

Dissociating temporal inhibition of return and saccadic momentum across multiple eye-movement tasks

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Saccade latencies are longer prior to an eye movement to a recently fixated location than to control locations, a phenomenon known as oculomotor inhibition of return (O-IOR). There are theoretical reasons to expect that O-IOR would vary in magnitude across different eye movement tasks, but previous studies have produced contradictory evidence. However, this may have been because previous studies have not dissociated O-IOR and a related phenomenon, saccadic momentum, which is a bias to repeat saccade programs that also influences saccade latencies. The present study dissociated the influence of O-IOR and saccadic momentum across three complex visual tasks: scene search, scene memorization, and scene aesthetic preference. O-IOR was of similar magnitude across all three tasks, while saccadic momentum was weaker in scene search.

oculomotor inhibition of return (O-IOR) or sometimes inhibition of saccade return (ISR).

O-IOR has been observed in a variety of visual tasks, including simple eye-movement tasks (Farrell, Ludwig, Ellis, & Gilchrist, 2010; Hooge & Frens, 2000; Ludwig, Farrell, Ellis, & Gilchrist, 2009), search tasks (Bays & Husain, 2012; Dodd, Van der Stigchel, & Hollingworth, 2009; Hooge, Over, van Wezel, & Frens, 2005; Klein & MacInnes, 1999; MacInnes & Klein, 2003; Smith & Henderson, 2011a, 2011b; Thomas et al., 2006), non-search tasks such as scene memorization and free viewing (Bays & Husain, 2012; Hooge et al., 2005; Luke, Schmidt & Henderson, 2013; Smith & Henderson, 2009; Wilming, Harst, Schmidt, & König, 2013), and reading (Henderson & Luke, 2012; Rayner, Juhasz, Ashby, & Clifton, 2003; Weger & Inhoff, 2006). The fact that O-IOR has been observed across many different tasks suggests that O-IOR is a domain-general oculomotor phenomenon. However, it remains unclear whether O-IOR is equivalent across different tasks. There is some evidence that task demands do modulate O-IOR. For example, Dodd et al. (2009) observed O-IOR in scene search, but not in scene memorization, aesthetic preference, or free viewing. Several authors have argued that O-IOR will be most pronounced during search due to the need to dismiss the information at fixation and move on to new locations as quickly as possible until the search target is found (Dodd et al., 2009; Klein & Hilchey, 2011). By comparison, a task that requires

Introduction

Reorienting attention to a previously attended location is usually accompanied by an increase in response time, a phenomenon called inhibition of return (IOR; Posner & Cohen, 1984). IOR applies both to covert shifts of attention and to overt shifts of attention in the form of eye movements (for review, see Klein & Hilchey, 2011). When IOR manifests as an increase in saccade latencies prior to an eye movement back to a previously fixated location, it is called

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more detailed foveal processing, such as scene memorization, may exhibit less O-IOR (Dodd et al., 2009; Smith & Henderson, 2009). However, Bays and Husain (2012) observed O-IOR in both free viewing and visual search, and the effect was larger in free viewing. Farrell and colleagues (2010) reported that O-IOR is sensitive to environmental statistics: when more return saccades were required, the effect of O-IOR was weaker. These studies suggest that task may modulate the strength of O-IOR, but the nature of this modulation is far from clear.

The inconsistent modulation of O-IOR by task is further complicated by the fact that the nature of temporal O-IOR has recently been called into question. Temporal O-IOR is the increase in saccade latency when returning to a previously attended (fixated) location over a new location. Some studies have observed an increase in saccade latency as a function of the angular deviation (difference in direction) between the previous and current saccade (Klein & MacInnes, 1999; MacInnes & Klein, 2003; Smith & Henderson, 2009, 2011a, 2011b; Wilming et al., 2013). The greater the change in saccade direction from one saccade to the next, the longer it takes to initiate the second saccade. Smith and Henderson (2009), attributed this cost for changing direction to a strong bias for the eyes to continue moving in the same direction, a bias they termed *saccadic momentum*. Saccadic momentum appears to have both temporal and spatial components, in that forward saccades are both faster to execute (with fixation duration increasing linearly as saccades deviate more from the direction of the previous saccade) and are more frequent than other saccades (Hooge et al., 2005; Luke, Schmidt et al., 2013; Smith & Henderson, 2009; Wilming et al., 2013). Smith and Henderson (2009) observed that this linear increase in fixation duration with angular deviation was unrelated to exactly where the eyes had previously been fixated, a finding that was consistent with saccadic momentum but inconsistent with the idea that the delay was due to saccades returning specifically to a previously fixated location as predicted by O-IOR.

Inhibition of a previously fixated spatial location (O-IOR) could result in increased fixation durations above and beyond saccadic momentum. Smith and Henderson (2009; 2011b) observed this significant additional delay for return saccades in combination to that predicted by saccadic momentum, suggesting that spatially specific O-IOR was also at work. However, other authors have failed to isolate a spatially specific delay as expected by O-IOR and instead have attributed the entire delay for return saccades to saccadic momentum (Wilming et al., 2013). Such differences in the reported contributions of O-IOR and saccadic momentum to fixation duration may be attributable to task differences, as noted above, or to

other differences between studies such as differences in stimulus features. Wilming and colleagues' (2013) analysis was based on data taken from five different studies using a range of stimulus types (including photographs, fractals, and pink noise) and a combination of free viewing and a delayed patch memory test. The absence of a search task may account for their failure to isolate temporal evidence of spatially specific O-IOR. In order to identify whether O-IOR and saccadic momentum are differentially affected by task demands, task must be manipulated within a single study.

