

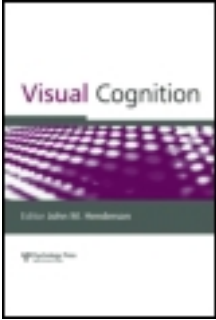
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Facilitation of return during scene viewing

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Inhibition of Return (IOR) is a delay in initiating attentional shifts to previously attended locations. It is believed to facilitate attentional exploration of a scene. Computational models of attention have implemented IOR as a simple mechanism for driving attention through a scene. However, evidence for IOR during scene viewing is inconclusive. In this study IOR during scene memorization and in response to sudden onsets at the last (1-back) and penultimate (2-back) fixation location was measured. The results indicate that there is a tendency for saccades to continue the trajectory of the last saccade (Saccadic Momentum), but contrary to the “foraging facilitator” hypothesis of IOR, there is also a distinct population of saccades directed back to the last fixation location, especially in response to onsets. Voluntary return saccades to the 1-back location experience temporal delay but this does not affect their likelihood of occurrence. No localized temporal delay is exhibited at 2-back. These results suggest that IOR exists at the last fixation location during scene memorization but that this temporal delay is overridden by Facilitation of Return. Computational models of attention will fail to capture the pattern of saccadic eye movements during scene viewing unless they model the dynamics of visual encoding and can account for the interaction between Facilitation of Return, Saccadic Momentum, and Inhibition of Return.

Keywords: Eye movement; Facilitation; Fixation duration; Gaze control; Inhibition of return; Naturalistic scene; Oculomotor capture; Real-world scene.

In order to accurately process a visual scene we must serially shift our attention. These overt attentional shifts create a sequence of fixations during which the eyes are relatively still and visual information is processed, interspersed with rapid eye movements (saccades) during which visual encoding is suppressed. Various models have been proposed that attempt to

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reproduce the processes influencing fixation location. These models differ according to whether they prioritize bottom-up stimulus-based factors such as luminance contrast (Itti & Koch, 2001; Parkhurst, Law, & Niebur, 2002; Rosenholtz, 1999) or supplement bottom-up information with top-down memory-based factors such as scene semantics or viewing task (Navalpakkam & Itti, 2005; Rao, Zelinsky, Hayhoe, & Ballard, 2002; Sun, Fisher, Wang, & Gomes, 2008; Torralba, 2003; Torralba, Oliva, Castelhana, & Henderson, 2006; Vincent, Troscianko, & Gilchrist, 2007). However, all computational models operate in a similar fashion: Regions of a visual scene are ranked in terms of their conspicuity, i.e., their salience or task relevance, and attention shifts between these regions in decreasing rank order. In order to ensure that attention does not oscillate between the two regions of highest conspicuity an extra mechanism is required that decreases the likelihood of returning to a previously fixated region. The mechanism chosen for this purpose in all models that produce scan paths is Inhibition of Return (Itti & Koch, 2001; Navalpakkam & Itti, 2005; Parkhurst et al., 2002; Sun et al., 2008).

Inhibition of Return (IOR) is a behaviourally observed difficulty in orienting to a previously attended location. IOR results in longer manual and saccadic reaction times to targets presented at the last fixation location. The phenomenon was first reported by Posner and Cohen (1984) in the context of cueing paradigms but has subsequently been observed in visual search (Klein, 1988; Klein & MacInnes, 1999), reading (Rayner, Juhasz, Ashby, & Clifton, 2003; Weger & Inhoff, 2006), auditory and manual reaction tasks (Spence & Driver, 1998; Tassinari & Berlucchi, 1995) and search in three-dimensional environments (Thomas et al., 2006). It has been proposed that this *temporal* inhibition may have a *spatial* consequence: By inhibiting previously examined locations the probability of orienting to new locations will increase (Klein, 1988; Klein & MacInnes, 1999; Posner & Cohen, 1984). This “foraging facilitator” hypothesis is supported by evidence that during visual search, saccadic eye movements tend to be directed away from the last fixation location (Gilchrist & Harvey, 2000; Klein & MacInnes, 1999; Peterson, Kramer, Wang, Irwin, & McCarley, 2001), and saccades back to the last fixation location are preceded by longer fixations than saccades away from the last fixation location (Boot, McCarley, Kramer, & Peterson, 2004; Hoge, Over, van Wezel, & Frens, 2005; Klein & MacInnes, 1999; Snyder & Kingstone, 2000).

The prevalence of empirical support for IOR would appear to promote it as a suitable mechanism for inclusion in a model of natural attentional behaviour (e.g., Itti & Koch, 2001). However, although IOR is well established during the search of abstract object arrays, it is currently unclear whether IOR exists when viewing naturalistic visual scenes. During physical search of real-world scenes, participants rarely revisit searched locations (Gilchrist, North, & Hood, 2001; Thomas et al., 2006), but this may be the result of participants remembering

where they have previously searched rather than a *spatial* consequence of IOR. When viewing natural visual scenes, viewer's fixations cluster around a small number of regions that are deemed significant by the viewer (Buswell, 1935; Yarbus, 1967). Viewers may revisit regions several times in order to encode information necessary for their viewing task (Yarbus, 1967), to detect changes (Henderson & Hollingworth, 1999), or to prepare for future actions (Mennie, Hayhoe, & Sullivan, 2006). Inhibition of these return fixations may be detrimental to the successful processing of the visual scene.

Hooge et al. (2005) examined eye movement behaviour during scene viewing and found that saccades landing precisely on the last fixation location (return saccades) occurred significantly more often than would be predicted by chance. Similar evidence of frequent and highly accurate return saccades has been demonstrated in monkeys during classic conjunction and feature search tasks (Motter & Belky, 1998). The accuracy of these saccades suggests that a mechanism may exist that facilitates, rather than inhibits immediate return when processing of the last fixation location is inadequate. We refer to this alternative mechanism as Facilitation of Return (FOR). Such a mechanism would be analogous to the regressive return saccades observed when reading difficult or ambiguous text (Rayner et al., 2003; Rayner & Pollatsek, 1989; Vitu, 2005). FOR may be needed for viewing realistic visual scenes because the complexity of the scene, number of objects, and difficulty in discriminating individual details may mean that a single fixation on an object is insufficient to extract all necessary information (Henderson & Pierce, 2008; Rayner, Smith, Malcolm, & Henderson, 2009). Further evidence for the relationship between processing during fixations and saccade programming can be found in Henderson and Smith (this issue 2009).

In order for IOR to provide a suitable mechanism for driving attention through a scene, fixations at previously viewed locations would have to occur significantly less often than fixations at novel locations. If, as suggested by Hooge et al. (2005), IOR does not function as a foraging facilitator, then it could not provide the mechanism required by current saliency-based computational models to keep the eyes moving through a scene.

