saccades (**Table 2**). Moreover, despite a greater frequency of secondary saccades at larger amplitudes, dwell times became shorter as amplitude increased (**Table 3**). These findings suggest that independent mechanisms may underlie the duration of dwell times and secondary saccade occurrence.

4.1 Specificity for Return Saccades

The most striking aspect of our results was the substantial increase in dwell time when saccades were made directly to a previously viewed target location, the return condition. Saccades to the same side (or lower/upper region), directed to target locations separated by as small as 0.5° or a change in return angle of 3° (**Table 3**), resulted in significant reductions in saccade dwell times (~ 40 ms) compared to when the saccade returned to the same target. The increase in dwell time for return saccades is in accord with the original study of Hooge & Frens, (2000; see also, Luke et al., 2014).

In studies of visual scanning (Tatler & Vincent, 2008; Smith & Henderson, 2009; Bays & Husain, 2012; Wilming et al., 2013), the magnitude of inhibition has been described as roughly linear with angle (Smith & Henderson, 2009; Bays & Husain, 2012) or absent entirely when the subsequent saccades have angular differences greater than 50° (Tatler & Vincent, 2008; Wilming et al., 2013). These results have led to the hypothesis that ISR can be best understood in terms of saccadic momentum, a bias for eye movements to continue in the same direction, and an amplitude effect in which subsequent saccades of the same amplitude are delayed (Smith & Henderson, 2009; Wilming et al., 2013). Our results are at odds with these hypotheses given that angular changes of 3° and amplitude changes of less than 1% still resulted in dramatic reductions in dwell time.

Several factors may account for the difference observed in the results from the present studies and past experiments on visual scanning. Because of the free-viewing nature in scanning studies, the data are typically binned by saccade angles, typically with a bin size of 30° or more. As such, they lack the spatial specificity employed here. The occurrence of saccades precisely matched in amplitude and angle are relatively rare events in free viewing studies. In addition, the presence and interaction between other bottom-up (e.g. luminance, contrast, complexity) and top-down factors (e.g. center-bias, task demands, search strategy, attention) known to influence dwell durations in visual scanning tasks may present additional confounds. The RAS task allows us to ensure that incoming and outgoing saccades are matched in both amplitude and angle, providing a more controlled context for assessing ISR.

4.2 Zone vs. Angle

Hooge & Frens (2000) proposed that, after each saccade, an inhibitory region of approximately 4° is generated around the target (see also, Luke et al., 2014). An alternative hypothesis is that the magnitude of ISR is inversely related to the angular change between successive eye movements (Tatler & Vincent, 2008; Smith & Henderson, 2009; Bays & Husain, 2012; Wilming et al., 2013). To adjudicate between these two hypotheses, Experiment 2 included conditions in which the angle or zone were held constant across different amplitudes. The results provided clear evidence that, for horizontal saccades, ISR is dependent on the angle and not the zone. Moreover, the fact that the magnitude of ISR did not vary with amplitude when the angle change was constant, distinguishes IOR (Bao & Pöppel, 2007) from ISR.

We did not test zones larger than 8° or angular differences greater than 22° . As such, we cannot address whether a sharp change in the strength of inhibition occurs when the angular difference surpasses 62° as suggested by Wilming et al. (2013). Furthermore, our task does not allow us to isolate the influence of saccadic momentum independent from ISR (Smith & Henderson, 2009), given that all saccades within a condition were of roughly the same amplitude. Future studies should investigate the effect of saccadic momentum for saccades of varying amplitudes to further disentangle the two phenomena.

4.3 Horizontal Vertical Differences

In a previous study with the RAS task, Hooge and Frens (2000) had observed shorter dwell durations for vertical saccades compared to horizontal saccades. We observed a similar asymmetry in Experiment 1. Going beyond their work, we also found that the release from inhibition is reduced for vertical saccades: the difference between the return and hourglass conditions was smaller in the vertical conditions compared to the horizontal conditions. This finding suggests that the magnitude of ISR is not solely governed by the angle between subsequent eye movements.

