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The spatial impact of visual distractors on saccade latency

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ABSTRACT

Remote transient changes in the environment, such as the onset of visual distractors, impact on the execution of target directed saccadic eye movements. Studies that have examined the latency of the saccade response have shown conflicting results. When there was an element of target selection, saccade latency increased as the distance between distractor and target increased. In contrast, when target selection is minimized by restricting the target to appear on one axis position, latency has been found to be slowest when the distractor is shown at fixation and reduces as it moves away from this position, rather than from the target. Here we report four experiments examining saccade latency as target and distractor positions are varied. We find support for both a dependence of saccade latency on distractor distance from target and from fixation: saccade latency was longer when distractor is shown close to fixation and even longer still when shown in an opposite location (180°) to the target. We suggest that this is due to inhibitory interactions between the distractor, fixation and the target interfering with fixation disengagement and target selection.

1. Introduction

We move our eyes to gather visual information about our environment (Findlay & Gilchrist, 2003; Land & Tatler, 2009). Changes in the environment at locations away from that of the next saccadic eye movement impact on its execution. If the change, such as the onset of a distracting visual stimulus, is local to the saccade target then it will impact by shifting the trajectory and landing position of the saccade closer to the change (Deubel, Wolf, & Hauske, 1984; Findlay, 1982; He & Kowler, 1989; McSorley, Cruickshank, & Inman, 2009) and speeding up the response time of saccade initiation (McSorley, Cruickshank, & Inman, 2009; Walker et al., 1997). However, if the change is more remote then its impact is largely shown through a slowing of the latency (i.e., the saccadic response time) of the response (Walker, Kentridge, & Findlay, 1995; Walker et al., 1997; Walker & McSorley, 2006), although there is still an impact on the trajectory of the saccade (McSorley, Haggard, & Walker, 2004, 2006, 2009; McSorley, Cruickshank, & Inman, 2009; Walker & McSorley, 2008). While it is clear that as distractors become more remote from the target their influence on saccade landing position and trajectory deviation changes, it is less clear that latency changes as a function of the distance between the target and distractor. Conflicting results have shown either a dependence on target-distractor distance (McSorley, Cruickshank, & Inman, 2009) or a dependence on distractor eccentricity from fixation (Walker et al., 1997). In this paper we will examine possible explanations for this conflict.

1.1. Remote Distractor Effect (RDE)

Walker et al. (1997) examined the spatial impact of distractor onsets on target driven saccades. They showed that their effect on saccade landing position was limited to a window of 20° in extent, centered on the target (known as the Global Effect or Center of Gravity Effect; Deubel, Wolf, & Hauske, 1984; Findlay, 1981; Findlay & Benson, 2006a, 2006b; Glimcher & Sparks, 1993; He & Kowler, 1989; McSorley, Cruickshank, & Inman, 2009; Ottes, van Gisbergen, & Eggermont, 1985; van Opstal & van Gisbergen, 1989; Walker et al., 1997). Outside of this window the distractor interference on saccade programming was shown through a slowing of saccadic response (known as the Remote Distractor Effect (RDE): Bompas & Sumner, 2009; Born & Kerzel, 2008; Griffiths, Whittle, & Buckley, 2006; Honda, 2005; Lévy-Schoen, 1969; Ludwig, Gilchrist, & McSorley, 2005; Walker, Kentridge, & Findlay, 1995; Walker et al., 1997; White, Gegenfurtner, & Kerzel, 2005) with a maximum disruption when a distractor was at fixation in a temporal window of about 100 ms of target onset (Bompas & Sumner, 2009; Buonocore & McIntosh, 2008; Ross & Ross, 1980; Walker, Kentridge, & Findlay, 1995). This effect occurs even when high level components of the task, such as target selection (i.e., searching for the target and selecting it as the next location for a saccade), are minimized by restricting the target to appear in a single hemifield and axis (e.g., on the horizontal meridian to the right of fixation) while the distractor appears on other non-target axes.

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This suggests that it is an automatic effect not subject to voluntary control (Benson, 2008; Walker, Kentridge, & Findlay, 1995; Walker et al., 2000).

1.2. Dependence of RDE on distractor distance from fixation

Walker et al. (1997) found that RDE reduced in line with the ratio of the distance between the target and fixation compared to the distance between the distractor and fixation (see Walker et al., 1997, Fig. 8), i.e., when the target and distractor eccentricities are kept constant and the axis on which they are shown is varied then RDE remained the same despite an increase in distance of the distractor from the target. This suggests that it is the distance of the remote distractor from fixation that determines the latency of the response.

Findlay and Walker (1999) explained RDE in their framework for saccade control. In this they envisaged that "when" a saccade is made is dependent on the competition between a fixate center and a move center. When the activity at fixation is high then a saccade cannot be elicited as this inhibits the move center through reciprocal inhibitory connections. As activity in the move center increases, this inhibits the activity in the fixate center and eventually activity is reduced such that a saccade is elicited. They proposed that RDE is a consequence of distractor presence strengthening the activity at fixation. This leads to increased saccade latency because this elevated fixation-related activity needs to be inhibited in order for activity at the target site to reach a threshold to initiate the saccade.

1.3. Dependence of RDE on distractor distance from target

In contrast to this there have recently been a number of behavioral studies that have found that saccade latency rises as the distractor distance from target increases. These have been mostly concerned with examining the impact of distractors on the trajectory of target driven saccades, (Godijn & Theeuwes, 2002; McSorley, Haggard, & Walker, 2009; McSorley, Cruickshank, & Inman, 2009; see Van der Stigchel (2010) and Walker and McSorley (2008) for recent reviews of the saccade trajectory literature). For example, McSorley, Cruickshank, & Inman, 2009 (see also McSorley, Haggard, & Walker, 2009; McSorley et al., 2004; Van der Stigchel, Meeter, & Theeuwes, 2007) examined saccade control over a large number of distractor distances from the target while distractor distance from fixation was held constant, i.e., target and distractor have the same eccentricity. They found that when the distractor is close to the target, saccade latencies to the target are quicker (in fact quicker than in target alone conditions) and trajectory deviations are toward the distractor. When the distractor is further away from the target, latencies are slower and deviations are progressively away from the distractor location as latency increases. Following Tipper, Howard, and Paul (2001) they posited that target and distractor activity is pooled (Dorris, Olivier, & Munoz, 2007; Godijn & Theeuwes, 2002; Meeter, Van der Stigchel, & Theeuwes, 2010; Trappenberg et al., 2001). When they are close, this pooling results in saccade deviations toward the distractor location and quicker saccade latencies (activity reaches a threshold more quickly). When they are further apart, distractor activity is no longer pooled with, or perhaps actively inhibited by, target activity and this produces saccade deviations away from the distractor location and slower saccade latencies. These results and the underlying explanation run counter to Findlay and Walker's (1999) account of RDE and suggest that the effect of distractors on saccade latency may be the result of direct interaction of distractor and target rather than the distractor impacting on fixation-related activity.

1.4. Search and saccade selection

One clear difference between those experiments explicitly examining RDE and those examining saccade trajectory control is the potential location of the target and distractor. In RDE experiments, the target is restricted to appear on a single axis and the distractor never appears in a potential target location. However in experiments examining saccade trajectory the target can appear in multiple locations and across trials the distractor can appear in target locations. So unlike those papers which we can confidently say have examined RDE, in which target direction was pre-defined (e.g., Walker et al., 1997), an element of higher-level search and selection processes has been reintroduced back into saccade selection that had been minimized by restricting target presentation to a single hemifield.