Importantly, evidence against the *spatial* impact of IOR on the distribution of attention across a scene does not rule out the possibility that IOR has a *temporal* impact on attentional shifts during scene viewing. The classic measure of IOR is the time taken to initiate an attentional shift to the last location of attention (e.g., Posner & Cohen, 1984). Return saccades during scene viewing take longer to initiate than saccades elsewhere, confirming the *temporal* impact of IOR even in the absence of the *spatial* impact, i.e., decreased probability of return saccades (Hooge et al., 2005; Klein & MacInnes, 1999). However, the temporal effect usually associated with IOR also requires further subdivision to identify its true origin. Recent

psychophysical evidence indicates that two saccades in the same direction (forward saccades) will be separated by a shorter fixation than two saccades in opposite directions (regressive saccades), even if the saccades do not land on a previous fixation location, i.e., are not regressive *return* saccades (Anderson, Yadav, & Carpenter, 2008). We refer to this phenomenon as Saccadic Momentum. This simple increase in fixation duration caused by reversing the direction of the eyes could account for the temporal effects previously attributed to IOR (Hooge et al., 2005; Klein & MacInnes, 1999). However, evidence from psychophysical studies has indicated that IOR only acts upon a small region (radius $\sim 4^\circ$ of visual angle) around the last fixation location (Hooge & Frens, 2000) with inhibition decreasing with eccentricity (Dorris, Taylor, Klein, & Munoz, 1999). If saccades directed back to the last fixation during scene viewing are affected by this highly localized temporal IOR, they should exhibit latency greater than that caused by the simple reversal of the direction of the eyes (i.e., Saccadic Momentum).

The main goal of this study was to clear up the conflicting evidence for IOR and FOR during scene viewing. A thorough analysis of fixation location and fixation duration during scene memorization allowed the *spatial* (frequency of return saccades) and *temporal* (fixation duration) predictions of IOR and FOR to be tested. If IOR has a spatial impact on eye movement behaviour, return saccades will occur significantly less often than saccades to novel locations. By comparison, FOR would predict that return saccades are significantly more likely than saccades to randomly chosen novel locations. If IOR has a temporal impact on eye movement behaviour, saccades landing within a small region around previous fixation locations (regressive *return* saccades) will be preceded by significantly longer fixations than saccades in the opposite direction (forward saccades) or in the same direction but landing outside of this region (regressive *nonreturn* saccades), dissociating IOR from Saccadic Momentum. If return saccades are facilitated they may be quicker to initiate than fixations to novel locations. To test these hypotheses, the probability that a saccade is a return saccade and fixation durations preceding return saccades were analysed both during normal viewing and in response to peripheral onsets at the last (Experiment 1) and penultimate (Experiment 2) fixation locations.

EXPERIMENT 1

Method

Participants. Sixteen members of the Edinburgh University community participated for payment (four male; mean age = 21 years, range 18–29). All

participants had normal or corrected to normal vision and were naïve with respect to the purposes of the study.

Apparatus. Eye movements were monitored by an SR Research Eyelink 1000 eyetracker. Fixation position was sampled at 1000 Hz and saccades prior to critical fixations were detected using a 17-sample saccade detection model with a velocity threshold of $30^\circ/\text{sec}$, an acceleration threshold of $8000^\circ/\text{s}^2$, and a minimum amplitude of 0.5° . Viewing was binocular, but only the right eye was tracked. The images were presented on a 21-inch CRT monitor at a viewing distance of 90 cm with a refresh rate of 140 Hz. The experiment was controlled with SR Research Experiment Builder software.

Stimuli. Participants were presented 100 unique full-colour 800×600 pixel \times 24 bit photographs of real-world scenes from a variety of scene categories (subtending a visual angle of $25.7^\circ \times 19.4^\circ$).

Procedure. Participants were told to view the scenes in preparation for a memory test that would be administered after all trials. They were told that they may experience a brief flash while viewing the scenes. This was irrelevant to their task and they were told to ignore it. After the experiment, participants were informed that there would be no memory test and were told the true intention of the study.

An experimental trial took place as follows. First, calibration was checked using a central fixation point presented on the CRT. If gaze position was more than 0.5 degrees away from the fixation point a nine-point recalibration was performed. The scene was presented for an initial 1000 ms during which time the participant was free to explore. After 1000 ms, a critical fixation was identified and a pink square, 1° of visual angle in width, was presented for 250 ms in one of four positions on the circumference of a circle with the centre at the current fixation location and a radius equivalent to the amplitude of the last saccade. The angular deviation of the onsets from the last fixation was 0° (onset at the last fixation), 90° , 180° (onset in the same direction as the last saccade), or 270° (see Figure 1). If any of these points lay off the screen or the last saccade had an amplitude less than 1° (to exclude correction saccades), the program waited until the next suitable fixation to show the onset. Each participant was presented an equal number of onsets at each of the four locations randomly ordered and the location of onset within each scene was counterbalanced across participants.

After the onset had been presented for 250 ms, it was removed from the display and the participant was given a further 5000 ms to view the scene before the next trial began.

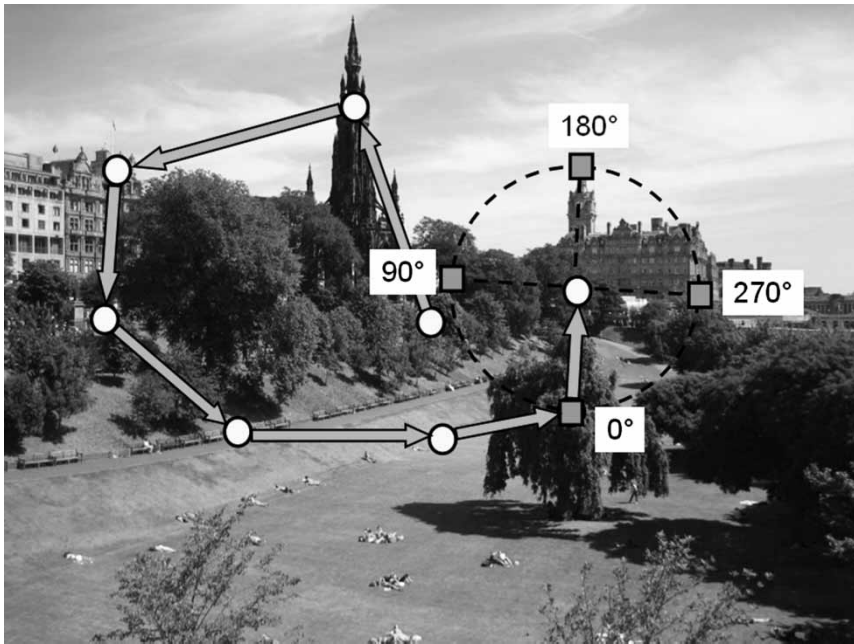


Figure 1. Sequence of events in each trial. Participants initially viewed a scene for 1000 ms (circles indicate fixations). An onset (grey square; bright pink in the actual experiment) was then presented at one of four locations around the current fixation at relative angular deviation from the last fixation location: 0° (last fixation), 90°, 180°, 270°. Onset was presented for 250 ms during a fixation then removed. Participants were given a further 5000 ms to view each scene.

Results

To aid evaluation of the predictions of IOR and FOR, the results were analysed according to *spatial* (fixation probabilities) and *temporal* (preceding fixation duration) predictions.

Spatial: Fixation probability during normal viewing and following an onset

If IOR functions as a foraging facilitator during scene viewing we should observe a general tendency for saccades to be directed away from the last fixation location. This tendency can be examined by calculating the angular deviation of every saccade relative to the last fixation location. The angular deviation was calculated for all saccades except saccades following an onset and saccades in which the onset could not have been presented, i.e., the last saccade amplitude was less than 1° or any of the potential onset locations, 0°, 90°, 180°, and 270° fell off the display edge. After these exclusions 19,541

regular fixations remained. In our coding scheme, a regressive saccade has an angular deviation of 0° or 360° , whereas a forward saccade (continuing the vector of the last saccade) has an angular deviation of 180° (see Figure 1 for a map of angular deviation values).