The present study attempted to define task-based differences in O-IOR and saccadic momentum more clearly by investigating both O-IOR and saccadic momentum in three separate scene-viewing tasks: scene search, scene memorization, and aesthetic preference judgment. Seventy-two participants completed all three tasks, and each scene appeared in each task (counter-balanced across participants), making this both a within-subjects and within-items design. Thus, any differences observed in O-IOR and saccadic momentum can be attributed to task differences.

Method

Participants

Seventy-two undergraduate students from the University of Edinburgh completed the experiment. All participants were native English speakers with 20/20 corrected or uncorrected vision. They were naïve concerning the purposes of the experiment.

Apparatus

Eye movements were recorded via an SR Research Eyelink 1000 eye tracker, with spatial resolution of 0.01° and sampling at 1000 Hz (SR Research, Ottawa, ON, Canada). Participants were seated 90 cm away from a 21-inch monitor. Head movements were minimized with a chin and head rest. Although viewing was binocular, eye movements were recorded from the right eye. The experiment was controlled with SR Research Experiment Builder software.

Materials

During the task phase of the experiment, 135 unique full-color 800×600 pixel (32 bit) photographs of real-world scenes, from a variety of scene categories, were used.

	Search	Memory	Preference
Return saccades	247 (33)	280 (30)	275 (34)
Nonreturn saccades	231 (25)	252 (26)	250 (28)
O-IOR effect	16	28	25

Table 1. Mean fixation durations (and standard deviations) in ms for the three tasks for return saccades and nonreturn saccades.

Procedure

The scenes were split into blocks of 45 images and the participants were instructed to perform one of three tasks during each block: search for an object (cued with a word template), memorize the scene in preparation for a later memory test, or view the scene in preparation to make an aesthetic judgment. Each trial began with a gaze trigger, a black circle presented in the center of the screen. Once a stable fixation was detected on the gaze trigger, the trial began. For the preference and memory encoding blocks, the scene was immediately presented. For the search block a target word (e.g., “clock”) was presented for 800 ms, followed by a central fixation cross for 200 ms, and then the search scene. All scenes were presented for 8 s. Search responses were logged during the trial by the participant responding using either of the shoulder trigger buttons on a games controller; only fixations and saccades prior to the first fixation on the target during search were included in the analyses. The scene stayed up for the full 8 s, then a new gaze trigger appeared and the next trial began. Within each task, scenes were presented in a random order for each participant. The preference judgment (on a scale from 1 = dislike to 4 = like, with responses made via the A–D triggers on the controller) was made after the scene’s presentation.

The order of blocks and task was counterbalanced across participants using a Latin-square design to create nine order conditions. Thus, each scene appeared in each task, and each task was performed in each order position.

Results

ANOVAs

A first set of analyses was conducted to replicate the methods of several previous studies (Hooge et al., 2005; Luke, Schmidt et al., 2013; Smith & Henderson, 2009, 2011a, 2011b), and is typical of studies that investigate O-IOR. In both the temporal and spatial analyses, return saccades were defined as saccades that were similar in amplitude to the previous saccade ($\pm 4^\circ$) and in approximately the opposite direction from the

previous saccade ($180^\circ \pm 30^\circ$). In other words, a return saccade carried the eyes back to the just-viewed location, or close to it. Saccades longer than 20° , shorter than 1° , and the fixations preceding these saccades were excluded from the data. Saccades that differed in amplitude from the preceding saccade by more than $\pm 4^\circ$ were also excluded (Hooge et al., 2005), so that nonreturn and return saccades were matched in their amplitude deviation but varied in angular deviation. Further, only fixations and saccades prior to the first fixation on the target during search were included (mean search time = 3.25 s). When the data in the memory and preference tasks were trimmed to include only the first 3.25 s of data from each trial, the pattern of results was identical to those reported below. The final data set included 98,202 saccades. Follow-up *t* tests were corrected for multiple comparisons.

Temporal analysis

Descriptive statistics are reported in Table 1. A 3×2 ([task: search, memory, preference] \times [return: return saccade vs. nonreturn saccade]) by-participant ANOVA was conducted. There was a main effect of task, $F(2, 66) = 96.3$, $MSE = 329$, $p < 0.0001$, indicating that fixation durations in search (239 ms) were shorter than in the other two tasks (memory: 266 ms, preference: 262 ms; both $ps < 0.0001$), which did not differ (both $ps > 0.31$). There was also a main effect of return, $F(1, 66) = 236$, $MSE = 242$, $p < 0.0001$, with longer fixation durations for return saccades (267 ms) than for nonreturn saccades (244 ms; $t(71) = 7.49$, $p < 0.0001$). Finally, the interaction of task and return was significant, $F(2, 142) = 11.68$, $MSE = 129.3$, $p < 0.0001$. Follow-up *t* tests on the simple effects indicated that while the effect of return was significant in all three tasks, the O-IOR effect was larger in the memory and preference tasks (both $ts > 4.8$, both $ps < 0.0001$) than in the search task, $t(71) = 3.26$, $p = 0.0014$; see Table 1).

Spatial analyses

In order to evaluate the observed proportions of saccades in the current data, it was necessary to create a baseline comparison condition. This baseline was generated by shuffling each participant’s saccades within each trial fifty times. Shuffling saccades within each trial for each participant rather than simply generating random saccades helps control for content relevance and individual differences in attentional settings (Hooge et al. 2005; Smith & Henderson, 2011a). The experimental data and these shuffled data were then trimmed as described above.

