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Inhibition of return is not a foraging facilitator in saccadic search and free viewing

Ignace Th.C. Hooge [a,*], Eelco A.B. Over [b], Richard J.A. van Wezel [c], Maarten A. Frens [d]

[a] *Psychonomics, Helmholtz Institute, Utrecht University, Heidelberglaan 2, NL-3584 CS Utrecht, The Netherlands*
[b] *Physics of man, Helmholtz Institute, Utrecht University, Princetonplein 5, NL-3584 CC Utrecht, The Netherlands*
[c] *Neurobiology, Helmholtz Institute, Utrecht University, Padualaan 8, NL-3584 CH Utrecht, The Netherlands*
[d] *Neuroscience, Helmholtz Institute, Erasmus MC, Rotterdam, P.O. Box 1738, NL-3000 DR Rotterdam, The Netherlands*

Abstract

The ability to search and scan the environment effectively is a prerequisite for spatial behavior. A longstanding theory (Posner M. I., & Cohen, Y. (1984). Components of visual orienting. In H. Bouma, & D. Bouwhuis (Eds.), *Attention and performance X* (pp. 531–556). London: Erlbaum) proposes that inhibition of previously attended loci (Inhibition of return; IOR) serves to facilitate exploration by increasing the likelihood to inspect new areas instead of returning to locations that have been inspected before. In this eye movement study we tested whether we could find evidence in favor of this hypothesis. Here we report that IOR does occur during search and free viewing, because we found increased fixation times preceding return saccades (eye movements that return to previously fixated locations). Meanwhile we observed no influence of IOR on the search strategy. Rather than the predicted low number we found many return saccades. Therefore, IOR does not serve as a foraging facilitator in saccadic search and free viewing. We hypothesize that IOR is an intrinsic aspect of shifting attention and gaze direction and furthermore that it is not always advantageous to prevent return saccades.
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1. Introduction

Inhibition of return was first described by Posner and Cohen (1984). Due to IOR, both manual and saccadic reaction times to targets appearing at previously attended locations are longer (10–100 ms) than to targets appearing at new locations. IOR occurs in response to visual (Posner & Cohen, 1984), auditory (McDonald & Ward, 1999; Schmidt, 1996; Spence & Driver, 1998) and tactile (Poliakoff, Spence, O'Boyle, McGlone, & Cody, 2002) stimuli and cues (see recent reviews by Taylor and Klein (1998) and Klein (2000)).

Since the original publication by Posner and Cohen (1984), the properties of IOR have been topic of a large number of studies (e.g. Castel, Pratt, & Craik, 2003; Klein, 1988; Klein & Dick, 2002; Maylor & Hockey, 1985; Schmidt, 1996; Tipper, Weaver, Jerraut, & Burak, 1994). Posner and Cohen (1984) suggested that IOR could act as memory for already attended locations. They write: "the long-lasting nature of inhibition (1.5 s or more) seems to be about the right length to ensure the next movement or two will have a reduced probability of returning to the former target position". IOR might therefore increase the chance to attend or direct a saccade to a new location. We will refer to this

* Corresponding author. Tel.: +31 30 2533633; fax: +31 30 2534511.
E-mail addresses: i.hooge@fss.uu.nl (I.T.C. Hooge), e.a.b.over@phys.uu.nl (E.A.B. Over), r.j.a.vanwezel@bio.uu.nl (R.J.A. van Wezel), m.frens@erasmusmc.nl (M.A. Frens).

mechanism as the foraging facilitator hypothesis (FF-hypothesis).