In line with this explanation, bilateral presentation of targets, in which participants may saccade to either target, has been found to increase saccade latency compared with unilateral presentation (Findlay, 1983; Lévy-Schoen & Blanc-Garin, 1974; Walker, Kentridge, & Findlay, 1995). Furthermore, when a target may appear bilaterally and is accompanied by a distractor (in a large majority of trials), then both overall latency and RDE were also found to increase (Benson, 2008). However, contrary to this, Walker, Kentridge, and Findlay (1995) found no difference in the saccade latencies to bilateral targets when participants were free to choose and when they were instructed to attend and saccade to one side only (thus the non-attended target became the remote distractor). Furthermore, Cruickshank and McSorley (2009), in an experiment examining the impact of remote distractors on accuracy, also found no difference between saccade latencies when targets were restricted to appear on one axis in one hemifield or could appear in either.

Overall then, the evidence that a process of search and saccade selection may promote and engender a direct competition between the target and distracter that is not present in the pure RDE case is mixed. However, it remains the case that while a competition between possible saccade programmes (i.e., the selection of the next saccade) may not result in an increase in saccade latency, it still may explain the rise in RDE as distractor distance from target increases found in the trajectory experiments: when the target is restricted to appear unilaterally a remote distractor increases activity at fixation thereby disrupting disengagement, whereas when the target can appear in multiple locations the remote distractor acts as another potential saccade program and the processes of selection between the target and distractor slows saccade initiation. Of course it is also possible that impairment of fixation disengagement may also occur in the latter case.

1.5. Current study

Here we test this explanation by examining the impact of remote distractors on saccade latency when target presentation is unilateral or bilateral, i.e., whether the latency of a target guided saccade is affected differentially by the presence of a distractor when target direction is uncertain and selection processes are invoked. Target direction was either restricted to one direction (participants only made saccades to the left or right of fixation, not both – Exp. 1a) or unrestricted (participants made saccades to both the left and right – Exp. 1b) while distractors were presented in a large number of "remote" locations, at a range of distances from fixation and the target location similar to those used of Walker et al. (1997, Exp. 3). Given the research outlined previously (Walker et al., 1997) we would expect to see the ratio of distractor distance from fixation and target being the determinant of saccade latency in Exp. 1a. While for Exp. 1b, previous research (e.g., McSorley, Cruickshank, & Inman, 2009) suggests that distractor distance from target may start to play a role not seen when target selection processes are minimized, and saccade latency will increase as the remote distracter distance from the distractor is increased.

2. Experiment 1

2.1. Method

2.1.1. Observers

There were 22 naïve observers, 13 females and nine males, with an age range from 19 to 21. 14 participants took part in Exp. 1a – seven made saccades to the left and seven to the right. One participant from the "right only" condition was dropped due to excessive errors in saccade direction (~50%) that suggested a misunderstanding of the instructions. The remaining eight participants took part in the bilateral target presentation (Exp. 1b). All observers had normal, or corrected to normal, vision. Ethical approval from School of Psychology, University of Reading was obtained for this study and all participants gave their informed consent prior to inclusion.

2.1.2. Apparatus and materials

Stimuli were vertically oriented Gabor patches with a spatial frequency of two (target) or four (remote distractor) cycles per degree (cpd), with a standard deviation of 0.3 deg of visual angle and a contrast of 90% (as used previously in Cruickshank & McSorley, 2009 in examining the interaction between saccade latency and accuracy). These were generated using Matlab (Mathworks Ltd.) and saved as a lossless image format to be called during the experiment. All stimuli were presented on a grey background, with the same mean luminance as the Gabor patches, of 23 cd/m^2. Eye movements were recorded using a head-mounted, video-based, eye-tracker with a sampling rate of 500 Hz (Eyelink II, SR Research). Viewing of the display was binocular and we recorded monocularly from observers' right eyes. Stimuli were presented in greyscale on a 21″ color monitor with a refresh rate of 75 Hz (DiamondPro, Sony) in sequences developed using Experiment Builder (SR Research Ltd.). Synchronization between the display and the eye tracker was controlled through Experiment Builder. Head movements were constrained with a chin-rest, which held participants so their eyes were in-line with the horizontal meridian of the screen, at a viewing distance of 1 m. The eye-tracker was calibrated using a standard 9 point grid, carried out at the beginning of the experiment and after any breaks where the observer removed their head from the rest or removed the eye-tracker. Calibration was only accepted once there was an overall difference of less than 0.5 deg between the initial calibration and a validation retest: in the event of a failure to validate, calibration was repeated.

2.1.3. Design

Target stimuli were presented on the horizontal meridian at near (3 deg from fixation) or far (6 deg from fixation) locations (see Fig. 1). A target stimulus was always present. A distractor, remote from the target could also be present. This appeared in a non-target location 3, 6 or 9 deg of visual angle from fixation and at an angular deviation of 45°, 90°, 135° or 180° from the horizontal meridian on which the target lay (here we use deg to refer to degrees of visual angle and ° to refer to angular degrees or polar angle). The distractor could also appear at the center, replacing the fixation marker. For Exp. 1a this gives two target locations and 22 remote distractor locations, while for Exp. 1b this gives four target locations and 44 distractor locations. Interleaved with these distractor trials a baseline condition was also shown in which

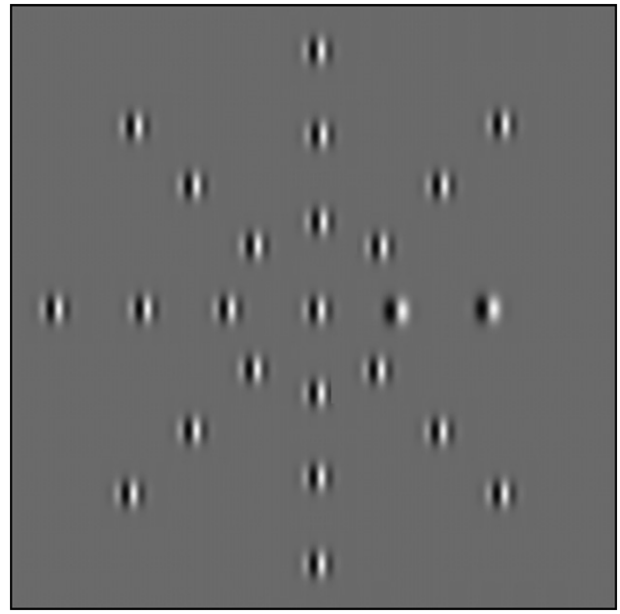

Fig. 1. Possible target and distractor locations for Experiment 1. Target positions are shown as low spatial frequency Gabor patches on the horizontal axis at 3 or 6 deg from fixation. Higher spatial frequency Gabor patches show the potential locations for the remote distractor. On any trial a target would always be present, a single remote distractor could also be present. Target and distractor locations are illustrated for rightward saccades only, the display was flipped across the vertical axis for leftward saccades. In Exp. 1a participants saw only target and distractor positions from one of these while for Exp. 1b positions could be drawn from either the left or right displays.

the target was presented by itself. This allowed a measure of a change in saccade latency to be determined. There were 10 trials per condition: each observer carried out 460 trials for 1a and 920 trials for 1b. All trials were randomly interleaved. Of the 13 observers in Exp. 1a, seven made saccades to targets shown only on the left and six different observers made saccades to targets shown on the right.

2.1.4. Procedure

Observers were shown examples of target and distractor stimuli. Following this, an introductory block of up to 20 trials was presented to familiarize observers to the timing and spatial configuration of the experimental trials. Observers were instructed to move their eyes "as quickly and accurately as possible" to the target Gabor patch, ignoring any distractors. Trials began with a central fixation cross (+) subtending 0.5 deg of visual angle, presented for a varying duration, between 800 and 1300 ms. The fixation cross disappeared at onset of the stimuli, which were displayed for 1s. This was followed by a blank screen, for 500 ms, then the reappearance of the fixation cross for the next trial. Once the observer re-fixated within a 1 deg area centered on the central cross the next trial commenced.