Figure 2A illustrates the distribution of angular deviations relative to the last fixation. There is a very clear tendency to saccade away from the last fixation location (the peak of fixations with angular deviation $130\text{--}230^\circ$). We refer to this tendency as Saccadic Momentum. Previously this tendency has been interpreted as evidence for the foraging facilitator function of IOR (Klein & MacInnes, 1999). However, there is also a narrower but pronounced tendency to saccade back in the direction of the last fixation (angular deviations $> 330^\circ$ and $< 30^\circ$). The prevalence of regressive saccades during normal viewing is not consistent with the interpretation of IOR as a foraging facilitator.

Inhibition is believed to be at the maximum for saccades that land at the last fixation location and decrease as the distance between the landing position and the last fixation location increases (Bennett & Pratt, 2001; Dorris et al., 1999; Hooge & Frens, 2000). The angular deviations in Figure 2A do not allow the dissociation of regressive saccades landing at the last fixation location from saccades that over- or undershoot. To test whether there was a specific bias against saccading to the last fixation location, the probability that the next fixation landed within 1 degree of visual angle of the last fixation location (0°) and three distance matched locations (90° ,

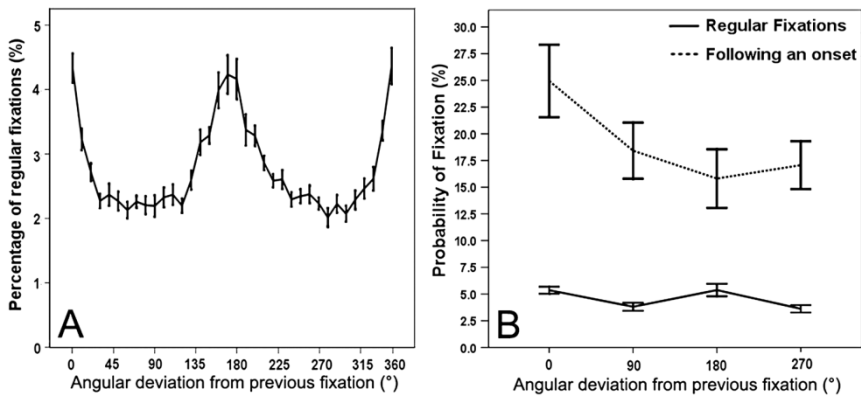


Figure 2. (A) Angular deviation of all saccades during normal viewing relative to the last fixation (10° bins). See Figure 1 for map of angular deviations. (B) Mean probability (percentage of all fixations) of fixating four peripheral locations (0° , 90° , 180° , or 270° relative to the last fixation) during normal viewing (solid line) and in the fixation following an onset at the peripheral location (dotted line). Error bars represent ± 1 standard error.

180°, and 270°; see Figure 1) was calculated for all regular fixations in which the onset could have been presented and following an onset at the four locations. After all exclusions 19,541 regular fixations and 1220 fixations following onsets remained. A repeated-measures ANOVA of fixation probability (Figure 2B), with factors onset (free view vs. following an onset) and location (0°, 90°, 180°, and 270°), showed significant main effects of onset, $F(1, 15) = 48.372$, $MSE = 0.675$, $p < .001$, and location, $F(3, 45) = 4.478$, $MSE = 0.016$, $p < .01$, and a significant interaction, $F(3, 45) = 3.446$, $MSE = 0.012$, $p < .05$. This result indicates a clear increase in fixation probability in response to an onset across all four onset locations (the difference between the solid and dashed lines in Figure 2B). The interaction can be attributed to the difference in the effect of location between the onset conditions. A simple repeated-measures ANOVA (Greenhouse Geisser corrected due to violation of sphericity) within the normal viewing condition reveals a main effect of location, $F(1.67, 25.10) = 19.379$, $MSE = 0.003$, $p < .001$. As can be seen from Figure 2B (solid lines), this effect can be attributed to the probability of fixating the last fixation location (0°, $M = 5.4\%$, $SD = 1.3$) being higher than the probability at 90° ($M = 3.8\%$, $SD = 1.5$) or 270° ($M = 3.6\%$, $SD = 1.4$). There is no difference between the probability of fixating the last fixation location and the distance-matched location 180° away ($M = 5.4\%$, $SD = 1.4$). Planned post hoc comparisons reveal that the difference between the fixation probabilities at 0° and 180° are significantly different to those at 90° and 270° (all $ps < .001$).

A simple repeated-measures ANOVA of fixation probabilities following onsets (dashed lines in Figure 2B) reveals a main effect of location, $F(3, 45) = 3.815$, $MSE = 0.026$, $p < .05$. The expected low probability of fixation for onsets at the last fixation location was not observed. In fact, onsets at the last fixation location were fixated significantly more often (0°, $M = 25.0\%$, $SD = 13.6$) than onsets at 90° ($M = 18.4\%$, $SD = 10.5$; $p < .05$), 180° ($M = 15.8\%$, $SD = 11.0$; $p < .05$), and 270° ($M = 17.1\%$, $SD = 9.0$; $p < .05$). There were no other significant differences. This absence of inhibition for involuntary saccades back to the last fixation location further indicates an absence of any spatial impact of IOR during scene viewing, and instead suggests that viewers are more susceptible to oculomotor capture at the last attended location, consistent with Facilitation of Return.

Temporal: Fixation durations preceding normal saccades and following onsets

The classic measure of IOR used in attentional cueing paradigms is response time to a peripheral target (e.g., Posner & Cohen, 1984). In IOR studies investigating overt attentional shifts, this measure has been reinterpreted as the duration of a fixation preceding a critical saccade (Hooge et al.,

2005). Mean fixation durations preceding saccades landing within 1° of the last fixation location (0° angular deviation) and the three distance matched locations (90° , 180° , and 270° ; see Figure 1) were calculated for all regular fixations in which the onset could have been presented and following an onset at the four locations. A repeated-measures ANOVA of preceding fixation duration (Figure 3), with factors onset (free view vs. following an onset) and location (0° , 90° , 180° , and 270°), showed significant main effects of onset, $F(1, 13) = 5.052$, $MSE = 3234$, $p < .05$, and location, $F(3, 39) = 10.028$, $MSE = 1520$, $p < .001$, but no interaction.¹ Planned post hoc comparisons revealed that the effect of onset is due to overall mean fixation durations being significantly longer during normal viewing ($M = 286.6$ ms, $SD = 10.34$) compared to following an onset ($M = 262.4$ ms, $SD = 7.23$; $p < .05$).