Horowitz and Wolfe (2001) suggest that the presence of IOR may depend on the nature of the visual search. IOR would be less likely in searches that allow for very rapid shifts of attention. However, Dodd, Castel, and Pratt (2003) reported IOR to be present after fast shifts of attention (50 ms per cue). They also found that the magnitude of IOR was stronger after longer cue durations and that cue magnitude decreased with temporal order of the cue. Later cues caused a stronger IOR effect. Based on the findings of Dodd et al. (2003), we expect IOR to occur in search tasks that contain components of attention that shift a few times per second. An obvious candidate for such a task is saccadic search (extreme serial search for which saccades are required) because Deubel and Schneider (1996) have clearly shown that attention precedes saccades. These saccades follow each other usually at a rate of 3–4 per second during search (Hooge & Erkelens, 1996). Based on this rationale we expect IOR to occur because during saccadic search attention will shift every 200–300 ms. The FF-hypothesis has been adopted in several studies (e.g. Klein, 1988; Klein & MacInnes, 1999; Müller & von Mühlenen, 2000; Pratt & Abrams, 1995; Snyder & Kingstone, 2001). However, to our knowledge the FF-hypothesis has never been tested in a free search (in which saccades are allowed) or free viewing experiment.

If the FF-hypothesis holds we expect IOR to facilitate saccadic search by making it more systematic (less refixations, Bloomfield, 1972; Gilchrist & Harvey, 2000). Indeed there is a reduced probability to saccade to an already covertly attended location in a single saccade task (Posner, Rafal, Choate, & Vaughan, 1985). However, search for a small detail in a complex scene usually requires more than one saccade to bring locations of interest upon the fovea. If IOR facilitates search, it should affect the scan path in such series of saccades by reducing the number of saccades that return to locations that were fixated immediately before ('return saccades'). In other words: the effect of IOR should not be looked for in the durations of fixations preceding return saccades but rather in the relative occurrence frequency of return saccades.

The effect of IOR on series of saccades has been tested in three human studies (Gilchrist & Harvey, 2000; Hooge & Frens, 2000; Klein & MacInnes, 1999). All these studies report increased fixation times preceding return saccades. However, the reports on spatial behavior are mixed. One study claims that saccades show a strong directional bias away from a previously fixated region and suggests that this is a reflection of IOR (Klein & MacInnes, 1999). In this study subjects were asked to look for a character named Waldo in complex pictures. During search a dot was flashed and subjects were asked to make a saccade to the dot. Fixations to dots that were

part of the—already followed—scan-path were preceded by prolonged fixations. However, this is a temporal rather than a spatial effect and no direct evidence for a directional bias. Klein and MacInnes also analyzed other saccades than those made to the probe. Here they report a directional bias away from the previous fixation. The study of Hooge and Frens (2000) did not allow for an analysis of biases away from targets because subjects were instructed to make predefined saccades as fast as possible. Their main result was that the temporal effects of IOR can even be found in self-paced series of saccades without any cue. Gilchrist and Harvey (2000) measured re-fixations in a letter search experiment to determine whether there is memory for already fixated objects. They determined the distribution of intervals between refixations (these were not necessarily *direct* refixations). Based on the fact that they find relatively few refixations that occur within 400 ms, Gilchrist and Harvey suggest that refixations are prevented by IOR.

In monkeys that performed a search task both a bias away from the previous fixation point and many return saccades have been reported (Motter & Belky, 1998). However, in this study fixation times preceding return saccades were indistinguishable from the average fixation time.

To clarify the effect of IOR on scan-paths in humans we recorded a large number of saccades during viewing pictures and search for targets in complex and uniform backgrounds. These tasks have in common that they resemble every day tasks and require series of saccades. If IOR acts as a short term memory for already fixated locations, we expect IOR to affect the shape of scan paths. This will be tested by counting the number of return fixations (fixation preceding a return saccade) and compare this number by the expected number of return fixations on the basis of chance (no bias away of the target).

2. Methods

2.1. Apparatus

The orientation of the right eye was measured at a sampling rate of 500 Hz with an induction coil mounted in a scleral annulus (Skalar Medical, The Netherlands) in an AC magnetic field (Collewijn, van der Mark, & Jansen, 1975; Robinson, 1963). An Apple G4/450 equipped with a national instruments PCI 1200 I/O Board presented the stimuli and measured the eye movements and manual reaction times simultaneously. The field generators and lock-in amplifiers were customly built by our technicians and reach specifications of a Remmel system or better (Remmel, 1984). The noise level reached at most 0.05°. The data were stored on the computer hard disk for off-line analysis.