2.1.5. Data analysis

A parser integral to the eye-tracking software, was used to identify saccade start and endpoints using a 22 deg/s velocity and 8000 deg/s^2 acceleration criteria (SR Research Ltd.). Further analysis was undertaken using in-house software developed in Matlab (Mathworks Inc.). Saccade amplitude, latency and overall direction were derived from the eye movement records for the first saccade in each trial. Saccade latency is the interval between the onset of the target and the initiation of the saccade (in ms). Amplitude was defined as the horizontal component of the distance between eye start and end point (in degrees of visual angle). Saccades were excluded from further analysis in this order: saccade amplitude was less than or greater than 3 standard deviations away from the mean for each target distance (Exp. 1a 11%; Exp. 1b 14%); saccade latency was less than 80 ms or greater than 500 ms (deemed anticipatory or not stimulus elicited respectively – Exp. 1a 0.1%; Exp. 1b 0.6%); saccade landing position was outside of a window centered on the target location of 45 angular degrees in extent (Exp. 1a 5%; Exp. 1b none). Data were collapsed across distance of the remote distractor from target location: Those distractors at 45°, 90° and 135° clockwise and counter-clockwise from the target are collapsed. Data were further collapsed across left and right for Exp. 1b. This gives 20 (Exp. 1a) and 40 trials (Exp. 1b) per participant for these conditions and 10 (Exp. 1a) and 20 (Exp. 1b) trials for the center and 180° position.

2.2. Results

Median saccade latencies for Exp. 1a and b are shown in Fig. 2 plotted as function of angular deviation of remote distractor from target position for each target distance separately. Each line shows remote distractor distance from fixation. The dashed lines show the no remote distractor condition as baseline. It can be seen that RDE seems to depend upon distance from fixation and its distance from the target.

We analyzed the data using ANOVA. As the design was naturally not fully factorial (the central remote distractor cannot vary in its axis) two repeated measures ANOVA's were carried out. The first was a three-way ANOVA that examined the impact of the remote distractor on saccade latency when shown centrally, at any other location (all other remote distractor locations) and no remote distractor present. This has experiment (two levels: Exp1a and 1b), target location (two levels: 3 and 6 deg) and remote distractor locations (three levels: not present, central and other) as factors and shows a main effect of remote distractor presence and a significant interaction of this with experiment (remote distractor location: $F(2,38) = 79.6$, $p < 0.01$; interaction: $F(2,38) = 8.08$, $p < 0.01$). Contrasts show that the remote distractor, shown both centrally and in an "other" location, produces a significant increase in saccade latency in both experiments (p's < 0.05).

A second four-way ANOVA examined the "other" remote distractor locations. This has experiment (1a and 1b), target location (3 and 6 deg), remote distractor distance from fixation (3, 6 and 9 deg) and remote distractor axis (45°, 90°, 135° and 180°) and

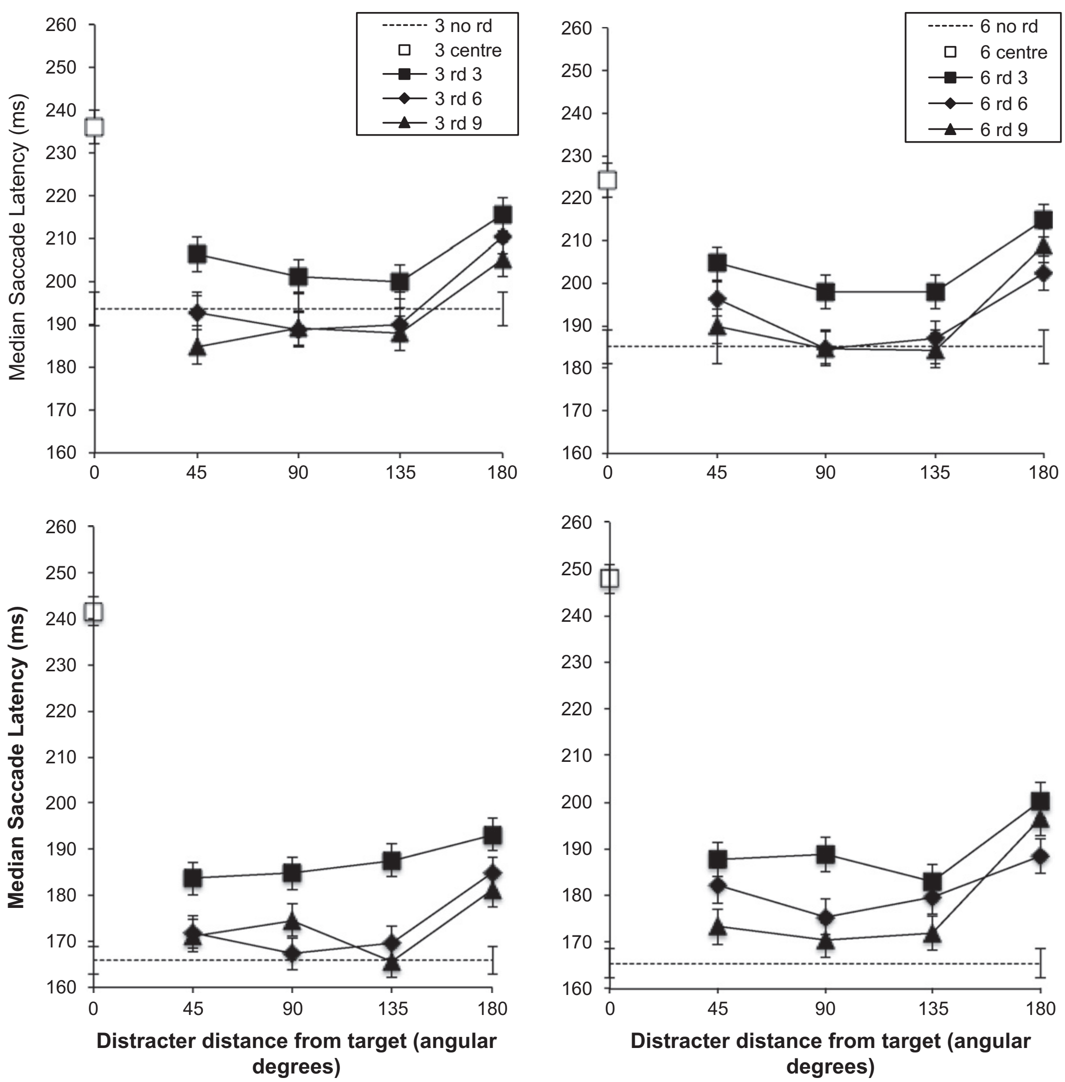

Fig. 2. Saccade latency (ms) is shown as a function of remote distractor distance from target, separately for each distance from fixation (3, 6 and 9 deg). The results from Exp. 1a (unilateral target presentation) are shown in the upper two quadrants and Exp. 1b (bilateral target presentation) in the lower two. The columns are when the target is at 3 deg (rightward column) and 6 deg (leftward). The dashed line indicates saccade latency when no remote distractor was shown. The central remote distractor is shown as a single square data point on the ordinate. A general increase in latency was found in the presence of the remote distractor but this was found to depend on distance from fixation and target. Repeated measures error bars are shown (Loftus & Masson, 1994).

shows a main effect of remote distractor distance from fixation and axis only (remote distractor distance from fixation: $F(2,38) = 30.4$, $p < 0.01$; remote distractor axis: $F(3,57) = 17.3$, $p < 0.01$). To take these in turn, contrasts show that Remote Distractor Effect is largest at 3 deg and drops off as distance from fixation increases (3 vs 6 deg, 3 vs 9 deg, p's < 0.01), whereas there is no difference in the Remote Distractor Effect when the remote distractor is at 6 and 9 deg ($p > 0.05$). This pattern remains as the remote distractor axis changes with a larger Remote Distractor Effect when it is 180° from the target compared with all other remote distractor axes (45° vs 180°, 90° vs 180°, 135° vs 180°, p's < 0.01; all other comparisons p's > 0.05).