A simple repeated-measures ANOVA within the normal viewing condition (Figure 3, solid line) revealed a main effect of location, $F(3, 45) = 14.638$, $MSE = 1125$, $p < .001$. Planned post hoc comparisons revealed that return saccades were preceded by significantly longer fixations (0° , $M = 328.8$ ms, $SD = 67.01$) than saccades 90° ($M = 282.2$ ms, $SD = 42.5$; $p < .01$), 180° ($M = 250.9$ ms, $SD = 23.54$; $p < .001$), and 270° ($M = 284.1$ ms, $SD = 52.8$; $p < .01$) away from the last location. Saccades perpendicular to the current fixation (90° and 270°) were also preceded by significantly longer fixations than those directed straight ahead, 180° ($p < .01$). These results support previous evidence of a temporal delay when initiating voluntary saccades back towards the last fixation location (Hooge et al., 2005; Klein & MacInnes, 1999). However, the effect of location disappears when saccades

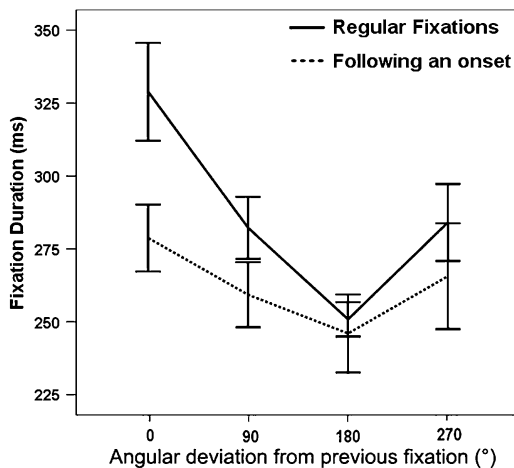


Figure 3. Mean duration (ms) of the fixation preceding a fixation at the four locations (0° , 90° , 180° , or 270° relative to the last fixation) during normal viewing (solid line) and in the fixation following an onset at the peripheral location (dotted line).

are initiated in response to onsets (Figure 3, dashed line). A simple repeated-measures ANOVA of preceding fixation duration within the onset condition shows no main effect of location, $F(3, 39) = 1.001$, $MSE = 2590$, $p = .403$, *ns* (see Footnote 1). There is a trend for return saccades to be preceded by longer fixations (0° : $M = 278.7$ ms, $SD = 43$) than saccades directly away (180° : $M = 246$ ms, $SD = 50$), but this difference does not reach significance ($p = .116$, *ns*). These results indicate that there is no temporal evidence of IOR when return saccades are initiated in response to onsets at the last fixation location.

Temporal: Localized temporal effects on normal saccades relative to last fixation location

So far the results indicate that during normal scene viewing, return saccades are as common, if not more common, than saccades directed to any other location. Also, oculomotor capture by an onset at the last fixation location is more likely than by an onset elsewhere, and this capture shortens saccade initiation time. These results support the view that return to the last fixation location is spatially facilitated not inhibited. However, the finding that such return saccades are preceded by significantly longer fixation durations during normal viewing supports the idea of temporal IOR. Another interpretation of this temporal effect is that it is caused by Saccadic Momentum: The oculomotor bias to continue moving the eyes in the same direction. Our spatial data support the existence of such a bias (Figure 2A). If the longer preceding fixation duration is simply a function of the oculomotor cost introduced when the saccade trajectory is reversed, then the effect should increase linearly as the angular deviation from the last fixation location decreases. If, on the other hand, this difficulty with programming a voluntary refixation is due to localized inhibition of the last fixation location, then the difficulty should be a function of both the angular deviation and the spatial distance from the last fixation location.

To test the predictions of the Saccadic Momentum hypothesis versus localized temporal IOR, the location of all saccade targets were identified relative to the last fixation for the entire viewing period except for the fixations following an onset (Figure 4A). First, the angular deviation of all saccades from the last fixation was calculated and grouped into 45° bins (collapsed across bins with the same angular deviation clockwise and counterclockwise). Second, the difference between the amplitude of the next saccade and the last saccade was calculated. All saccades with

¹ Two participants had to be omitted from this analysis due to missing data in some conditions.

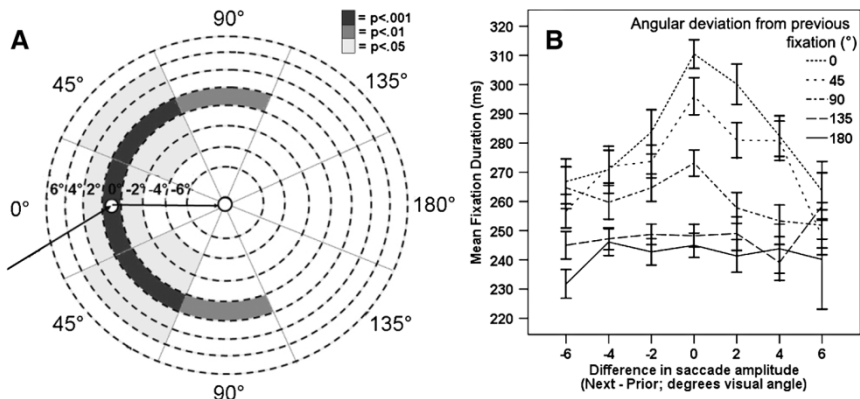


Figure 4. (A) Next saccade target location relative to current (centre spot) and last (left spot) fixations. Locations are binned in 45° regions beginning at the last fixation and encircling the current fixation. These regions are further divided according to the difference in amplitude between the next and last saccade (concentric rings; degrees of visual angle). Zone of IOR according to the significant peaks in preceding fixation durations is superimposed onto this chart: Black = $p < .001$, dark grey = $p < .01$, light grey = $p < .05$. (B) Mean fixation durations (ms) preceding fixations at the locations illustrated in A.

amplitudes less than 1° were removed to exclude corrective and microsaccades and only saccades with differences in saccade amplitudes greater than -8° and less than 8° were included to exclude outliers. After exclusions, 22,024 fixations remained in the analysis. By combining these two measures the location of each saccade target relative to the last fixation could be identified. The mean duration of fixations preceding saccades to each region of this saccade target map were then calculated (Figure 4B).

A repeated-measures ANOVA with the factors angular deviation (0° , 45° , 90° , 135° , and 180°) and difference in saccade amplitude (-6° , -4° , -2° , 0° , 2° , 4° , and 6°) revealed a main effect of angular deviation, $F(4, 60) = 21.660$, $MSE = 1761$, $p < .001$, difference in saccade amplitude, $F(6, 90) = 4.460$, $MSE = 1116$, $p < .01$, and a significant interaction, $F(24, 360) = 1.852$, $MSE = 1768$, $p < .01$. The main effect of angular deviation is due to a linear increase in mean preceding fixation duration as angular deviation decreases. This cost associated with reversing saccade direction, i.e., Saccadic Momentum, could completely account for the longer fixations preceding return saccades demonstrated in Figure 4B and previously attributed to IOR (Hooge et al., 2005; Klein & MacInnes, 1999). However, there is also evidence of localized temporal IOR. When saccades are directed back towards the last fixation location (0° angular deviation) there is a main effect of difference in saccade amplitude (repeated-measures ANOVA within the 0° angular deviation condition),

$F(6, 90) = 4.091$, $MSE = 1392$, $p < .001$, due to saccades landing within $+/- 2^\circ$ of the last fixation location being preceded by significantly longer fixations (0° : $M = 316.8$ ms, $SD = 53.43$) than saccades that over- (-6° : $M = 264.9$ ms, $SD = 37.95$, $p < .001$) or undershoot the last fixation (6° : $M = 266.8$ ms, $SD = 12.5$, $p < .05$). The effect of difference in saccade amplitude is also observed for saccades directed 45° away from the last fixation, $F(6, 90) = 5.837$, $MSE = 786$, $p < .001$. Angular deviations of 90° show a peak in fixation durations preceding saccades of the same amplitude as the last saccade but this does not result in a main effect of difference in saccade amplitude. Angular deviations of 180° and 135° showed no effect of difference in saccade amplitude on preceding fixation duration.