Subjects sat in the field coils (Remmel Labs, USA; dimensions $1.0\,m \times 1.0\,m \times 1.0\,m$) in front of a SONY E400 19 in. monitor (distance 0.41 m; resolution 1024 pixels by 768 pixels; refresh rate 85 Hz; 256 gray values). Translations and rotations of the head were prevented by a two-axis bite-board. The light was turned on in the experimental room during the experiments.

2.2. Subjects

Six male observers (AK, CE, EO, IH, MB and RW) and three female observers (EL, JZ and RO) participated in the experiments. None showed any visual or oculomotor pathology other than refraction anomalies. The observers had normal or corrected to normal vision. Subjects were allowed to wear their contact lenses (RO and EL) or glasses (CE, RW and MB). We carefully checked that the frames of the glasses did not affect the accuracy of our system. IH and EO and RW are authors on this paper. The other subjects were naive concerning the goal of this experiment. There were no practice trials. This study was approved by the local ethical committee according to standards laid down in the declaration of Helsinki (1964).

2.3. Stimuli and task

Condition 1: Picture viewing (to which we refer as PV). The subjects were asked to subsequently view 16 grayscale pictures (Fig. 1A). Presentation time was 30 s. There were no other instructions then: "look at the pictures". The collection of pictures included traffic situations, fractals, art (Escher and Dali), cartoons, animals, people and landscapes.

Condition 2: Picture search (PS). The subjects were asked to subsequently view 24 identical grayscale pictures (of a group of friends watching the 1999-eclipse in France (Fig. 1B)) containing 0–7 little crosses. The dimensions of the cross were $0.24° \times 0.24°$. The subjects were instructed to push a button with their right thumb when they detected a cross. When they were sure that they had found all the crosses the subject had to push a button with the left thumb. The subjects did not know the number of targets in advance.

Condition 3: Uniform search (US). This condition resembles the PS condition except for the stimulus. The stimulus consisted of a light gray screen containing 0–7 dark gray crosses (dimensions: $0.14° \times 0.14°$, Fig. 1C). To minimize pop-out effects the target was smaller than in the PS condition.

2.4. Data analysis

Saccades were detected with a velocity threshold of 25°/s. After the detection of a saccade our matlab program searched back and forth until the velocity was
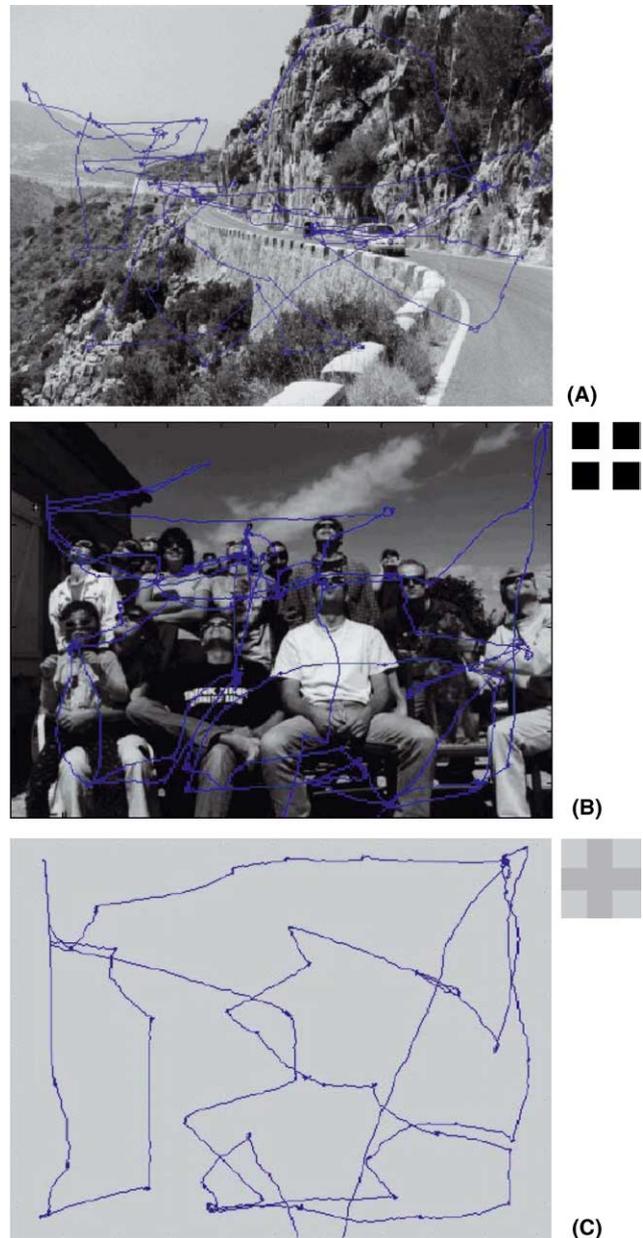