2.3. Discussion

Differences found in RDE dependency on distractor position between the traditional RDE (Walker et al., 1997) and saccade trajectory experiments (McSorley, Cruickshank, & Inman, 2009) could be due to the latter experiments involving a saccade selection process. We suggested that the competition between possible saccade programmes (i.e., the selection of the next saccade) may explain the rise in RDE as distractor distance from target increases found in the trajectory experiments (McSorley, Cruickshank, & Inman, 2009): when the target is restricted to appear unilaterally a remote distractor increases activity at fixation thereby disrupting disengagement, whereas when the target can appear in multiple locations the remote distractor acts as another potential saccade program and the processes of selection between the target and distractor slows saccade initiation. We would have expected to see the ratio of distractor distance from fixation and target being the determinant of saccade latency in Exp. 1a, and distractor distance from target being the determinant in Exp. 1b. However we found no differences in the pattern of RDE dependency on distractor position. In both experiments we found that the magnitude of the RDE is dependent upon distractor distance from fixation (Walker et al., 1997) and, to some extent, the distractor distance from the target (McSorley, Cruickshank, & Inman, 2009; McSorley, Haggard, & Walker, 2009) regardless of whether the selection processes were minimized (Exp. 1a) or not (Exp1b) (cf Benson, 2008). RDE was found to increase as the distractor distance from fixation was reduced from 9 to 3 deg to the same extent for all axes (45–180°). This mirrors the results reported by Walker et al. (1997). However, coupled with this, there was an unexpected overall increase in RDE (across all three distances from fixation) when the distractor appears in the opposite location axis (i.e., 180° away) relative to the target. This latter finding is completely unlike previous RDE findings from Walker et al. (1997) and is more akin to the saccade trajectory studies in which a steady rise in RDE magnitude was found as the remote distractor moved further away from the target (McSorley, Cruickshank, & Inman, 2009; McSorley, Haggard, & Walker, 2009). However nothing like a steady rise was found here. The rise in RDE was not present at all at 135° or less, but was very pronounced when in the opposite (180°) location.

2.3.1. Unilateral vs bilateral presentation

The lack of difference in RDE pattern between experiments could be taken to suggest that the task differences (Exp. 1a vs Exp. 1b) did not invoke the desired difference in target selection processes and that in turn led to no differences in the pattern of RDE. In support of this position, there was found to be no increase in overall saccade latency for bilateral target presentation compared with unilateral presentation. This is clearly different from some previous research in which a saccade latency increase was found when target presentation was bilateral or when the target was accompanied by a distractor (Benson, 2008; Findlay, 1983; Lévy-Schoen & Blanc-Garin, 1974). Thus it may be the case that the bilateral target presentation design used in Exp. 1b did not induce target selection processes. This may be due to the fact that the target was restricted to appear only on the horizontal axis. However, counter to this interpretation is that McSorley, Cruickshank, and Inman, (2009) found a distractor to target dependency of RDE magnitude using a target which appeared in only two locations "up" and "down" on a single vertical axis. Alternatively, it may be the case that the task changes between Exp. 1a and Exp. 1b did differ in invoking a target selection processes but that this competition did not manifest itself as a change in the overall saccade latency or in the dependency of the effect on the position of the RD. In support of this are the results reported by Walker, Kentridge, and Findlay (1995) and Cruickshank and McSorley (2009) who also found no differences in bilateral and unilateral target presentation conditions (attentional biasing in the case of Walker, Kentridge, and Findlay (1995)).

2.3.2. Opposed distractor effect

The main finding of interest here, and the one which we will pursue in the remaining set of experiments, is that of RDE increasing suddenly when the distractor is shown opposite the target. The next experiment will address whether the difference between this and the finding of a steady rise, when compared with McSorley and colleagues (McSorley, Cruickshank, & Inman, 2009; McSorley, Haggard, & Walker, 2009), is that the target axis is limited to the horizontal meridian, whereas in McSorley et al. the target could appear on a number of axes. It may be the case that the rise in the RDE for distractors shown opposite the target is restricted to the horizontal axes only and is not a more general "opposed distractor effect". However, it is important to note that it remains the case that this aspect of the results directly contradict those of Walker et al. (1997) in which RDE was found to be the same across all target axes.

To examine the role of the axis of target presentation we ran a reduced version of Experiment 1 with targets in three different locations both on and off the horizontal axis held constant in three separate blocks. Distractors were shown remotely at 90°, clockwise and counter-clockwise, and 180° from target location. If there is something special about the location opposite to the target then changing its location should show a similar rise in saccade latency when the remote distractor is shown 180° from its location. On the other hand if the effect is due to stimuli being shown on the horizontal meridian we should only see this rise in saccade latency when the target and remote distractor are on this axis.

3. Experiment 2

3.1. Method

All methods are as in Exp. 1 with the following exceptions.

3.1.1. Observers

Eight new and naïve observers, six female and two male with an age range from 19 to 21 were recruited. All observers had normal, or corrected to normal, vision. Ethical approval from School of Psychology, University of Reading was obtained for this study and all participants gave their informed consent prior to inclusion.

3.1.2. Design

There were three possible target locations (horizontal meridian (0°), and 45° and 135° from this) all at 6 deg of visual angle from fixation (see Fig. 3). These locations were blocked such that observers responded to only a single target location for a series of trials before moving on the next block. These blocks were counterbalanced across observers using a Latin square design. A target stim-