The peak in preceding fixations visible in Figure 4B can be extracted by performing pairwise t -tests within each angular deviation condition and projecting the significant differences relative to a baseline ($+/- 6^\circ$ difference in saccade amplitude) on to the saccade target map (Figure 4A). The resulting region represents the saccades affected by localized temporal IOR independent of the latency attributed to Saccadic Momentum.

In combination, the results of Experiment 1 confirm the existence of temporal IOR during scene viewing but not its spatial function as a foraging facilitator. The majority of saccades are directed away from the last fixation but there is also a distinct population returning to the last fixation location. These voluntary return saccades will take longer to initiate due to the lag associated with reversing the direction of the saccade (Saccadic Momentum) and localized temporal IOR acting on saccades with the same amplitude as the last saccade. However, if refixation of the last location is required this temporal IOR does not appear to stop it from happening.

EXPERIMENT 2

The temporal IOR affecting return saccades during normal viewing in experiment 1 disappeared when the return saccade was triggered by an onset. Similar weak inhibition of return saccades has been observed during search of complex scenes (Klein & MacInnes, 1999) and coloured object arrays (Paul & Tipper, 2003). Facilitation of Return to the last fixation location has been attributed to either greater conspicuity of the 1-back location due to the recency of its processing and representation in memory, or to delayed shifting of covert attention to the current fixation location (Klein, 2000; Klein & MacInnes, 1999; Lupianez, Milliken, Solano, Weaver, & Tipper, 2001; Paul & Tipper, 2003). Up to 300 ms following the appearance of an attentional cue, attentional shifts to the cue are facilitated (Posner & Cohen, 1984). After 300 ms such shifts

are inhibited (Posner & Cohen, 1984). This crossover time is roughly equivalent to the average duration of fixations during scene viewing (Henderson, 2003), suggesting that attentional shifts back to the last fixation location may be facilitated early on in a fixation. In previous studies (Klein & MacInnes, 1999; Paul & Tipper, 2003), IOR reappeared when saccades were directed to the penultimate fixation location (2-back). By the time the fixation is 2-back, facilitation for this location is believed to have ended and inhibition taken its place. Whether saccades to the 2-back location are inhibited or facilitated during scene viewing was investigated in Experiment 2.

Method

The stimuli, apparatus and procedure for Experiment 2 were identical to Experiment 1. The only difference between Experiments 1 and 2 was the location of the onset (see Figure 5). After 1000 ms of scene exploration, a

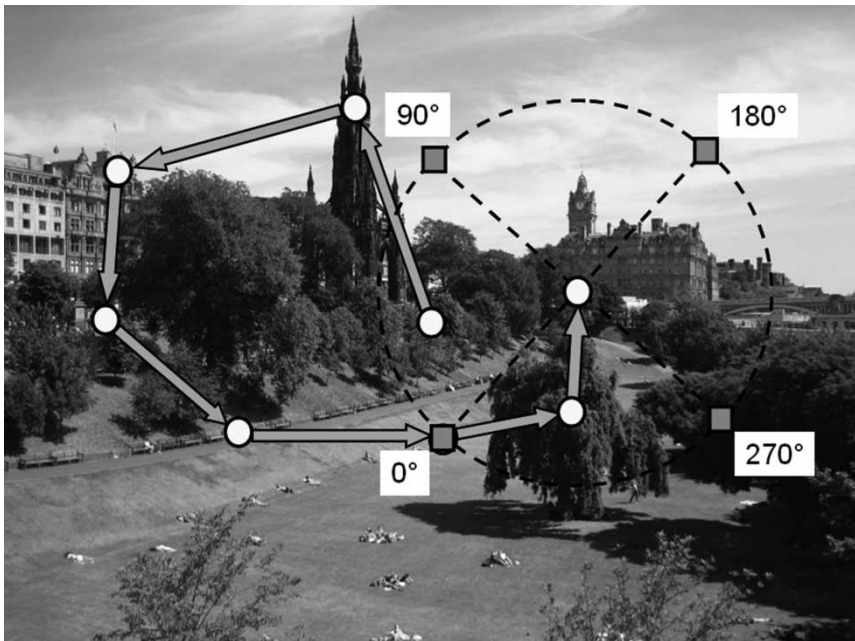


Figure 5. Sequence of events in each trial. Participants initially viewed a scene for 1000 ms (circles indicate fixations). An onset (grey square; bright pink in the actual experiment) was then presented at one of four locations around the current fixation at relative angular deviation from the penultimate fixation location: 0° (penultimate fixation), 90°, 180°, 270°. Onset was presented for 250 ms during a fixation then removed. Participants were given a further 5000 ms to view each scene.

critical fixation was identified and a bright pink square (1° of visual angle) was abruptly presented for 250 ms in one of four locations on the circumference of a circle with its origin at the current fixation point and radius equal to the distance between the current fixation and the penultimate fixation (2-back). The angular deviation of the abrupt onset from the penultimate fixation location was 0° (back in the direction of the penultimate fixation), 90° , 180° (away from the penultimate fixation), or 270° . If any of these points lay off the screen or the distance to the penultimate fixation location was less than 1° (to exclude correction saccades) the computer waited until the next suitable fixation. Each participant saw an equal number of onset cues at each of the four locations randomly ordered, with onset location within each scene counterbalanced across participants. After the onset was removed the scene remained in view for 5000 ms.

Participants. Sixteen Edinburgh University first year Psychology students took part for course credit (seven male; mean age = 19.75 years, range 18–27).

Results

Spatial: Fixation probability during normal viewing and following an onset

To first check whether saccades were biased away from the penultimate fixation location, we calculated the angular deviation of every saccade (except those from fixations immediately following the onset) relative to the penultimate fixation location. Only saccades in which the onset could have been presented were used: The distance to the penultimate fixation location had to be greater than 1° and all potential onset locations (0° , 90° , 180° , and 270°) had to lie on the screen (see Figure 5 for map of angular deviations relative to 2-back). After all exclusions, 16,881 fixations remained. Figure 6A illustrates the distribution of angular deviations relative to the last fixation. The tendency for saccades to be directed away from the 2-back location was less pronounced than observed in Experiment 1 relative to the 1-back location, but it was still present. The intervening saccade could have been in any direction relative to the 2-back location, but given that the majority probably continued the vector of the last saccade (as shown in Figure 2A), when the next saccade was directed away from the 1-back location it was also away from the 2-back. Similarly, the cumulative pattern of angular deviations may also account for the distinct population of saccades directed back towards the 2-back location (Figure 6A, angular deviations $> 330^\circ$ and $< 30^\circ$): A saccade in the direction of the 2-back fixation may also be in the same direction as

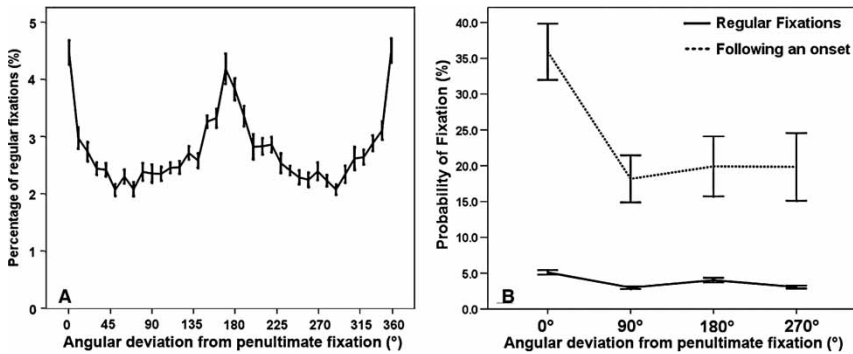


Figure 6. (A) Angular deviation of all saccades during normal viewing relative to penultimate fixation (10° bins). See Figure 5 for map of angular deviations. (B) Mean probability (percentage of all fixations) of fixating four peripheral locations (0° , 90° , 180° , or 270° relative to the penultimate fixation) during normal viewing (solid line) and in the fixation following an onset at the peripheral location (dotted line). Error bars represent ± 1 standard error.