Fig. 1. Examples of presented stimuli with saccadic scan paths superimposed. (A) Picture viewing (PV). (B) Picture search (PS). Observers were instructed to search for small white crosses. (C) Uniform search (US). In this condition the stimulus consisted of a gray screen containing 0–7 dark gray crosses (size: 0.14°) at random locations (invisible in this figure). Right: enlarged version of the targets of the PS and US conditions.

two standard deviations higher than the velocity during fixation (as in Van der Steen & Bruno, 1995). Saccades with amplitudes smaller than 1° were removed from the analysis. A second matlab program determined saccade direction, location of fixation, fixation time, saccade amplitude and the angle between two succeeding saccades (to which we will refer as $\Delta\phi$). Fixations shorter than 50 ms and longer than 700 ms were removed from the analysis.

In order to determine the fraction return saccades we calculated for each saccade (except the first one of each trial) the difference in direction ($\Delta\phi$) and amplitude (ΔR) with respect to the preceding saccade. Pure return saccades have a $\Delta\phi$ of 180° and their amplitude is identical to the amplitude of the previous saccade ($\Delta R = 0°$). In this paper we consider return saccades to be all saccades having $|\Delta\phi| > 150°$ and $|\Delta R| < 4°$ with respect to the previous movement. The value of 4° for ΔR is taken from Hooge and Frens (2000). They report the area around the previously fixated dot in which IOR is active to have a radius of 4°.

3. Results

In order to analyze the scan-paths such as shown in Fig. 1, we calculated the values of $\Delta\phi$ and ΔR for all but the first saccade in each scan-path (see Section 2). In Fig. 2 we plot the combined $\Delta\phi$–ΔR histogram. As one can see there is no qualitative task-dependence on the distribution of $\Delta\phi$ and ΔR, since all graphs look similar. Furthermore, if one compares the different panels, it is striking that there is very little inter-observer variability.

In all observers the distribution of $\Delta\phi$–ΔR contains two peaks. The majority of the saccades have a ΔR that is restricted to ±10°. As reported before (Klein & Mac-Innes, 1999), there is a relatively large fraction of saccades that continue in roughly the same direction as the previous movement ($\Delta\phi < 35°$, left peak of Fig. 2). The second peak ($\Delta\phi > 150°$) is of interest, since it contains return saccades. In order to estimate the chance distribution of return saccades, we created 50 permutations of each recording by putting the detected saccades in a random order (see also Frens, van Beuzekom, Sandor, & Henn, 1998). For each permutation we determined the $\Delta\phi$–ΔR histogram. The number of return fixations in the real distribution was then compared with the average chance distribution by means of a two-tailed Student *t*-test. In 18 out of 27 conditions (PV: 9/9; PS: 6/9; US:3/9) this value was *higher* than would be expected on the basis of chance ($p < 0.01$). Subsequently, in none of the conditions the fraction of return saccades was *less* than chance. Therefore, return saccades are not suppressed with respect to other saccades. Especially in the PV and PS condition return saccades occur even more often than expected on the basis of chance.