Afterward, both the observed data and the shuffled data sets were binned. Saccades were grouped into 30° angular difference bins. The first bin (0° – 30°) represents

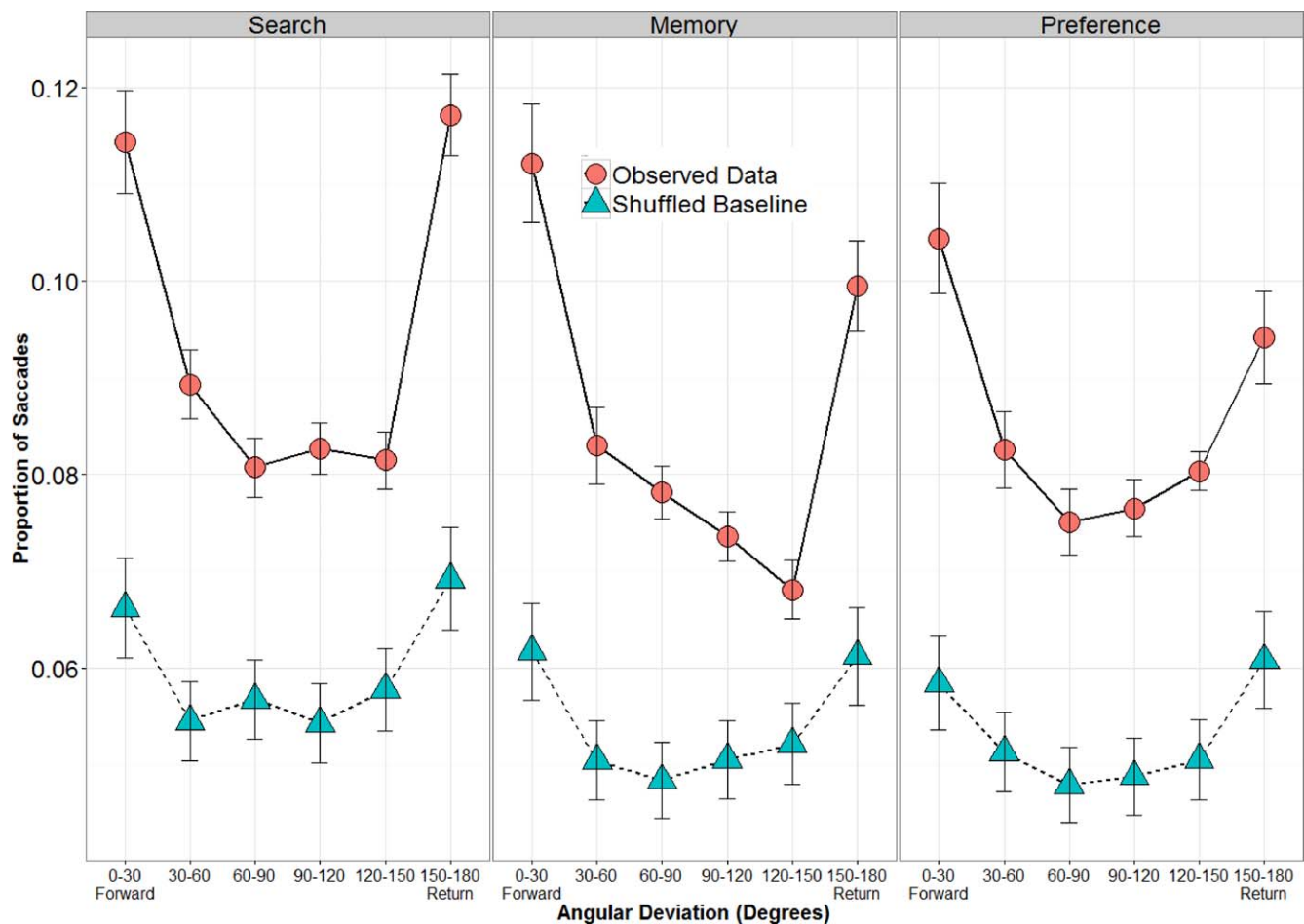


Figure 1. Proportion of saccades as a function of angular deviation for the three tasks. Data included only saccades that were similar in amplitude to the preceding saccade ($\pm 4^\circ$ amplitude). Error bars represent standard error.

forward momentum saccades that differed in angle from the preceding saccade by no more than 30° , and the final bin (150° – 180°) represents return saccades that differed in angle from the preceding saccade by no less than 150° . Other bins represent saccades that turned to the left or right by varying amounts. For the shuffled data, the average proportion of saccades in each bin across all fifty shuffles was then calculated.

Mean proportions of saccades for each bin are shown in Figure 1. A separate 6×2 ([angular deviation bin: 0° – 30° {forward}; 30° – 60° , 60° – 90° , 90° – 120° , 120° – 150° , 150° – 180° {return}] \times [data group: observed data vs. shuffled baseline]) by-participant ANOVA was conducted for each task. For all three tasks, there were main effects of *angular deviation* and *data group* (all $F_s > 31.58$, all $p_s < 0.0001$). In addition, in all three tasks, the interaction was also significant (all $F_s > 6.96$, all $p_s < 0.0001$). Follow-up t tests indicated that the proportion of observed saccades was always greater compared to the shuffled baseline (all $t_s > 3.1$, all $p_s < 0.0022$), indicating that saccades were more likely to be matched for amplitude in the observed data relative to the shuffled baseline data. For the observed data,

participants made significantly more return saccades compared to all nonforward saccade bins (all $t_s > 2.69$, all $p_s < 0.0078$), although in the preference task, the difference between the return and the 30° – 60° bin was nonsignificant after controlling for multiple comparisons ($t = 1.88$, $p = 0.061$). The proportion of forward and return saccades did not differ in any of the tasks (all $t_s < 1.64$).

In order to compare the different tasks directly, a 6×3 ([angular deviation bin: 0° – 30° {forward}; 30° – 60° , 60° – 90° , 90° – 120° , 120° – 150° , 150° – 180° {return}] \times [task: search, memory, preference]) by-participant ANOVA was conducted on the observed saccade data only. There was a main effect of *angular deviation* and *task*, and a significant interaction (all $F_s > 3.14$, all $p_s < 0.00061$). Follow-up t tests revealed that none of the task differences were significant for forward saccades. However, more return saccades were made in search than in the other two tasks (both $t_s > 2.81$, both $p_s < 0.0056$), which did not differ from each other ($t < 0.81$). Thus, it appears that in absolute terms, more return saccades were made in search than in the other tasks.