1-back. However, irrespective of where the intervening fixation was located, if the 2-back location had been spatially inhibited there would be no peak in the frequency of angular deviations around 0° .

To examine whether these return saccades hit the penultimate fixation location, the probability that the next fixation landed within 1 degree of visual angle of the penultimate fixation location and three distance matched locations (see Figure 5) was calculated for all regular fixations in which the onset could have been presented (16,881 fixations) and following an onset at the four locations (1302 fixations). A repeated-measures ANOVA of fixation probability (Figure 6B), with factors onset (free view vs. following an onset) and location (0° , 90° , 180° , and 270°), showed significant main effects of onset, $F(1, 15) = 29.427$, $MSE = 0.042$, $p < .001$, and location, $F(3, 45) = 17.382$, $MSE = 0.004$, $p < .001$, and a significant interaction, $F(3, 45) = 11.353$, $MSE = 0.004$, $p < .001$. The interaction can be attributed to the 0° location having significantly greater fixation probability following an onset than any other location ($ps < .001$, planned post hoc comparison). A simple repeated-measures ANOVA within the normal viewing condition (Figure 6B, solid line) revealed a significant main effect of location, $F(3, 45) = 44.338$, $MSE = 0.00004$, $p < .001$, with saccades directed back to the 2-back location (0° , $M = 5.10\%$, $SD = 1.23$) significantly more likely than saccades directed 90° ($M = 2.99\%$, $SD = 0.83$; $p < .001$), 180° ($M = 4.03\%$, $SD = 1.30$; $p < .05$) and 270° ($M = 3.06\%$, $SD = 0.84$; $p < .001$) away. Also, saccades directed away from the 2-back location (180°) were significantly more likely than perpendicular saccades (90° and 270° , $ps < .001$). A similar repeated-measures ANOVA within the onset condition also revealed a main effect of location, $F(3, 45) = 14.236$, $MSE = 0.008$, $p < .001$, but this effect was

only due to return saccades (0° , $M = 35.9\%$, $SD = 15.7$) being significantly more likely than saccades directed 90° ($M = 19.2\%$, $SD = 13.2$; $p < .001$), 180° ($M = 19.9\%$, $SD = 16.7$; $p < .001$), and 270° ($M = 19.8\%$, $SD = 18.9$; $p < .001$) away. There were no other significant differences.

The fixation probability results indicate that there was no evidence of more pronounced IOR for the 2-back fixation location. In fact, the return probability was greater than the probability of a fixation at the other three distance-matched locations both during normal viewing and following an onset, consistent with FOR at the penultimate fixated location.

Temporal: Fixation durations preceding normal saccades and following onsets

Are the saccades back to the penultimate fixation location delayed due to IOR? A repeated-measures ANOVA of preceding fixation duration for 2-back (Figure 7A) with factors onset (free view vs. following an onset) and location (0° , 90° , 180° , and 270°) showed a significant main effect of onset, $F(1, 11^2) = 6.497$, $MSE = 5435.647$, $p < .05$, no significant main effect of location, $F(3, 33) = 0.281$, $MSE = 1728.551$, $p = .782$, *ns*, and a significant interaction of the two factors, $F(3, 33) = 3.236$, $MSE = 2346.535$, $p < .05$. The absence of a main effect of location can be attributed to the interaction with onset. A simple

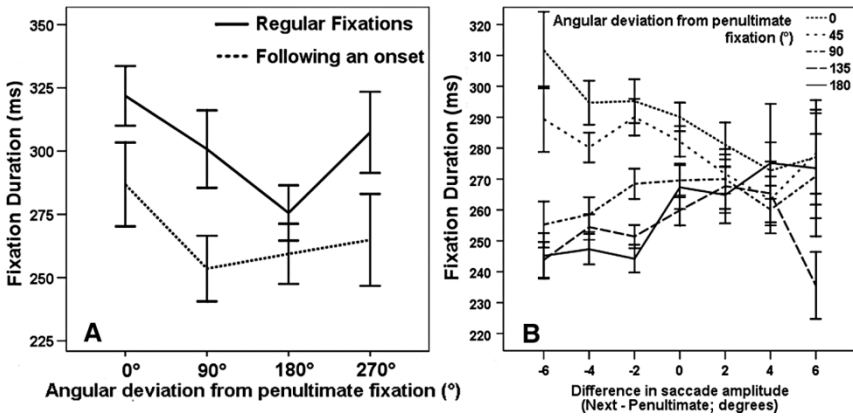


Figure 7. (A) Mean duration (ms) of the fixation preceding a fixation at the four locations (0° , 90° , 180° , or 270° relative to the penultimate fixation) during normal viewing (solid line) and in the fixation following an onset at the peripheral location (dotted line). Error bars represent ± 1 standard error. (B) Mean fixation durations (ms) preceding all saccades during normal viewing classified according to angular deviation from the penultimate fixation (lines) and difference in saccade amplitude (next—distance to penultimate location; x-axis).

² Four subjects had to be omitted from this analysis due to missing data in some conditions.

repeated-measures ANOVA within the free-view condition (Figure 7A, solid line), showed a main effect of location, $F(3, 45) = 5.789$, $MSE = 1033.8$, $p < .01$, with saccades directed to the 2-back location (0° , $M = 321.8$ ms, $SD = 47.11$) preceded by significantly longer fixations than saccades directed to the 180° location ($M = 275.6$ ms, $SD = 43.68$; $p < .001$). No other differences were significant. The main effect of location disappeared following onsets (Figure 7A, dotted line), $F(3, 33) = 1.478$, $MSE = 2814.758$, $p < .239$, *ns*, as did the pairwise differences between onset locations, although there is a nonsignificant trend for saccades directed to the 2-back location (0° , $M = 289.0$ ms, $SD = 67.97$) to be preceded by longer fixations than saccades to the 180° location ($M = 259.36$ ms, $SD = 46.05$), $t(14) = 1.916$, $p = .076$, *ns*.