One of the reasons that we find so many return saccades might be that they serve to keep the eyes within
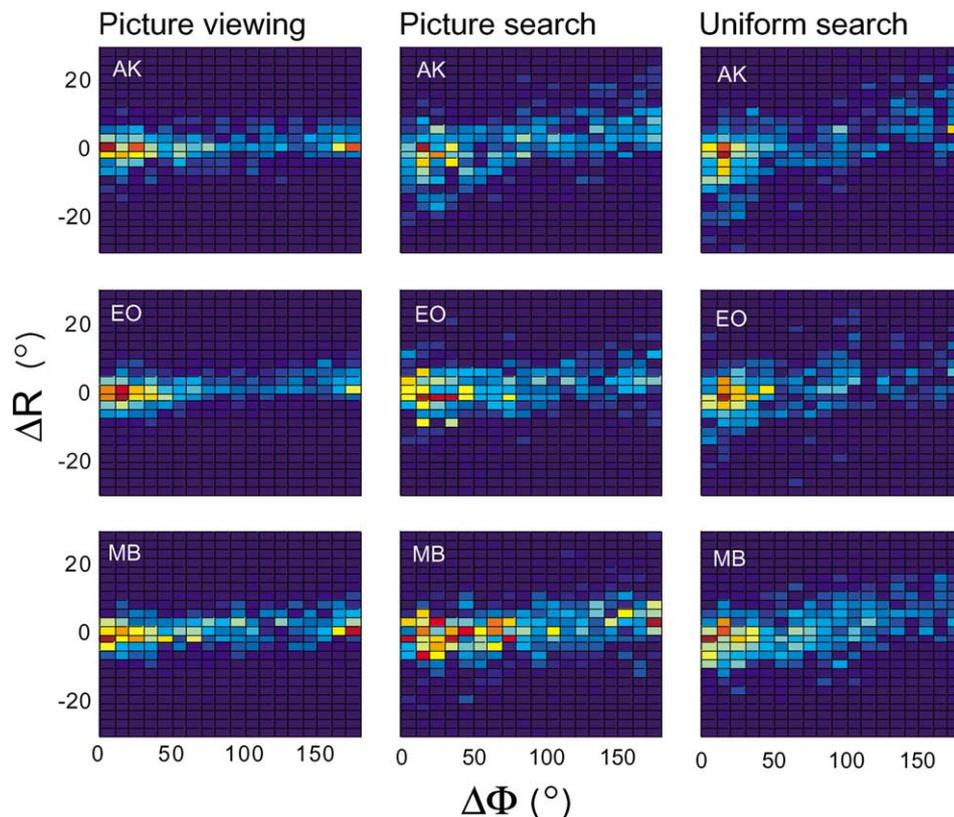

Fig. 2. Normalized $\Delta\phi$–ΔR histogram of three representative observers. $\Delta\phi$ is the angle between two succeeding saccades and ΔR is the difference between their amplitudes. Hot colours (i.e. yellow and red) denote high occurrence frequencies, cold colours (i.e. blue and dark blue) denote lower frequencies. Note the peak at the right of each panel, which contains return saccades.

the stimulus range. The large number of saccades that continue in roughly the same direction (left peak in Fig. 2) may necessitate such returning movements. If return saccades were used to keep the eyes in the stimulus range, one would expect to find many return saccades at the edges of the stimulus. However, this is not the case. Return saccades are made throughout the stimulus range, and not only at the edges (Fig. 3).

Even though we do not find evidence in favor of IOR affecting scan paths in such a way that return saccades are prevented, return fixations last significantly longer than regular fixations in both the PS ($t(8) = 4.96$, $p < 0.001$) and PV condition ($t(8) = 12.09$, $p < 0.001$). Return and regular fixations do not differ significantly in the US condition ($t(8) = 1.58$, $p = 0.076$). The mean IOR effect on fixation duration is comparable with the values reported in the literature (Hooge & Frens, 2000; Klein, 2000; Klein & MacInnes, 1999; Taylor & Klein, 1998). This means that IOR does occur during saccadic

search and picture viewing, and that it affects the fixation times between self-paced saccades during natural tasks like viewing and searching. On the other hand, IOR does not affect scan paths in the sense that return saccades are prevented because the number of return fixations is higher than may be expected on the basis of chance.