Summary

In previous research, O-IOR has been defined as an increase in saccade latency prior to a return saccade. In the temporal analyses reported above, O-IOR was observed in all tasks. In addition, task differences were observed; the O-IOR effect was stronger in the nonsearch tasks than in search. This finding is consistent with the results reported by Bays and Husain (2012), but inconsistent with the idea that O-IOR should be stronger in search (Dodd et al., 2009; Klein & Hilchey, 2011). The spatial analyses revealed more return saccades in search than in the other tasks, so that the observation of weaker O-IOR in search is consistent with the findings of Farrell et al. (2010), in that O-IOR appears to decrease as the number of return saccades in a task increases.

Disentangling temporal O-IOR and saccadic momentum

As noted in the Introduction, the observed increase in fixation durations for return saccades may be due to O-IOR, saccadic momentum, or a combination of the two, so it is important to find a way to dissociate these phenomena before interpreting task differences. To accomplish this, additional analyses were conducted on the fixation duration data described above. In these analyses, instead of defining return saccades categorically as was done in the previous temporal analysis, angular deviation (the difference in angle between the critical saccade and the previous one) was included as a continuous predictor.

As mentioned, increased fixation durations for return saccades are consistent both with saccadic momentum and O-IOR. Saccadic momentum refers to the tendency of the eyes to repeat saccade programs, a tendency manifested temporally as a linearly (Smith & Henderson, 2009, 2011a, 2011b) increasing cost for changes in direction (i.e., fixation duration should increase linearly as angular deviation increases). O-IOR, on the other hand, should manifest as a nonlinear increase in fixation durations as a function of angular deviation, because the temporal delay associated with O-IOR occurs only for return saccades, meaning that the relationship between fixation duration and angular deviation should be relatively flat until angular deviation begins to approach 180°. Thus, an increase in fixation durations as a function of angular deviation is highly expected and would be consistent with either phenomenon. If fixation durations increase nonlinearly with an increase as angular deviation approaches 180°, this would provide evidence for a spatially specific additional increase in fixation durations prior to return saccades, consistent with O-IOR.

It is important to note that this nonlinearity must be of a particular sort to provide evidence for O-IOR. Wilming et al. (2013) observed an increase in fixation durations as angular deviation increased, consistent with saccadic momentum, but this line flattened out for the highest angular deviations. This finding, although nonlinear, is not consistent with O-IOR. Instead, only a curve that *increases* in slope for the highest values of angular deviation would reflect the predicted additional temporal cost associated with O-IOR. Saccadic momentum, on the other hand, should be associated with a linear increase (Smith & Henderson, 2009) or possibly a nonlinear *decrease* in slope for the highest values of angular deviation (Wilming et al., 2013).

It is possible that both saccadic momentum and O-IOR will be observed in the data. That is, fixation durations could increase with angular deviation, consistent with saccadic momentum, and if O-IOR is an independent phenomenon, then the rate of increase should be greatest for the largest angular deviations and weakest for smaller angular deviations. To test this, the linear and quadratic terms for angular deviation were modeled orthogonally, so that each was tested independently of the other. The data were analyzed using linear mixed models in R (R Development Core Team, 2013), a type of multilevel regression model that controls for by-participant and by-stimulus variability. Unlike an ANOVA, mixed models test simple effects. For a categorical predictor, such as task, the model compares each level of the variable to a baseline condition; in this case, fixation durations in the search task and the preference task would both be compared separately to the baseline memory task. For the continuous predictor of angular deviation, the model fits a linear and a quadratic function (separately) to the data and reports the relevant coefficients. In mixed models, interactions between the different simple effects (i.e., between task and angular deviation) reflect statistical differences in the magnitude of these effects. Thus, when our models include the interaction of angular deviation and task, the models will first test the effect of angular deviation in the baseline memory task, which will be reported as a simple effect, and then test whether this effect was significantly different in either of the other two tasks (interactions). The actual coefficients for the functions in the other nonbaseline conditions can be derived by summing the relevant simple effect coefficient and interaction coefficient. The model included random intercepts for participant and scene, and all random slopes that contributed to the model, as indicated by likelihood ratio tests. All models included task (as a categorical predictor), angular deviation (linear and quadratic terms), and the interactions between the different levels of task and the angular deviation terms.

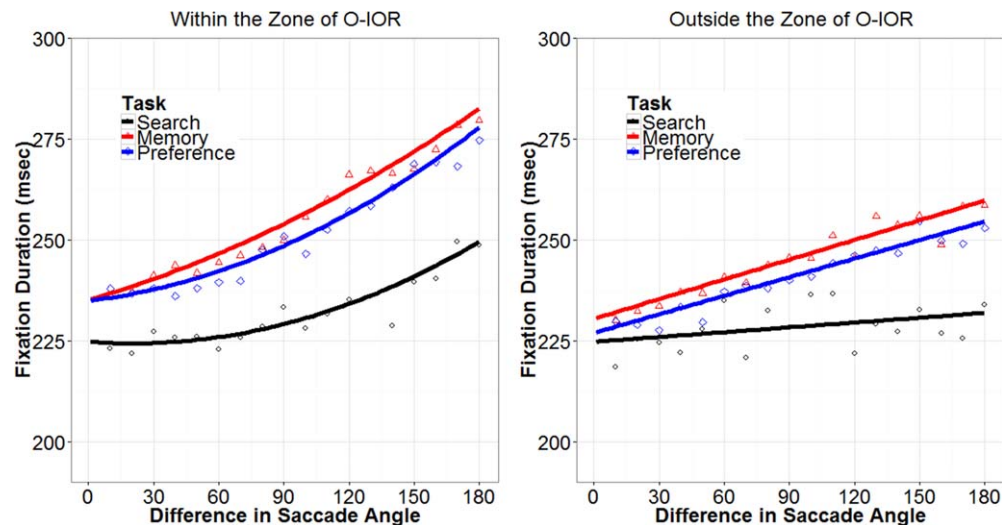


Figure 2. The increase in fixation duration as a function of difference in saccade angle (angular deviation) between the critical saccade and the previous one. The separate lines represent the different tasks. The data points represent mean fixation durations for 10° angular difference bins, collapsing across participants. The left panel includes saccades with amplitude differences of less than 4° (within the zone of IOR), and the right panel includes saccades with amplitude differences of more than 4° .