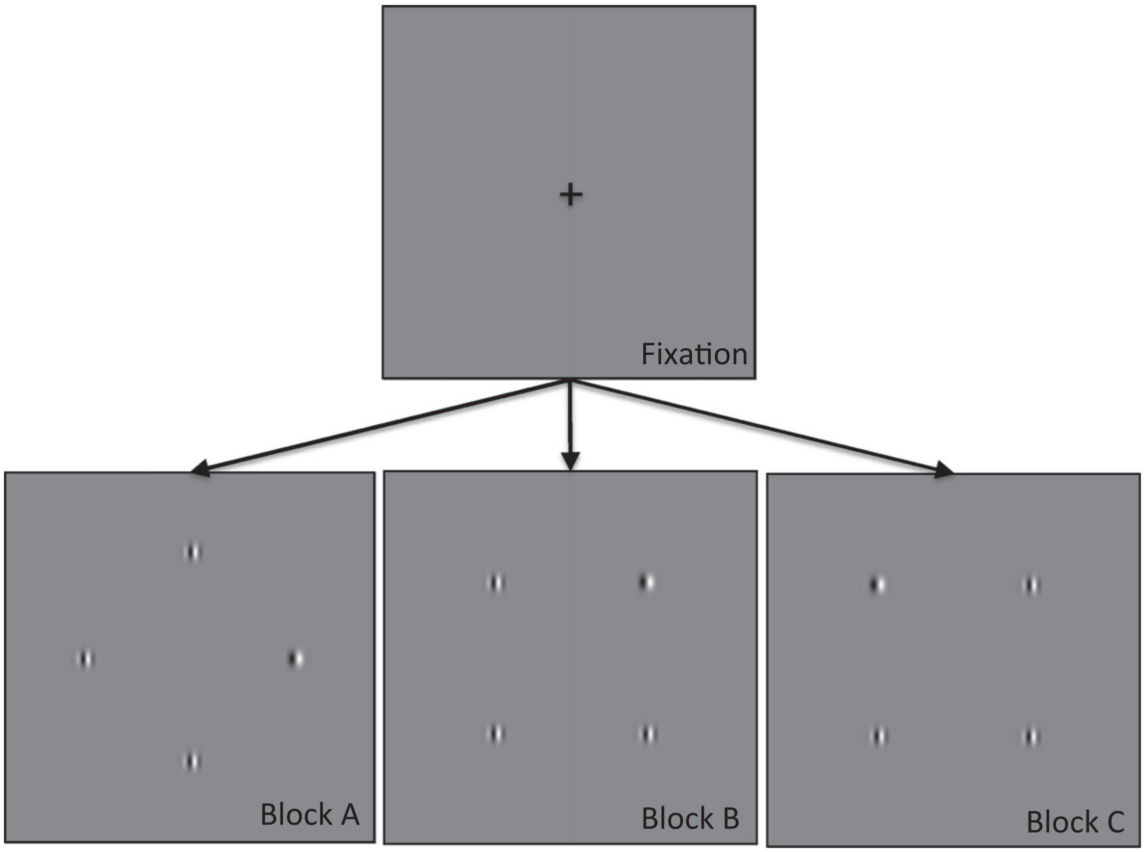

Fig. 3. Target and distractor locations for Experiment 2. Possible target positions are shown as low spatial frequency Gabor patches 6 deg from fixation on the horizontal 0° (Block A), 45° (Block B) or 135° (Block C). Higher spatial frequency Gabor patches show the potential locations for the remote distractor. On any trial a target would always be present, a single remote distractor could also be present. The upper display shows fixation. The three lower boxes represent three displays which were blocked and counterbalanced, i.e., observers saccaded to a target in a single location for a block before moving on to the next.

ulus was always present. A distractor, remote from the target, could also be present. This appeared in a non-target location 6 deg of visual angle from fixation and either 90°, clockwise or counter-clockwise, or 180° from target location. This gives three target locations and three remote distractor locations. Within each block a baseline condition was also shown in which the target was presented by itself. These were randomly interleaved with the other trials in which the distractor was present. This allowed a measure of a change in saccade latency to be determined. There were 20 trials per condition: each observer carried out 200 trials per block.

3.1.3. Data analysis

Data were collapsed across distance of the remote distractor from target location. Those distractors at 90° clockwise and counter-clockwise from the target are collapsed. This gives 40 trials for the 90° condition and 20 trials for the 180° position. Saccades were excluded from further analysis if saccade amplitude was greater or less than three standard deviations from the mean (4%); saccade latency was less than 80 ms or greater than 500 ms (deemed anticipatory or not stimulus elicited respectively – 0.4%); or saccade landing position was outside of a window centered on the target location which was 2 deg of visual angle in width and 45 angular degrees in extent (none).

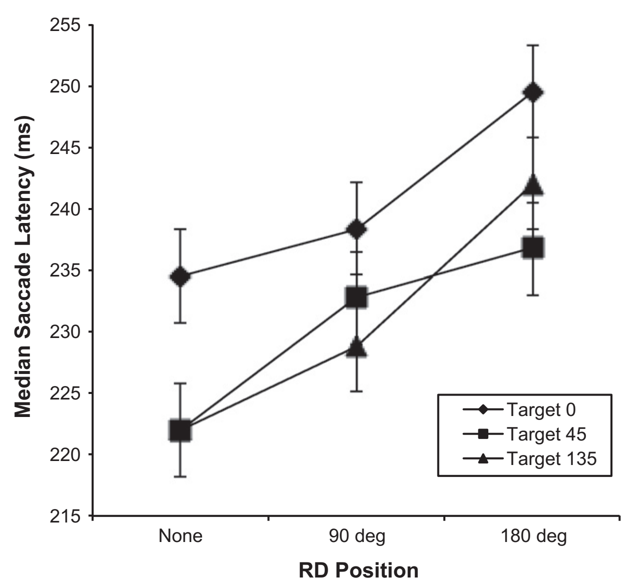

Fig. 4. Saccade latencies are shown by angular deviation of remote distractor from target position for each target distance separately. Repeated measures error bars are shown (Loftus & Masson, 1994).

3.2. Results

Saccade latencies are shown in Fig. 4 by angular deviation of remote distractor from target position for each target distance separately. Note that the three baseline no remote distractor conditions are plotted as symbols rather than reference lines (as used in Fig. 2) to aid clarity of the data. The data show a similar increase in saccade latency as remote distractor distance from the target increase across all target locations. A two-way ANOVA with target axis (0°; 45° and 135°) and remote distractor position (none; 90° and 180° from target) as factors shows a main effect of remote distractor position only ($F(2,16) = 13.6$, $p < 0.01$; others $F < 1$). Contrasts show a significant slowing of saccade latency when remote distractor was 180° from the target, compared with the remote distractor at 90° ($p < 0.01$) regardless of target position.

3.3. Discussion

The results show that saccade latencies rise when the remote distractor is shown in the diametrically opposed location to the target regardless of its axis. Thus the dependency of the magnitude of RDE on its spatial relationship with the target is not limited to or a function of any primacy of the horizontal meridian suggesting a more general "opposed distractor effect" which extends across all visual axes.

A further possible explanation for the rise in RDE at positions opposite the target comes from reports of experiments in which the effect of the history of previous saccade directions on the latency of the next saccade has been examined (Anderson, Yadav, & Carpenter, 2008; Fecteau & Munoz, 2003; Fecteau et al., 2004). They have shown (in humans) that when a saccade is made in the same direction as the previous one then its latency is reduced both in comparison to those made in the opposite direction and the average latency. This has been suggested to be due to an increase in the activity at the location coding for the similar movement. Therefore in terms of the experiments presented here, the activity at 180° from the target may be elevated due to the saccade made back to fixation following the target directed saccade which leads to an increase in RDE at these locations. Thus activity at those locations is elevated relative to other possible distractor locations. Because of this the impact of the remote distractor fixation disengagement would be greater leading to longer saccade latencies. This elevation in activation at opposite locations may be a function of the direction of "return to fixation" saccades from previous trials. Exp. 3 examines this explanation. Saccades are made to one of two potential targets off-axis. Distractors are presented in a number of locations relative to the target. Trials can be classified as having a remote distractor in a position along the same axis as the return saccade of the previous trial or not. If this explanation is correct we would expect to see distractors eliciting a larger RDE when they are in the same direction as the return saccade on the previous trial regardless of whether they are opposite the target on the current trial or not.

4. Experiment 3

4.1. Method

All methods are as in Exp. 1 with the following exceptions.

4.1.1. Observers

Eight new and naïve observers, four female and four male with an age range from 19 to 21 were recruited. All observers had normal, or corrected to normal, vision. Ethical approval from School of Psychology, University of Reading was obtained for this study and all participants gave their informed consent prior to inclusion.

4.1.2. Design

There were two possible target locations (45° above and below the horizontal meridian) 6 deg of visual angle from fixation (see Fig. 5). A distractor, remote from the target, could also be present. This appeared in a non-target location 6 deg of visual angle from fixation and, running counter-clockwise, 90°, 120°, 150°, 180° and 210° (note this is equivalent to 150° running clockwise from the target, these conditions were collapsed in the analysis of the saccade data) from target location. This gives two target locations and five remote distractor locations. Two baseline conditions (one for each target location) were also shown in which the target was presented by itself these were randomly interleaved with the other trials in which the distractor was present. This allowed a measure of a change in saccade latency to be determined. There were 20 trials per condition: each observer carried out 240 trials. Four observers responded to targets appearing on the right hand side of the display and four responded to targets on the left.