On the basis of the above we cannot exclude the possibility that IOR modifies scan-paths in a subtle way and that such a putative effect would then be masked by stronger factors. Therefore, we relate the fraction of return saccades with the strength of the temporal IOR effect in individual subjects and conditions. If the FF-hypothesis holds, we expect a lower fraction of return saccades if the temporal manifestation of IOR is strong (i.e. a large difference in duration of regular and return fixations). Fig. 5 shows the opposite: There is a significant positive correlation ($r = 0.44$, $p = 0.02$) between relative IOR time difference and the fraction of return saccades. This means that with stronger IOR, the fraction of return saccades does not decrease. Again we did not find evidence in favor of the FF-hypothesis.

4. Discussion

Based on the present results we conclude that there is IOR in picture viewing and visual search in stimuli that contain visible objects (local contrasts). This conclusion is based on the observation that return fixations last longer than regular fixations. The effect is robust and independent of task (viewing or searching). However, in search stimuli with a uniform gray background (US condition) we did not find a temporal IOR effect. The main difference between the US and the other two conditions is that stimuli from the US condition do not contain any objects. According to Tipper et al. (1994) IOR has location and object based components. In the US condition we expect only the location based component to be active.

From the analysis of the scan-paths we conclude that at least in serial overt tasks such as saccadic search and picture viewing IOR does not play an important role as a short term spatial memory. In the introduction we state that if IOR acts as a short term memory for fixation location that the effect of IOR should not be looked for in the durations of fixations preceding return saccades but rather in the relative occurrence frequency of return saccades. We do not find evidence for a directional bias away from a previously fixated region. We cannot completely exclude the possibility that IOR modifies scan-paths in a subtle way, but such a putative effect is then masked by stronger factors. However, we think this is unlikely because a strong temporal IOR did not lead to a smaller fraction of return saccades (Fig. 5).
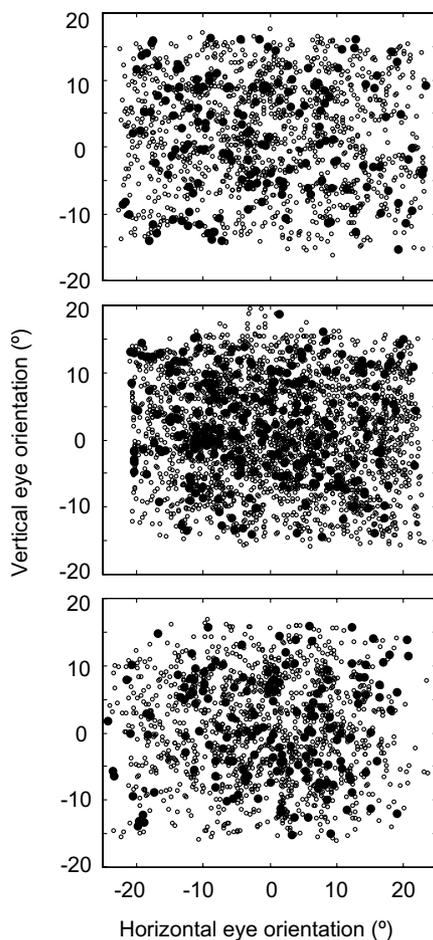

Fig. 3. Examples of spatial distributions of return (fat black circles) and regular fixations (small open circles). This figure shows the onset position of saccades. As one can see, return saccades occur homogeneously throughout the stimulus. Data are from three representative observers during Picture Viewing (PV). All saccade onsets of the PV condition (16 pictures) were superimposed to produce this figure.

How do these findings relate to the literature? Both Klein and MacInnes (1999) and Gilchrist and Harvey (2000) suggest that IOR plays an important role as memory for previously inspected locations. As we stated in the introduction the effect of IOR should be looked in the spatial rather than the temporal domain. Klein and MacInnes (1999) report both temporal and spatial effects. The reported temporal effects of Klein and MacInnes (1999) are in agreement with our data. However, at first glance their report on spatial effect seems to disagree with our results. Klein and MacInnes report a directional bias away from the previous fixation. It should be noted though that Klein and MacInnes report only saccade directions and ignored the amplitudes. Furthermore, they used very broad bins (60°) in their analysis, which is less suitable to detect local phenomena such as IOR. As can bee seen in our Fig. 2, the return saccade peak is narrow. If we had chosen bin widths of 60° (as Klein and MacInnes did), we would not have seen the return saccade peak either, and only the large peak in the opposite direction would show up. Of course we do not know whether the data of Klein and MacInnes also contain a narrow return saccade peak. On the basis of their analysis Klein and MacInnes cannot conclude that there is not a significant number of return saccades.