Temporal: Localized temporal effects on normal saccades relative to penultimate fixation location

As in Experiment 1, the results for Experiment 2 indicate that during normal viewing, saccades back to a previously fixated location take significantly longer to initiate than saccades directed away from the previously visited location and that this delay is overridden by facilitation following an onset. This delay may be due to the oculomotor lag associated with reversing the eyes, i.e., Saccadic Momentum, or localized temporal IOR. To look for any evidence of localized temporal IOR all saccades during normal viewing were categorized according to their angle relative to the 2-back location (angular deviation) and the difference between the distance covered by the saccade and the distance between the current fixation and the 2-back location (difference in saccade amplitude). All saccades with amplitudes less than 1° were removed to exclude corrective and micro-saccades and only saccades with differences in saccade amplitudes between -8° and $+8^\circ$ were included to exclude outliers. After exclusions, 25,406 fixations remained in the analysis. A repeated-measures ANOVA of preceding fixation durations with the factors angular deviation (0° , 45° , 90° , 135° , and 180°) and difference in saccade amplitude (-6° , -4° , -2° , 0° , 2° , 4° , 6°) revealed a main effect of angular deviation, $F(4, 60) = 8.687$, $MSE = 2098.8$, $p < .001$, but no main effect of difference in saccade amplitude, $F(6, 90) = 1.138$, $MSE = 1445.9$, $p = .35$, *ns*, and a trend towards an interaction, $F(24, 360) = 1.458$, $MSE = 1204.6$, $p = .078$, *ns*. The results are shown in Figure 7B. Mean preceding fixation duration generally increased linearly as angular deviation decreased, although the effect was not as clear as in Experiment 1 due to an interaction with difference in saccade amplitude, i.e., change in gradient. This interaction is probably due to the indeterminate nature of the intervening saccade. Unlike in Experiment 1, the angular deviation relative to the penultimate fixation location does not

accurately express the change in saccade vector as the last saccade may have already reversed direction relative to 2-back saccade.

Even given the variable impact of angular deviation on preceding fixation duration, localized temporal IOR should still be visible as a selective peak in preceding fixation durations when saccades are directed back to the 2-back location, i.e., 0° angular deviation and 0° difference in saccade amplitude. A repeated-measures ANOVA within the 0° angular deviation condition revealed no effect of difference in saccade amplitude, $F(6, 90) = 1.324$, $MSE = 1324.8$, $p = .255$, *ns*. There was also no effect of difference in saccade amplitude within any of the other angular deviation conditions except 135° , $F(6, 90) = 3.204$, $MSE = 713.6$, $p < .01$. Therefore, there was no evidence that saccades directed back to the 2-back fixation location were preceded by significantly longer fixations than those in the same direction but with shorter or longer amplitudes. These results are consistent with Saccadic Momentum but not with localized temporal IOR.

GENERAL DISCUSSION

The experiments presented here investigated whether IOR influences eye movements during naturalistic scene viewing. There were three main findings. First and foremost, the probability of returning the eyes to previous fixation locations is higher than predicted if IOR were functioning as a “foraging facilitator” (Klein, 1988; Klein & MacInnes, 1999; Posner & Cohen, 1984). The probability that a saccade returns to the last (1-back) and penultimate (2-back) fixation locations was greater than or equal to other distance-matched locations with and without an onset at those locations. This finding provides evidence against the view that IOR drives attention through a scene by decreasing the probability of return (Klein, 1988; Klein & MacInnes, 1999; Posner & Cohen, 1984) but complements evidence of above-chance levels of return saccades reported during psychophysical studies (Motter & Belky, 1998), array search (Peterson et al., 2001), and scene viewing (Hooge et al., 2005).

Second, evidence of IOR was found in the time taken to initiate a saccade to the last (1-back) fixation location during normal viewing. Saccades directed within $+/-2^\circ$ of the last fixation location or with similar amplitudes but an angular deviation from the last fixation of up to 90° were preceded by significantly longer fixations than saccades in the same direction but with longer or shorter amplitudes. This zone of IOR is not observed for involuntary saccades (i.e., those initiated in response to onsets) or relative to the penultimate (2-back) fixation location. Although our analysis does not allow us to investigate the precise spatial extent of the zone of IOR, the $+/-2^\circ$ is similar to the region previously reported in

psychophysical studies (Bennett & Pratt, 2001; Berlucchi, Tassinari, Marzi, & Di Stefano, 1989; Dorris et al., 1999; Hooge & Frens, 2000; Maylor & Hockey, 1985; Tassinari, Aglioti, Chelazzi, Marzi, & Berlucchi, 1987).

Third, we found that the saccadic latency effects for return saccades previously attributed to IOR (Horton, 2005; Klein & MacInnes, 1999) can be accounted for by Saccadic Momentum, i.e., the tendency for saccades to continue the trajectory of the last saccade, and the oculomotor lag associated with reversing direction. We found that the time taken to initiate a saccade was inversely proportional to the angular deviation from the last fixation. For saccades in the direction of the last fixation, this delay was supplemented by localized inhibition for saccades with the same amplitude as the last saccade. However, for saccades relative to the penultimate saccade, no such localized inhibition was present and the delay in initiating these saccades can be entirely attributed to Saccadic Momentum. Similar evidence that attention is biased towards continuing in the same direction as the last attentional shift can be found in reaction times during covert attentional shifts (Bennett & Pratt, 2001; Pratt, Adam, & McAuliffe, 1998; Pratt, Spalek, & Bradshaw, 1999), and saccade initiation times in cueing tasks (Anderson et al., 2008; Ro, Pratt, & Rafal, 2000), double-step tasks (Hou & Fender, 1979; Komoda, Festinger, Phillips, Duckman, & Young, 1973) and during free-viewing of scenes (Tatler & Vincent, this issue 2009). Other systematic tendencies in eye movement behaviour during scene viewing such as a bias of fixations towards the screen centre and a prevalence of horizontal and vertical saccades have recently been reported by Tatler and colleagues (Tatler, 2007; Tatler & Vincent, 2008). It is an open question how saccadic momentum interacts with these screen biases. An examination of the distribution of critical fixation locations in the present study revealed no obvious bias towards the centre for any of the potential onset locations. We are confident that facilitation of return and saccadic momentum cannot be attributed to screen biases in the present study although more intelligent baselines such as cumulative fixation locations across all participants and the distribution of visual features may be used in the future to control for such biases.

Our study is the first to dissociate the impact of Saccadic Momentum from IOR during scene viewing. Future investigations of IOR must perform a similar dissociation if they are to ensure differences in saccade initiation time can be attributed to IOR and not Saccadic Momentum.

Can the complex pattern of localized temporal IOR, spatial FOR, and Saccadic Momentum be accommodated by current theories of IOR and attentional control? The zone of IOR observed relative to the last fixation location in Experiment 1 (Figure 4A) is compatible with the view that the neural structure subserving IOR is the superior colliculus (SC; Danziger, Fendrich, & Rafal, 1997; Dorris et al., 1999; Posner, Rafal, Choate, & Vaughn, 1985; Rafal, Calabresi, Brennan, & Sciolto, 1989; Sapir, Soroker,

Berger, & Henik, 1999; Taylor & Klein, 1998). The neurons of the intermediate layer of the superior colliculus are organized into an oculocentric map (Robinson, 1972) with each neuron discharging action potentials for saccades of particular amplitudes and directions (Wurtz & Goldberg, 1972). Activation of saccade neurons in one region of the saccade target map creates complementary inhibition of saccade neurons on the opposite side of the map (Munoz & Istvan, 1998). The spatial extent of inhibition observed in our study is similar to the region of reduced activation observed in the monkey superior colliculus when preparing a saccadic eye movement to a previously attended location (Dorris, Everling, Klein, & Munoz, 2002; Dorris et al., 1999). This inhibition is believed to spread to adjacent regions (Munoz & Istvan, 1998) affecting neurons coding saccades in the same direction and saccades in a different direction but with the same amplitude. This separation between direction and distance may explain why the region of IOR observed in our study also affected saccades with the same amplitude as the last saccade but with angular deviations up to 90°.