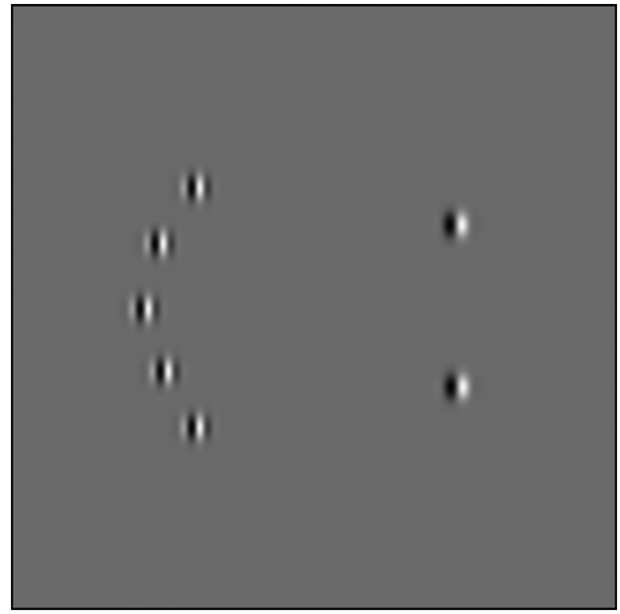

Fig. 5. Possible target and distractor locations for Exp. 3. Target positions are shown as low spatial frequency Gabor patches on the horizontal axis at 6 deg from fixation. Higher spatial frequency Gabor patches show the potential locations for the remote distractor (90°, 120°, 150°, 180° and 210° from the target location). On any trial a target would always be present, a single remote distractor could also be present. Target and distractor locations are illustrated for rightward saccades only, the display was flipped across the vertical axis for leftward saccades.

4.1.3. Data analysis

Data were collapsed across distance of the remote distractor from target location. Those distractors at 150° clockwise and counter-clockwise from the target are collapsed. This gives 40 trials for the 150° condition and 20 trials for all other conditions per observer. Saccades were excluded from further analysis if saccade amplitude was three standard deviations away from the mean (16%) saccade latency was less than 80 ms or greater than 500 ms (deemed anticipatory or not stimulus elicited respectively – 3%); or saccade landing position was outside of a window centered on the target location 45 angular degrees in extent (1%).

In order to examine whether the direction of the return saccade could account for the rise in RDE at the opposite location shown in Exps. 1 and 2, the trials were classified as having a distractor in the "same" direction to the return saccade direction on the previous trial (rather than opposite the target location on the current trial) or simply classified as "other".

4.2. Results

Saccade latencies are shown in Fig. 6 (left) by angular deviation of remote distractor from target position as symbols. The reference saccade latency found when the target was presented alone is

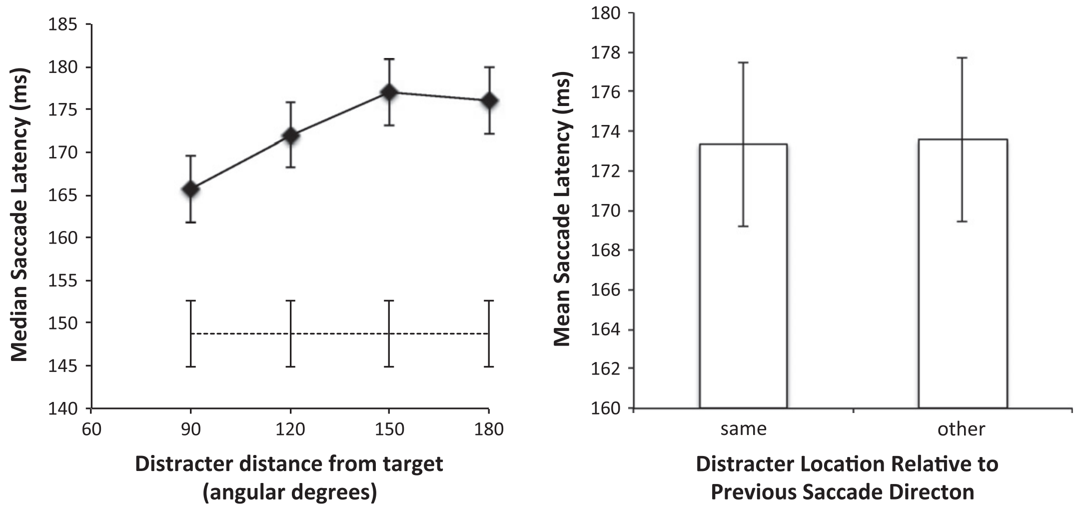

Fig. 6. (Left) Saccade latency shown as a function of remote distractor distance from target in angular degrees (symbols). The dotted line shows the baseline saccade latency found when the target was shown in isolation. (Right) Saccade latency shown as a function of the target position on the previous trial relative to the distractor location on the current trial. Same refers to when the return saccade on the previous trial and the distractor on the current trial are in the same direction. In this case, the direction of the return saccade on the previous trial is hypothesized to increase activation at the remote distractor site on the current trial thereby increasing its effect on saccade latency. Other refers to all other trial types. Error bars are repeated measures error bars (Loftus & Masson, 1994).

shown as a dotted line for comparison. The data show a general increase in latency when a distractor is present and this effect increased as the distractor distance from the target increased. A 1-way ANOVA with remote distractor position (none; 90°, 120°, 150°, 180° from target) as factor shows a main effect ($F(4,28) = 10.0$, $p < 0.01$). Contrasts show a significant slowing of saccade latency when remote distractor is present (all p's < 0.01). Linear trend shows significant linear component ($F(1,7) = 30.9$, $p < 0.01$) reflecting the steady rise in saccade latency as distractor moves away from the target. Coupled with this there was a significant quadratic component ($F(1,7) = 7.78$, $p < 0.05$). These results suggest a rise then saturation in the effect of the remote distractor rather than a sharp increase for the distractor at the opposite location to the target as shown in Exps. 1 and 2.

Fig. 6 (right) shows trials that were recoded to reflect the direction of the return saccade of the previous trial. Here "same" refers to when the remote distractor on the current trial lies in the same direction as the return saccade from the previous trial regardless of its location relative to the target in the current trial. "Other" in Fig. 6 (right) refers to all other trial types. It can be seen that there is very little difference in saccade latency depending upon trial type: regardless of the direction of the return saccade the saccade latency is the same ($t(7) = .06$, $p > 0.05$). This shows that the idea of the return saccade increasing activation and thereby priming a saccade in the same direction cannot account for the results reported here or those from Exps. 1 and 2.

4.3. Discussion

Unlike the results from Exps. 1 and 2, the results from Exp. 3 show an increase in saccade latencies, not only when the distractor is in a location diametrically opposed to the target, but more generally when the distractor is contralateral to the target, both 150° and 180° from the target. This evidence does not support the suggestion that the increased Remote Distractor Effect at diametrically opposed locations to the target position may be due heightened activity at those locations because they follow in the same direction as the saccade immediately preceding the target driven saccade (the return to fixation saccade).

The gradual rise as opposed to sharp increase in latency as the distractor approaches opposite location is more akin to those effects found in experiments examining saccade trajectory (McSorley, Cruickshank, & Inman, 2009). In Exp. 1, we find no rise at 135° but do show one here at 150°. This suggests that the latency of the saccade may be more strongly influenced by distractors shown from 180° to 150° from the target axis (Exp. 3) than those at 135° (Exp. 1) or less (120° and 90°, Exp. 3) suggesting a spatial scale to the Opposed Distractor Effect. On the other hand, it may simply be due to changes in the design of the experiment, such as the fact that the targets here were no longer on the same axis whereas they were shown along the horizontal axis in Exp. 1. In order to examine these potential explanations a version of Exp. 3 was carried out but with distractors only at 90°, 135° and 180° from the target. If the remote distractor has no influence at 135° as with Exp. 1 then we should see no impact on the extent of RDE at 90° and 135° but a large increase at 180° mirroring the results of Exp. 1.

5. Experiment 4

5.1. Method

All methods are as in Exp. 3 with the following exceptions.

5.1.1. Observers

Eight new and naïve observers, six female and two male with an age range from 18 to 21 were recruited. All observers had normal, or corrected to normal, vision. Ethical approval from School of Psychology, University of Reading was obtained for this study and all participants gave their informed consent prior to inclusion.