Gilchrist and Harvey (2000) counted refixations. As mentioned in the introduction a refixation is a fixation on a letter that is revisited after any number of saccades. Gilchrist and Harvey measured distribution of intervals between fixation and refixation. This distribution peaks around 300 ms (their Fig. 4). From this they deduce that direct refixations are prevented by IOR since in their view 300 ms is equivalent to the duration of about two fixations. However we feel that this conclusion is unwarranted. Firstly, the measure used is a very indirect one as no direct refixations were counted. Secondly, the mean fixations reported in this paper are of the order of 200 ms. We expect the return fixation (as in Hooge and Frens (2000), Klein and MacInnes (1999), and the present study) to be at least 50 ms longer. Therefore their peak at around 300 ms may consist of direct and later refixations alike. The gap at shorter intervals may well be caused by extended return fixation durations.

Our results are in agreement with recent results obtained during reading (Rayner, Juhasz, Ashby, & Clifton, 2003). Subjects produce return saccades preceded by extended fixations while reading. Beforehand, Rayner and colleagues did not expect to find IOR effects in reading because low-level effects like inhibition of return may be dominated by linguistic variables. It is also unlikely that IOR has a tagging function in reading.
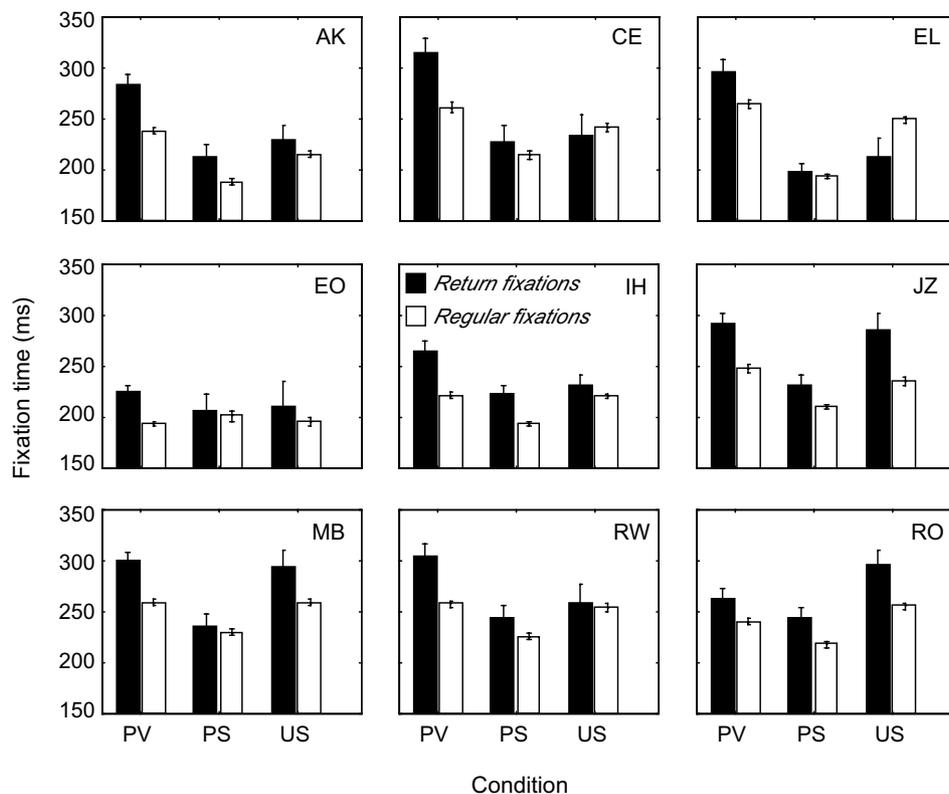