This analysis generally replicated the overall duration differences between the tasks observed in the first analysis, with longer fixations in the memory compared to the search task (coeff = -0.098 , $SE = 0.025$, $t = -3.9$, $p < 0.0001$) but not compared to the preference task ($t < 0.9$). In addition, there was a significant effect of the linear term for angular deviation in the memory task (coeff = 16.6 , $SE = 0.62$, $t = 26.8$, $p < 0.0001$). This linear effect interacted with task for search (coeff = -9.01 , $SE = 1.17$, $t = -7.7$, $p < 0.0001$) but not for preference (coeff = -1.42 , $SE = 0.86$, $t = -1.6$, $p = 0.11$), indicating that the linear trend observed in the memory task was of similar strength in the preference task but significantly weaker (although still significant) in search. The quadratic term for angular deviation was also significant in memory (coeff = 1.57 , $SE = 0.62$, $t = 2.5$, $p = 0.012$), with the positive coefficient indicating a u-shaped curve, consistent with O-IOR. The interactions of this term with task were not significant (both t s < 1.6), indicating that the curve was present and statistically equivalent in the other tasks as well. This pattern of results indicates that there was a general increase in fixation duration as angular deviation increased, but that this increase was not purely linear; for the lower values of angular deviation the slope was shallow, but as angular deviation increased, so did the slope (see Figure 2, left panel).

In this data set, the preceding and following saccades were closely matched in amplitude ($\pm 4^\circ$), so that a saccade with an angular deviation of about 180° moved the eyes back to the previously fixated location. It is important to note that saccadic momentum is unrelated to where the eyes were previously fixated (Smith & Henderson, 2009), so it should be observed even when

the current and previous saccades are not closely matched in amplitude; however, O-IOR should only occur if the two saccades are close enough in amplitude that the eyes are returning to a previously fixated location. If the observed nonlinearity of the function of angular deviation is truly the result of O-IOR and not of saccadic momentum, then, when the saccades are not closely matched in amplitude (more than 4° difference), the eyes will not land within the zone of O-IOR (Hooge & Frens, 2000) and no additional nonlinear influence of angular deviation on fixation durations should be observed. To test this prediction, an identical analysis was conducted on the complementary data set (amplitude deviation greater than $\pm 4^\circ$). In this data set, the differences in amplitude were large enough that no saccades returned to the previously fixated location, even if the angular deviation was 180° . As a result, no O-IOR should occur, so the increase in fixation durations should not deviate from linearity. This data set was somewhat smaller, but still contained 69,956 saccades.

In this analysis fixations were longer on average in the memory task than in the search task (coeff = -0.081 , $SE = 0.0093$, $t = -8.8$, $p < 0.0001$) but only marginally so when compared to the preference task (coeff = -0.012 , $SE = 0.0066$, $t = -1.8$, $p = 0.072$). The linear function of angular deviation was significant in the memory task (coeff = 8.23 , $SE = 0.63$, $t = 13.1$, $p < 0.0001$), indicating that fixation durations increased as angular deviation increased. This linear function did not interact with the preference task ($t < 0.2$) but did interact significantly with search (coeff = -7.84 , $SE = 1.22$, $t = -6.4$, $p < 0.0001$), indicating that the linear increase in fixation durations was present in the preference task but was not significant in the search