Directional effects on ISR may arise from neurophysiological differences between horizontal and vertical eye movements. Vertical and horizontal saccades involve distinct pulse generators, premotor neurons, and oculomotor muscles (Sparks, 2002). For example, vertical eye movements activate lateralized visuomotor structures bilaterally, whereas horizontal eye movements primarily generate activity in the hemisphere contralateral to the direction of the saccade. These differences have been used to explain why vertical saccades made in the presence of distracting objects display larger trajectory deviations than horizontal saccades (Van der Stigchel & Theeuwes, 2008).

Alternatively, the inhibition along the vertical axis may relate to the statistical distribution of saccades across the visual field. Across a variety of tasks, human observers make more horizontal than vertical eye movements (Tatler & Vincent, 2009; Bays & Husain, 2012). Decreased behavioral relevance for saccades along the vertical axis may limit the strength and importance of inhibiting return saccades.

4.4 Changes in Secondary Saccades

Our primary dependent variable, dwell time, includes the time required for secondary saccade planning and execution. The occurrence of a secondary saccade is known to prolong dwell times (Wu, Kwon, & Kowler, 2010) and, by one hypothesis, IOR in cue-target paradigms may be due to the occurrence of micro-saccades (Tian, Yoshida, & Hafed, 2016). As such, it was important to carefully evaluate the frequency and characteristics of secondary saccades in the RAS task.

The analyses revealed a clear increase in secondary saccade occurrence, as well as a decrease in secondary saccade amplitude when the eye returned to a previously viewed location. The fact that there were more secondary saccades in the return condition relative to the hourglass conditions is surprising given the potential distracting effect of nearby targets in the latter. The increase in frequency for return conditions also occurred despite the fact that the gain was lower for hourglass saccades and endpoint precision was similar

for return and hourglass saccades. Secondary saccades are generally assumed to function as an error correcting mechanism (Becker & Fuchs, 1969; Tian, Ying, & Zee, 2013), hence their traditional label as corrective saccades. However, recent work has shown that multiple factors, independent of the distance between saccade endpoint and the target, can influence secondary saccade occurrence (Lemij & Collewyn, 1989; Ohl, Brandt, & Kliegl, 2011; 2013; Schut et al., 2017). Our study adds to this body of evidence, illustrating the unique role that return saccades have on secondary saccade programming and execution.

The present study replicates previous work showing that the occurrence of secondary saccades prolongs dwell times (Wu, Kwon, & Kowler, 2010). Importantly, dwell times that encompassed secondary saccades were longer both for return and hourglass contexts. Because secondary saccade latency was similar between conditions, the greater frequency of secondary saccades in the return condition would imply comparatively longer dwell times compared to hourglass saccades. While this was the case, the longer dwell duration of return saccades was not a direct result of the higher secondary saccade frequency. Instead, because dwell durations for return saccades containing a secondary saccade were approximately 40 ms shorter than corresponding hourglass saccades, the contribution between the two conditions ended up being roughly equivalent.

Taken together, the current results suggest that the occurrence of a secondary saccade in the return condition led to a release of inhibition and allowed the eye to rapidly shift to the subsequent target location. The result has parallels with the literature on micro-saccades (Rolf, Laubrock, & Kliegl, 2006; Tian, Yoshida, & Hafed, 2016) and may provide a basis for linking the literature between the two fields.

5. CONCLUSION

We investigated how inhibition of saccadic return (ISR) is influenced by saccade amplitude and direction, as well as by the spatial arrangement of target locations. Our results provide clear evidence that return saccades prolong saccade dwell times beyond

what can be attributed to other oculomotor biases such as saccadic momentum. The magnitude of ISR was found to be primarily constrained by the angular differences between subsequent saccades and not a constant zone around the target. The independence of ISR from eccentricity, as well as the asymmetry between horizontal and vertical saccades further distinguishes ISR from traditional measures of IOR. We also uncovered a novel role for return saccades in the programming of secondary saccades that appears to operate independently from any error correcting mechanism. The RAS task provides a relatively bias-free way to measure ISR with considerable potential to inform computational accounts of how eye movements allow us to continuously sample information in the environment.

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