5.1.2. Design

There were two possible target locations (45° above and below the horizontal meridian) 6 deg of visual angle from fixation. A distractor, remote from the target, could also be present. This appeared in a non-target location 6 deg of visual angle from fixation and, running counter-clockwise, 90°, 135° and 180° from target location. This gives two target locations and three remote distractor locations. Two baseline conditions were also shown (one for each target location) in which the target was presented by itself these were randomly interleaved with the other trials in which the distractor was present. This allowed a measure of a change in saccade latency to be determined. There were 20 trials per condition: each observer carried out 160 trials. Four observers responded to targets appearing on the right hand side of the display and four responded to targets on the left.

5.2. Results

Fig. 7 (left) shows saccade latency as a function of remote distractor distance from the target axis in angular degrees in symbols. The dotted line shows the saccade latency when the target was shown alone. Unlike Exp. 3 but in line with the results from Exp. 1, the presence of the remote distractor increased saccade latencies compared with no remote distractor but the extent of this does not differ between 90° and 135°. There was however an increase in the magnitude of RDE when the distractor is shown in the opposite location, 180° away from the target. A one-way ANOVA with Remote Distractor as a factor (four levels: none, 90°, 135° and 180°) shows a significant difference between distractor condition ($F(3,21) = 21.681$, $p < 0.01$). Contrasts show a significant slowing of saccade latency when a remote distractor was present ($F(1,7) = 99.183$, $p < 0.001$) and in turn the RDE was greater when the distractor was shown 180° from the target (180° vs 90°: $t(7) = -3.368$, $p < 0.01$; 180° vs 135°: $t(7) = -4.511$, $p < 0.01$).

As a further examination of the return saccade idea explored in Exp. 3 we again classified saccades as being "same" or "other", i.e., was distractor on the current trial in the same direction as the return to fixation saccade on the previous trial or not (Fig. 7 (right)). Again the direction of the return saccade made to fixation on the previous trial was found not to influence the saccade latency on the current trial ($t(7) = .611$, $p > 0.05$).

5.3. Discussion

The results suggest a spatial scale to the Opposed Distractor Effect: a RDE will occur when the distractor is shown outside a window about 20° to 30° centered on the target location (Walker et al., 1997; Exps. 1–4) but the magnitude of this effect will be stronger when the distractor is close to the direction opposite the target location (180° from the target and at least 150° away, but not as far as 135°).

6. General discussion

A distractor shown at remote locations from a saccade target has been found to slow the response latency of the saccade (Bompas & Sumner, 2009; Born & Kerzel, 2008; Griffiths et al., 2006; Honda, 2005; Ludwig, Gilchrist, & McSorley, 2005; Lévy-Schoen, 1969; Walker, Kentridge, & Findlay, 1995; Walker et al., 1997; White, Gegenfurtner, & Kerzel, 2005). In conflicting reports the magnitude of this has been shown to depend upon distractor distance from fixation (more specifically the ratio of distractor and target distance from fixation; Walker et al., 1997), or distractor distance from target (McSorley, Cruickshank, & Inman, 2009; McSorley, Haggard, & Walker, 2009). These have been interpreted as distractor interference in fixation disengagement (Findlay & Walker, 1999; Walker et al., 1997), or a more direct distractor interference on target selection processes respectively (Godijn & Theeuwes, 2002). In order to examine this different explanation for the Remote Distractor Effect we directly pitted one explanation against another in a series of carefully controlled experiments. Exps. 1a and 1b showed, as Walker et al. (1997) reported, that the magnitude of RDE depends upon distance of RD from fixation across all axes. RDE decreased monotonically as distractor distance from fixation increased and the magnitude of this did not vary as the axis on which the distractor was shown increased its separation from the target, i.e., the relative change in saccade latency induced by a distractor at 3 deg and one at 6 or 9 deg was the same (~15 ms on each distractor axis). This is in line with the findings from Walker et al. (1997).

However, unlike Walker et al. (1997) and more akin to McSorley, Cruickshank, and Inman (2009) and McSorley, Haggard, and Walker (2009) we found a large rise in the RDE across all distractor distances from fixation (3, 6 and 9 deg from fixation) when they are shown on the opposite axis to the target, i.e., 180° away. Exp. 2 showed that this latter effect was not restricted to the horizontal axis: Targets shown on three different axes (0°, 45° and 135°) showed the same rise in RDE when distractor and target were opposed compared with 90° away.

One possible explanation for this finding was that saccades made in the same direction as previous ones are quicker than those made in the opposite direction (Anderson, Yadav, & Carpenter,

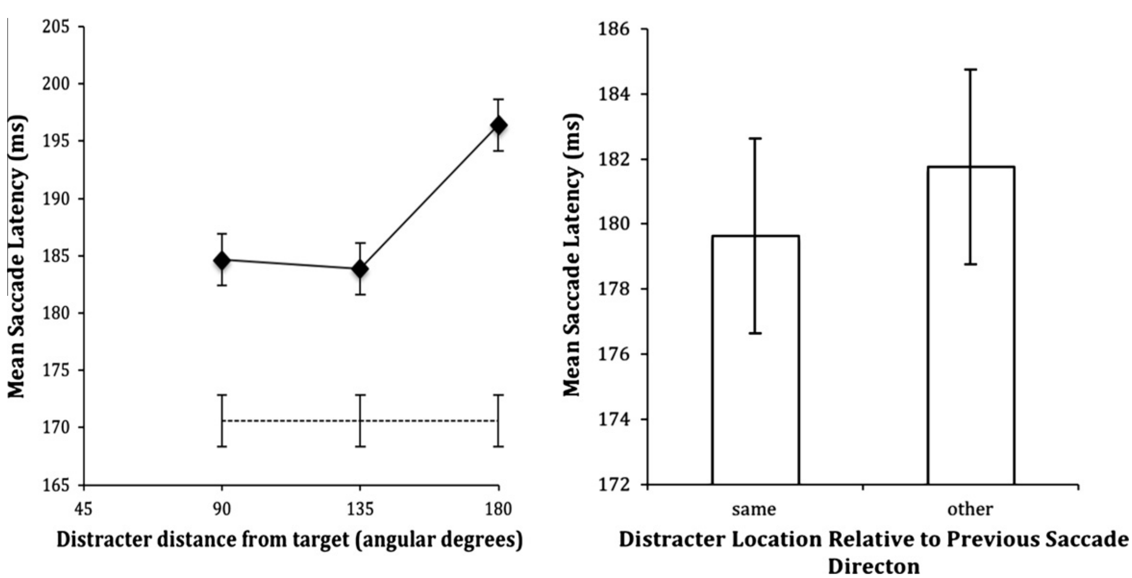

Fig. 7. (Left) Saccade latency shown as a function of remote distractor distance from target in angular degrees (symbols). The dotted line shows the baseline saccade latency found when the target was shown in isolation. (Right) Saccade latency shown as a function of the target position on the previous trial relative to the distractor location on the current trial. Same refers to when the return to fixation saccade and the distractor on the current trial are in same direction. In this case, the direction of the return saccade on the previous trial is hypothesized to increase activation at the remote distractor site on the current trial. Other refers to all other trial types. Error bars are repeated measures error bars (Loftus & Masson, 1994).

2008; Fecteau & Munoz, 2003; Fecteau et al., 2004). In Exp. 3, we examined this and hypothesized that the opposed target effect may be due to saccades being primed in the same direction as the return to fixation saccade on the previous trial. This priming may be the result of an increase in activation for saccades made in the same general direction as the previous saccade. This predicts that the rise in RDE previously found at opposed distractor locations would also be found at both opposed and non-opposed locations if they were in the same direction as the return saccade on the previous trial. However, the results from Exp. 3 (and those of Exp. 4) show that this was not the case. In both experiments trials were classified on the basis of the direction of the return to fixation saccade in the previous trial as being same or other but no difference in the RDE magnitude were found.