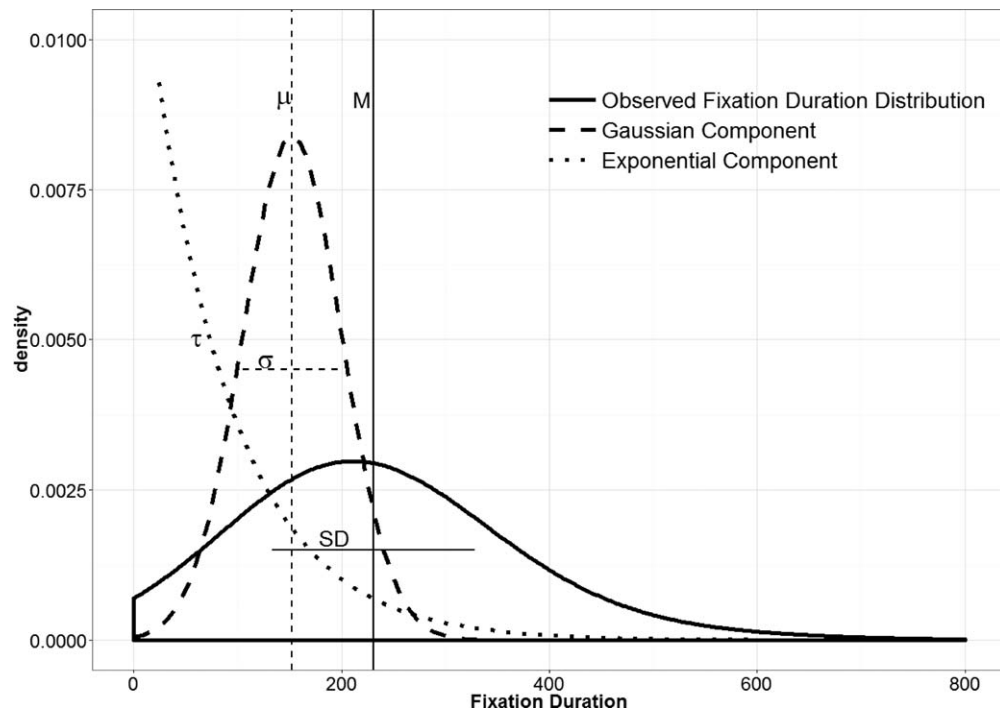


Figure 3. Fixation duration distribution for the search task, collapsing across participants. The solid curve shows the observed distribution of fixation durations in search. The solid vertical line shows the distribution mean (M) and the solid horizontal line shows the distribution standard deviation (SD). The figure also shows the components of the ex-Gaussian distribution. The dashed curve represents the normal (Gaussian) component, with the vertical dashed line representing μ (μ), and the horizontal dashed line representing σ (σ). The dotted curve shows the exponential component of the ex-Gaussian distribution captured by τ (τ).

task. No effects or interactions involving the quadratic term of angular deviation were significant (all t s < 1); the slopes did not deviate from a linear function (see Figure 2, right panel). Thus, when the amplitude of the critical saccade differed enough from that of the previous saccade that it did not land in the zone of IOR, a linear increase in fixation durations consistent with saccadic momentum was observed, but there was no additional cost for making return saccades. Thus, these data provide strong evidence that temporal O-IOR is a phenomenon independent of saccadic momentum; returning to a previously fixated location results in a greater delay than would be predicted by the linear change in angular deviation alone.

With regard to task differences, the linear function of angular deviation (which represents saccadic momentum) differed across tasks, such that it was weaker in the search task, whereas the quadratic function (representing O-IOR) was equivalent across tasks. Thus, it appears from these data that temporal O-IOR is constant across tasks, while saccadic momentum is not.

Fixation duration distribution analyses

The distribution of fixation durations, like that of other reaction time measures, is highly skewed to the

right (see Figure 3). For such distributions, an increase in the mean could be caused by one of two changes in the distribution. First, the center of the distribution might shift to the right, so that all fixations are longer. Second, the skewness of the distribution might increase because there are proportionately more long fixations, and these longer fixations shift the mean rightward. The increase in fixation durations observed in Figure 2 could be caused by either (or both) of these changes. Importantly, the changes in the center and skewness of reaction-time distributions can occur independently and often reflect separate processes (Balota & Yap, 2011; Luke, Nuthmann & Henderson, 2013; Staub & Benatar, 2013). Thus, if we examine the center and the skewness of the fixation duration distribution separately, it might be possible to further dissociate saccadic momentum and O-IOR.

In order to accomplish this, we applied a response time distribution analysis (Balota & Yap, 2011) to the fixation duration data. This analysis fits participants' response time data with an ex-Gaussian distribution (Ratcliff, 1979), which is the convolution of normal (Gaussian) and exponential distributions, with two parameters representing the normal component (μ , the mean, and σ , the standard deviation) and a single exponential parameter (τ). Any changes in μ therefore indicate shifts in the center of the distribution, whereas

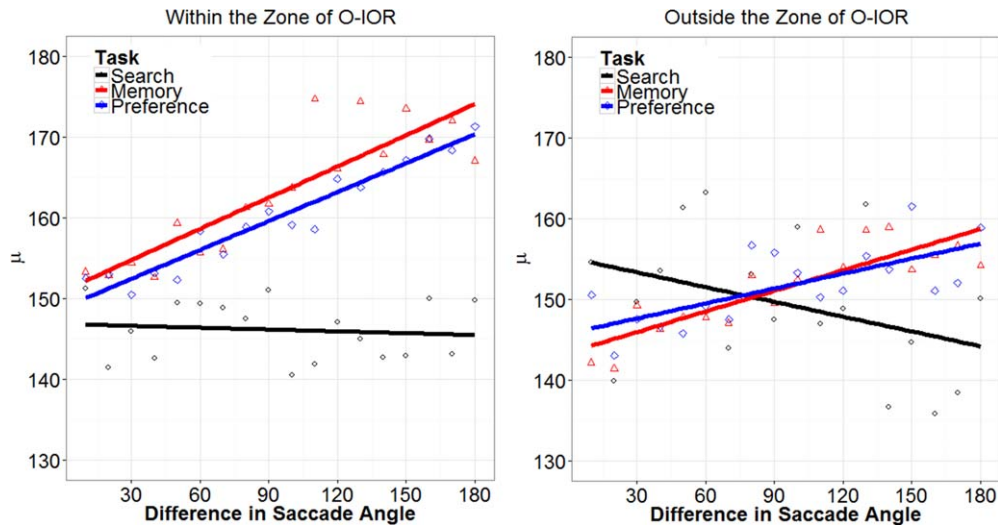


Figure 4. The change in μ (in ms), the center of the normal component of the fixation duration distribution, as a function of difference in saccade angle (angular deviation) between the critical saccade and the previous one. The separate lines represent the different tasks. The data points represent mean values of μ for 10° angular difference bins, collapsing across participants. The left panel includes saccades with amplitude differences of less than 4° (within the zone of IOR), and the right panel includes saccades with amplitude differences of more than 4° .

differences in τ indicate increases in the right tail of the distribution. Ex-Gaussian distributions have been shown to provide a good fit to eye-movement data (Luke, Nuthmann et al., 2013; Staub, 2011; Staub, White, Drieghe, Hollway, & Rayner, 2010; White & Staub, 2012).