Fig. 4. Durations of return (black bars) and regular (white bars) fixations. A return fixation precedes a saccade that has $|\Delta\phi| > 150°$ and $|\Delta R| < 4°$ with respect to the previous movement. Error bars denote standard error of the mean. Regular fixations are all other fixations. Note that for the majority of the observers and conditions the return fixations have longer durations than regular fixations.
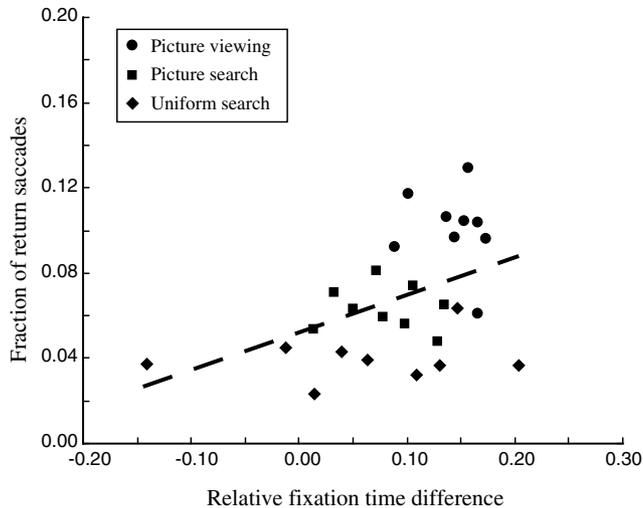
Fig. 5. Fraction of return saccades vs. relative fixation time difference. Fraction of return saccades is the number of return fixations divided by the total number of fixations. Relative fixation time difference is the difference between the return fixation duration and the regular fixation duration of return fixations divided by the regular fixation duration. Relative fixation time difference is an estimator of IOR strength. Each symbol represents a single subject in a certain condition (circle: picture viewing; squares: picture search; diamond: uniform search). These values are positively correlated ($r = 0.44$; $p = 0.02$). Note that this correlation is not critically dependent on the parameters chosen. For instance, using absolute rather than relative time differences, gives qualitatively the same outcome.

An important question remains: Why do observers make so many return saccades? Do they return to a previously fixated location because they forgot that they already inspected this location? We do not think so. They are probably due to other mechanisms that are important during search and viewing (and probably reading). In many cases it may be necessary to make a return saccade. For instance when the previous fixation was too short to allow complete visual analysis (Henderson, 1992; Hooge & Erkelens, 1996, 1998). When saccades are programmed directly using visual information from the immediate stimulus (Rayner & Pollatsek, 1981), one expects fixations to be long enough for the visual system to analyse the fixated part of the stimulus. But there are at least two other causes of saccades during sequences of saccades (e.g. reading, looking around or search).

(1) Saccades may be part of a pre-programmed sequence of saccades (Hooge & Erkelens, 1996; Vaughan, 1982; Zingale & Kowler, 1987).
(2) The origin of the saccades is exogenous (Theeuwes, Kramer, Hahn, Irwin, & Zelinsky, 1999) and has no relation with the immediate visual task. Exogenous saccades are usually found in tasks with abrupt onsets, but a rich visual stimulus may probably evoke these saccades too (Hooge & Erkelens, 1998).

In both cases the fixation may be too short to allow for completed analysis of the fixated object. Pre-programmed and exogenous saccades may interfere with visual and cognitive processes that occur during fixation because these saccades do not have a immediate relation with the task at hand. After such a pre-programmed or exogenous saccade a return saccade may be necessary to continue visual and cognitive processing at the previous fixation location. If IOR would prevent these returning eye movements, reading and search would become quite difficult, because the observer may miss relevant information. To check whether return saccades return to locations that were too briefly fixated before, we measured the durations of fixations preceding these return fixations. Indeed, our data support the idea that return saccades send the eye back to locations that were fixated too briefly. We find slightly shorter first fixations (up to 20 ms shorter, $p < 0.01$) on locations that were immediately re-fixated, suggesting that return saccades were made after fixations that were too short to allow for proper visual and or cognitive analysis.

On the basis of our results we can only speculate on what the role of IOR might be. We suggest that IOR may be a direct consequence of the neural processes that underlie shifts of attention or eye orientation. In this view IOR is an inevitable consequence of reallocating attention or gaze to previously attended locations, in analogy to for instance refractory periods that follow intense neural activity.

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