However, patterns of activation and inhibition in the superior colliculus cannot account for the Facilitation of Return observed in Experiments 1 and 2. It has been proposed that the superior colliculus is not alone in creating IOR but that it is acted upon by other cortical regions (Dorris et al., 2002; Klein, 2000; Mayer, Seidenberg, Dorflinger, & Rao, 2004). One candidate region is the frontal eye fields (Dorris et al., 2002; Lepsien & Pollmann, 2002; Ro, Farnè, & Chang, 2003), which is involved in the programming of voluntary saccades (Henik, Rafal, & Rhodes, 1994; Ro, Henik, Machado, & Rafal, 1997; Ro et al., 2000) and the inhibition of reflexive saccades (Rafal, Machado, Ro, & Ingle, 2000). During normal viewing, the command to initiate a voluntary saccade back to the last fixation comes through the FEF but is delayed due to the neural inhibition in the superior colliculus. When an onset occurs at the last fixation location, it is believed to be the FEF that implements the voluntary command to suppress the reflexive saccade generated by the superior colliculus (Ro et al., 2003). Such a pattern of increased saccadic latency to sudden onsets is typically observed using sparse cueing displays (e.g., Posner & Cohen, 1984). However, in our experiments the complexity of the stimuli seems to necessitate a higher frequency of voluntary return fixations. These voluntary return commands could be mediated by the FEF but experience temporal delay due to the neural inhibition present in the target region of the superior colliculus.

This division between cortical commands and neural inhibition of the oculocentric map in the superior colliculus may also explain why we find no localized temporal IOR for the 2-back location. When a return saccade is programmed back to the 2-back fixation location, the saccade amplitude and direction required to reach the 2-back location no longer matches the saccade originally used to leave that location because of the intervening

fixation. Therefore, a cortical command to saccade to the 2-back location will receive no neural inhibition in the superior colliculus because the new oculocentric coordinates of the 2-back location do not match the old oculocentric coordinates. Any inhibition of a 2-back return saccade would have to be generated cortically (Danziger et al., 1997) and, if such tagging occurs, it does not result in temporal IOR.

Why, when previous studies have reported return probabilities lower than chance (Boot et al., 2004; Gilchrist & Harvey, 2000; McCarley, Wang, Kramer, & Irwin, 2003; Peterson et al., 2001), do we observe return probabilities significantly above chance level? One possible factor is the complexity of stimuli and processing required during each fixation in scene viewing. All studies previously demonstrating return probabilities lower than chance used very sparse search arrays or saccade targets requiring simple discrimination (Boot et al., 2004; Gilchrist & Harvey, 2000; McCarley et al., 2003; Peterson et al., 2001). When the discrimination task (Motter & Belky, 1998; Peterson et al., 2001) or object complexity increased (Hooge et al., 2005; Paul & Tipper, 2003), return probability increased to above chance level (~ 3–4%). With more complexity, processing of foveal information may not have been completed during a single fixation, necessitating a return saccade. As the complexity of the visual scene reaches that of the real world, FOR, rather than IOR, may be more suitable for accurate processing of the complex visual details. Supporting evidence for a switch from IOR to FOR during scene viewing has been recently reported during scene memorization, preference judgement, and free viewing (Dodd, van der Stigchel, & Hollingworth, in press). With more complex, real-world encoding tasks, adequate processing of foveal information may not be completed before a saccade is initiated (Henderson & Pierce, 2008; Rayner et al., 2009). If the saccade programming system cannot be relied upon to hold fixation until adequate visual encoding has finished, a compensatory system which represents previously fixated locations and facilitates return saccades would be required. Such a system drives regressive saccades during reading (Rayner et al., 2003; Rayner & Pollatsek, 1989; Vitu, 2005) and appears to be in operation in the task presented here. Further experiments are required to understand whether FOR, IOR, and Saccadic Momentum are fundamental properties of the oculomotor system or under strategic control depending on viewing task or moment-by-moment processing requirements.

Implications for computational models of attentional control

All current computational models of attentional control during scene viewing require a mechanism for driving attention through conspicuous regions in a scene (Itti & Koch, 2001; Navalpakkam & Itti, 2005; Parkhurst

et al., 2002; Sun et al., 2008). Without such a system, the model would either be trapped on the highest region of conspicuity or oscillate between the two regions of highest conspicuity. Selective inhibition of a limited number of previously visited locations via IOR is usually chosen as a way to ensure that this does not happen (Itti & Koch, 2001; Navalpakkam & Itti, 2005; Parkhurst et al., 2002; Sun et al., 2008). IOR may be adequate within a model of attentional behaviour during the exploration of sparse displays, but as we have demonstrated here, during scene viewing return saccades occur more often than would be permitted by an ideal IOR system.

A first step towards capturing the natural frequency of return saccades would be to replace IOR with Saccadic Momentum: Weighing the probability for saccades that continue the trajectory of the last saccade higher than return saccades. Tatler and Vincent (this issue 2009) present a model incorporating biases in saccade amplitudes and directions that predicts human fixations during scene viewing more accurately than a system based only on image features. By incorporating the systematic tendencies of the human attentional system, a computational model may manifest behaviour similar to that exhibited in the studies presented here without the need for an explicit IOR system.

However, such probabilistic models would fail to capture the functional role of return saccades. Systematic tendencies and localized inhibition may modify the probabilities of a location being fixated given the saccade history, but higher order control mechanisms can still override these tendencies and choose to return to a previous location. Return saccades may occur for a variety of reasons such as inadequacy of processing, significance of the region, a change at the location, or to acquire more details and consolidate its representation in memory (Henderson, Weeks, & Hollingworth, 1999). Modelling these factors would require a representation of the cognitive relevance of fixated objects, the degree of processing occurring during each fixation, and the adequacy of this processing. Where the eyes go next is not just based on what is in the visual scene (e.g., its visual saliency), or where the eyes have been previously (e.g., memory), but what processing has happened along the way. By representing the processing that happens during every fixation, attentional models will be able to account for the real-time factors, both top-down and bottom-up, affecting saccade programming during scene viewing (for a first attempt at modelling these factors during scene viewing see Nuthmann, Smith, & Henderson, 2008).

CONCLUSION

This study investigated whether the inclusion of IOR in models of attentional control during scene viewing is justified. No evidence that IOR

functions as a foraging facilitator was found. Return saccades to both the last (1-back) and penultimate (2-back) fixation locations occur as often as saccades in other directions and are facilitated when an unexpected event occurs at the last fixation location. Evidence for IOR was only found in the time taken to initiate a voluntary saccade back to the last fixation location. These results highlight an important dissociation between the spatial and temporal aspects of saccade programming, with FOR characterizing the former process and IOR the latter. The absence of a spatial impact of IOR on saccade programming during scene viewing indicates that IOR does not provide the mechanism required by computational models to drive attention through a scene. Instead such models should look to modelling the dynamics of processing during each fixation.

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