As was done above, the data were divided into 1° angular difference bins separately for each task. In order to have enough fixations to fit a distribution to while still retaining a sufficiently fine angular difference measure, the data in these bins were collapsed across participants. Thus, the different bins contain fixations from many participants, so that the distribution may not reflect the distribution of any one individual participant. The ex-Gaussian distribution was fit separately to the data in each bin using QMPE software (Heathcote, Brown, & Cousineau, 2004) in order to derive the ex-Gaussian parameters. This procedure was performed separately for the data for the matched saccades ($\pm 4^\circ$ amplitude deviation) and for the mismatched saccades (amplitude deviation greater than $\pm 4^\circ$). The μ and τ parameters from each data set were then analyzed separately using simple linear regression with angular deviation and task as predictors. As in the previous analyses, the linear and quadratic terms for angular deviation were modeled orthogonally.

In the analyses of μ , the linear function of angular deviation was significant; in the memory task angular deviation was positively related to μ both for distance-matched saccades (coeff = 0.96, $SE = 0.13$, $t = 7.46$, $p < 0.0001$) and for mismatched saccades (coeff = 0.66, $SE = 0.2$, $t = 3.35$, $p = 0.00087$). However, the linear function significantly interacted with search (matched saccades:

coeff = -1.03 , $SE = 0.18$, $t = -5.65$, $p < 0.0001$; mismatched saccades: coeff = -1.2 , $SE = 0.28$, $t = -4.28$, $p < 0.0001$) but not with preference (both t s < 0.65 , both p s > 0.51) in both analyses, revealing that the positive effect of angular deviation was also present in the preference task but was not observed in the search task (for mismatched saccades the effect was actually negative in search). This interaction is illustrated in Figure 4. The fact that this same pattern was observed for both distance-matched and mismatched saccades indicates that the effect of angular deviation on μ is consistent with saccadic momentum and inconsistent with O-IOR. Neither the quadratic term nor any interactions involving that term were significant in either analysis (all t s < 1.47). Based on these results, it appears that there is no additional shift in the center of the distribution for return saccades beyond that which can be accounted for by saccadic momentum, indicating that O-IOR effects were not observed in this analysis of μ . Additionally, saccadic momentum was noticeably absent in search compared to the other tasks.

The analysis of τ revealed a different pattern of results. In this analysis the linear term was significant for both distance-matched saccades (coeff = 1.67, $SE = 0.31$, $t = 5.33$, $p < 0.0001$) and for mismatched saccades (coeff = 1, $SE = 0.45$, $t = 2.22$, $p = 0.027$), indicating an increase in skewness as angular deviation increased in the memory task. No interactions with task were significant (all t s < 1.4), indicating that this increase was present in the search and preference tasks as well (see Figure 5). The quadratic term for angular deviation was significant for matched saccades (coeff = 0.65, $SE = 0.31$, $t = 2.06$, $p = 0.04$) but not for mismatched saccades ($t = 0.58$, $p = 0.56$). This term

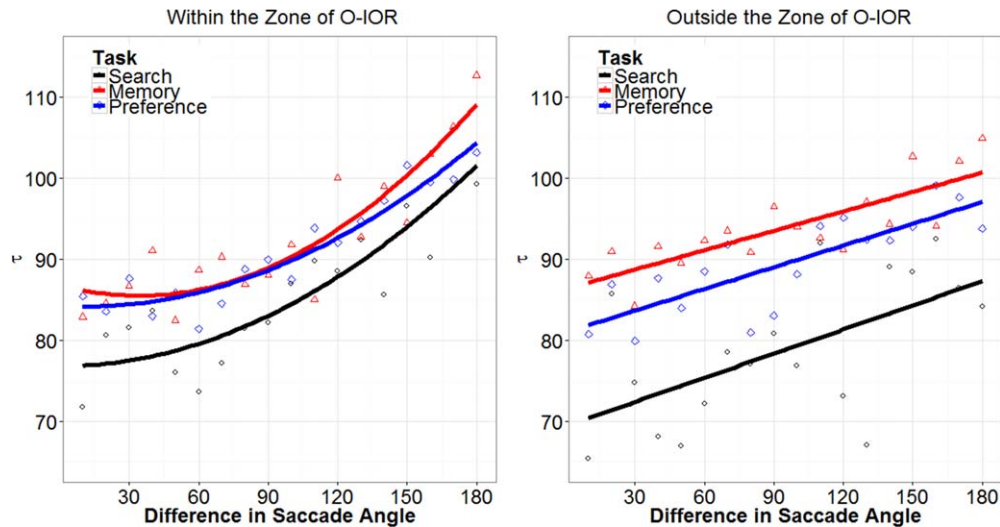


Figure 5. The change in τ (in ms), the parameter representing the exponential component of the fixation duration distribution, as a function of difference in saccade angle (angular deviation) between the critical saccade and the previous one. The separate lines represent the different tasks. The data points represent mean values of τ for 10° angular difference bins, collapsing across participants. The left panel includes saccades with amplitude differences of less than 4° (within the zone of IOR), and the right panel includes saccades with amplitude differences of more than 4° .

also did not interact with task (all t s > 1.14 , all p s > 0.25). This finding indicates that, for matched saccades, the increase in the tail of the distribution was small for small values of angular deviation (e.g., for forward saccades) and became progressively larger as angular deviation increased (see Figure 5, left panel). This significant quadratic function in the analysis of τ (but not in the analysis of μ) indicates that O-IOR manifests primarily as an increase in the rightward skewness of the distribution of fixation durations rather than a shift in the center of the distribution. The fact that O-IOR only manifested in the analysis of τ , and not in the analysis of μ , indicates that O-IOR influences only a subset of fixations. On the other hand, saccadic momentum had clear influences on μ in the memory and preference tasks, indicating that all fixations were affected. Notably, this was not the case in the search task, where only τ increased as a linear function of angular deviation.