While showing no effect of return saccade direction, Exps. 3 and 4 did reveal the spatial scale of the Opposed Distractor Effect. In Exp. 3, the magnitude of RDE was found to increase when the distractor was shown at least 150° from the target. Less than this separation and the RDE is still present but to a smaller degree, as shown by the presence of a RDE when the distractor is shown 135° (Exps. 1 and 4) from the target but of smaller magnitude than when shown 150° or 180° from the target (Exp. 3).

6.1. Fixation disengagement and saccade selection

The results show that the presence of a distractor remote from a target location slows the latency of the target driven saccade and that the magnitude of this slowing was found here to be dependent both on distractor distance from fixation (Exp. 1) and distractor distance from the target (Exp.'s 1 through 4). This reflects both the, seemingly conflicting, results of Walker et al. (1997) and those reported by McSorley, Cruickshank, and Inman (2009) and McSorley, Haggard, and Walker (2009) and seems to suggest that time taken to select the target of the next saccade is affected by distractor distance from both the current fixation location and from the target. In terms of RDE explanations outlined in the introduction, the dependence of the magnitude of RDE on the distractor distance from fixation suggests that the distractor interferes with the initiation of a saccade through impeding fixation disengagement more strongly when the RD is close to fixation on any axis (Findlay & Walker, 1999). In tandem with this, the finding of a dependence of distractor distance from the target on RDE suggests that the distractor interferes with target selection processes (Dorris, Olivier, & Munoz, 2007; Godijn & Theeuwes, 2002; Meeter, Van der Stigchel, & Theeuwes, 2010; Trappenberg et al., 2001) and it does this only as the distractor approaches the opposite location to the target.

6.2. Neurophysiology

Studies of the neural basis of target selection and saccade generation have suggested that the neurons coding potential targets compete as the sensory evidence which supports their location changes or accumulates over time (Glimcher, 2003; Gold & Shadlen, 2007; Schall, 2003; Smith & Ratcliff, 2004). There are a number of models which attempt to account for this that, although differing in their precise details, all suggest that evidence supporting target selection is integrated over time until some threshold is exceeded (Carpenter, Reddi, & Anderson, 2009; Kopecz, 1995; Meeter, Van der Stigchel, & Theeuwes, 2010; Purcell et al., 2010; Ratcliff et al., 2006; Smith & Ratcliff, 2004; Trappenberg et al., 2001). When there are a number of potential targets present these compete through mutually inhibitory connections and race toward that threshold. These models have been very successful at accounting for some aspects of the latency of saccadic responses and, more recently, in accounting for saccade landing position and trajectory deviations (Arai & Keller, 2005; Godijn & Theeuwes, 2002; Kopecz, 1995; Meeter, Van der Stigchel, & Theeuwes, 2010; Trappenberg et al., 2001; Walton, Sparks, & Gandhi, 2005). However, while some of these models (e.g. Meeter, Van der Stigchel, & Theeuwes, 2010; Trappenberg et al., 2001) show that a close distracter impacts on landing position while not affecting latency (Walker et al., 1997) and that as the distracter becomes more remote saccade latency increases, they do not account for the changes found in saccade latency found here (or those reported by Walker et al. (1997)) when the RD position is varied, i.e., the dependence of RDE on distance from fixation.

Findlay and Walker (1999) originally suggested that RDE was due to an extended fixation zone in which peripheral visual events, out to 10 deg from fixation, such as the onset of distractors, maintained activation at fixation for longer. This was based upon neurophysiological work by Munoz and Wurtz (1993, 1995a, 1995b) in which some neurons in caudal SC were classified as being fixation-related and forming a "fixation zone" (albeit a much smaller one than that suggested by Findlay and Walker (1999)). Here activity was suggested to maintain fixation and inhibit saccade related neurons in more rostral areas of SC. Thus the presence of the remote distractor was suggested to interact with this process perhaps by maintaining the activation at fixation for longer than would normally be expected. Under such a conception it was suggested that the interference in fixation disengagement decreases as the distractor moves further away from fixation.

More recent neurophysiological findings, however, show little support for this and instead it is generally becoming more accepted that neurons clustered rostrally in SC are actually coding for small amplitude saccades and fixation is maintained through a balance of activity around fixation (Gandhi & Katani, 2011; Hafed, Goffart, & Krauzlis, 2009). This suggests that distractor effects are all due to the interaction between saccade related neurons, e.g., those maintaining fixation and those coding for the distractor and the target, rather than the outcome of an interaction between saccade related and fixation-related neurons (e.g., Dorris, Olivier, & Munoz, 2007; Gandhi & Katani, 2011; Hafed, Goffart, & Krauzlis, 2009; McPeek, Han, & Keller, 2003). Behaviorally this fits well with distractor effects on landing position and trajectory deviations in which it has been suggested that potential saccade targets (or distractors) compete through a direct interactions on SC (Arai & Keller, 2005; Gandhi & Katani, 2011; McPeek, 2006; McSorley, Cruickshank, & Inman, 2009; Port & Wurtz, 2003; Van der Stigchel, 2010; Walton, Sparks, & Gandhi, 2005; although see White, Theeuwes, & Munoz, 2012) with the involvement of other oculomotor structures (such as FEF and cerebellum). On the other hand it is more difficult to explain RDE by these interactions. A relevant recent study examining the impact of RD's on target driven saccades was carried out by Dorris, Olivier, and Munoz (2007) in which they showed that a distractor activates a separate population of saccade related neurons and that this interacts directly with those neurons coding for target location: exciting target activation when close and inhibiting when farther away. Therefore one possible neural explanation for the RDE is that as the distractor is shown further away from the target its neuronal activity no longer pools with that coding target activity and indeed actively inhibits it thereby causing a slowing as the distractor and target separation increases (it should be noted however that Dorris, Olivier, and Munoz (2007), while showing that inhibition of the target increased when the distractor was remote from its location, did not find a RDE in their study).

Extending this finding to the findings here then: we suggest that RDE may be a function of neurons coding for the distractor interfering both with those coding for the small saccades involved in maintaining fixation and those coding for the target. Thus when the distractor is close to fixation its underlying neural activation pools with those neurons coding for small saccades serving to maintain fixation for longer. As it moves away from fixation this influence diminishes. With regard to the increase in RDE for distractors at large angular deviations from the target, this may be due to distractor activation inhibiting target activation at greater separations, in line with the findings of Dorris, Olivier, and Munoz (2007, albeit over a larger distance). While we have framed this discussion of RDE in terms of findings in SC we acknowledge that the interaction of target and distractors will involve other brain areas that are known to be involved in target selection and saccade control such as FEF and Posterior Parietal Areas.

6.3. Conclusion

In conclusion, the behavioral impact of distractors on the saccade latencies is both dependent on its distance from fixation and from the target:

(I) A distractor at or near fixation increases saccade latency dramatically (~40–50 + ms) (Walker et al., 1997).
(II) A distractor near the target (<30°) decreases saccade latency (McSorley, Cruickshank, & Inman, 2009), results in saccades landing in between the target and distractor (global effect, e.g., Findlay, 1982; Ottes, van Gisbergen, & Eggermont, 1985) and saccade trajectories deviating toward the distractor (McSorley, Cruickshank, & Inman, 2009).
(III) A more remote distractor from the target (>30° and <150°) increases saccade latency by ~15 ms when close to fixation and less as it moves away from fixation. We suggest that the distractor interferes with fixation disengagement. Distractors show no impact on landing position but still impact on saccade trajectory: more strongly when close to the target and less so by 135° away (McSorley, Cruickshank, & Inman, 2009; McSorley, Haggard, & Walker, 2004).
(IV) A very remote distractor from the target (⩾150°) increases saccade latency by ~25 ms when close to fixation and less so as it moves from fixation. We suggest that the distractor still interferes with fixation disengagement as in (iii) to explain a similar drop in RDE as it gets further from fixation as when shown between 30° and 150°. Coupled with this, to explain the overall rise in RDE, we suggest that there is interference in saccade selection only when the distractor is broadly opposite the target location giving an Opposed Distractor Effect.

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