General discussion

The goals of the present study were twofold: First, to attempt to dissociate O-IOR and a related phenomenon, saccadic momentum; and second, to explore whether task differences exist in the manifestation of either or both of these phenomena. There are theoretical reasons to expect that O-IOR might differ across task. In visual search tasks, O-IOR might be stronger, since in such tasks there is a strong need to move on to new locations quickly in order to locate the target (Dodd et al., 2009; Klein & Hilchey, 2011).

Conversely, other tasks such as scene memorization may require more detailed foveal processing and so may exhibit less O-IOR (Dodd et al., 2009; Smith & Henderson, 2009). The evidence to date has been mixed, with some studies finding greater O-IOR in search than in nonsearch tasks (Dodd et al., 2009) and other studies finding the reverse (Bays & Husain, 2012).

One potential explanation for these varied findings is that O-IOR is not the only influence on saccade latencies. Saccadic momentum is the tendency for the eyes to continue moving in the same direction (Smith & Henderson, 2009), and is manifest temporally as a linear increase in saccade latency as the saccade deviates from a forward trajectory. Saccadic momentum differs from O-IOR in two important ways. First, saccadic momentum is influenced primarily by changes in the direction of a saccade, while O-IOR is spatially specific, being related to the location that a saccade is targeting. In other words, saccadic momentum will influence any saccade that changes direction, while O-IOR will only appear if a saccade both reverses direction and returns to the previously fixated location. Second, the effect of saccadic momentum is linear; each additional degree of angular difference between the previous and current saccade produces an approximately equivalent increase in fixation duration. O-IOR, on the other hand, has no effect unless the saccade amplitudes are roughly matched and the angular difference is large enough that the current saccade is going in roughly the opposite direction, so as to take the eyes back to the previously viewed location.

When these criteria were applied to the data from the current study, O-IOR and saccadic momentum arose as

separate and distinct phenomena. Fixation duration increased linearly as angular deviation increased, reflecting saccadic momentum, but there was an additional delay for saccades that returned the eyes to the previously fixated location. This additional delay reflects spatially specific O-IOR. The current results thus support the idea that O-IOR and saccadic momentum are separate processes (Smith & Henderson 2009; 2011b) and contradict the idea that any delay associated with return saccades can be attributed entirely to saccadic momentum (Wilming et al., 2013).

In addition to investigating the independence of O-IOR and saccadic momentum, the current study explored cross-task differences in the influence of these two phenomena. The curvilinear, location-specific effect of O-IOR did not differ significantly across tasks, providing further evidence that O-IOR is primarily an oculomotor phenomenon that occurs independently of cognitive control (Henderson & Luke, 2012). Saccadic momentum, on the other hand, did vary significantly between tasks, being weaker in the search task. Thus, these results suggest that task-based differences observed in previous studies (Bays & Husain, 2012; Dodd et al., 2009; Farrell et al., 2010) may have reflected differences in saccadic momentum and not in O-IOR.

Several different brain regions have been associated with O-IOR, most notably the superior colliculus (Danziger, Fendrich, & Rafal, 1997; Dorris, Taylor, Klein, & Munoz, 1999; Posner, Rafal, Choate, & Vaughn, 1985; Rafal, Calabresi, Brennan, & Sciolto, 1989; Sapir, Soroker, Berger, & Henik, 1999; Taylor & Klein, 1998) and the frontal eye fields (Dorris, Klein, Everling & Munoz, 2002; Klein, 2000; Mayer, Seidenberg, Dorflinger, & Rao, 2004; Ro, Farnè, & Chang, 2003), which are involved in the generation of voluntary saccades (Henik, Rafal, & Rhodes, 1994; Ro, Henik, Machado, & Rafal, 1997; Ro, Pratt, & Rafal, 2000). To date, studies that have attempted to identify the neural locus of O-IOR have not consistently dissociated O-IOR and saccadic momentum. Thus, regions that have previously been associated with O-IOR may in fact reflect saccadic momentum, either instead of or in addition to O-IOR. The evidence presented here, that the two phenomena have separate and dissociable influences on the distribution of fixation durations and that saccadic momentum is task-sensitive while O-IOR is not, suggest that they could arise in different parts of the brain.

The analyses of the fixation duration distributions revealed that O-IOR manifests in the fixation duration distribution as an increase in skewness and not a shift in the distribution center. Such an increase in skewness would arise because there was a larger proportion of long fixations prior to return saccades than prior to other saccades. This means that temporal inhibition does not appear to precede all return saccades, only a subset

of them. This result is consistent with the idea that O-IOR may take some time to build up, and thus will only affect fixations of sufficient duration (Posner & Cohen, 1984). There is also evidence that O-IOR does not occur for intermediate saccades in a preprogrammed saccade sequence (MacInnes, Krüger, & Hunt, 2014), so if many saccades were part of a planned sequence then O-IOR would only occur for a subset of these saccades. An additional possibility is that O-IOR only applies to voluntary saccades. There is some evidence that O-IOR does not occur in response to involuntary saccades initiated in response to stimulus onsets (Smith & Henderson, 2009; but c.f. Dodd et al., 2009). Even when no such onsets are present, a significant proportion of saccades appear to occur independently of cognitive control (Henderson & Pierce, 2008; Henderson & Smith, 2009; Luke, Nuthmann et al., 2013), and it may be that O-IOR does not operate on these saccades, so that noncognitively controlled return saccades would not be preceded by longer fixations.

Conclusions

The present study investigated task-based differences in temporal O-IOR and saccadic momentum. O-IOR and saccadic momentum had separate and dissociable influences on fixation durations. Further, while the effect of O-IOR was constant across tasks, saccadic momentum was weaker in search than in the memory-encoding and preference tasks. These findings suggest that behavioral and neurological studies investigating inhibition of return should attempt to dissociate O-IOR and saccadic momentum.

Keywords: inhibition of return, O-IOR, saccadic momentum, visual scenes, visual search, eye movements

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