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Eye scanning of multi-element displays: II. Saccade planning

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Abstract

The properties of saccadic eye movements were studied in a task that required observers to scan through a display consisting of a set of discrete objects. The saccades forming the scanpath showed very high accuracy with almost no undershoot provided no distractor item was located within a critical region around the saccade target. When a distractor item was located in the critical region, saccade accuracy was impaired. This result suggests that the intrinsic spatial selection process for saccadic scanning movements is of low resolution. The initial saccade following display onset showed different properties. The instructions required the observer to look first at a clearly distinct target at the top left of the display. However, the first saccade frequently showed 'oculomotor capture' and was directed either to a different item in the display, or to a midway location between items. The fixation following such erroneous first saccades was generally very short and showed a substantial drift towards the instructed location.

Keywords: Amplitude; Human; Oculomotor; Saccade; Search

1. Introduction

This paper examines in detail the accuracy of saccades made while scanning a display containing a small number of near-identical items. The ability to select a saccade target in the presence of distractors provides important information about how attentional processes can affect the saccadic response. In the previous paper (Findlay and Brown, 2005, to be referred to as FB1) we reported results from a task which required an observer to carry out an eye scan to look at every item in a small (3–12) set of similar items. Our emphasis in that paper centred on the choice of scanning route through the items and particularly the sequence of item selection. In this paper, we focus on the properties of the individual saccadic movements in the scanpath.

Much early research on saccade programming studied the saccadic orienting response to the appearance of a single small target in the visual periphery. In this situation, reviewed by Becker (1989), the magnitude of the orienting saccade shows a variability of between 5% and 10% of the target eccentricity. The saccade generally undershoots the target with a secondary corrective saccade bringing the point of fixation on to the target although under some circumstances, the undershoot can be reduced or even eliminated (Kapoula & Robinson, 1986; Kowler & Blaser, 1995). The possibility that saccades elicited by newly appearing targets might show different properties to those made to targets already visible was raised by Lemij and Collewijn (1989). Lemij and Collewijn showed that saccades made to a pre-existing visible target were less variable and showed less undershoot than orienting saccades to a newly appearing target. In situations where a small number of isolated targets are presented with a requirement to scan these in a predetermined sequence, high accuracy (mean error 4% of saccade size) has been reported (Kowler & Blaser, 1995; Vishwanath & Kowler, 2003). However, such accuracy may not be characteristic of tasks where the scanning

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sequence is less predetermined and targets must be selected in the presence of nearby distractors.

A consideration that comes into play when targets and distractors occur together is the 'global effect' of saccadic averaging. If two stimuli appear together in neighbouring positions, their stimulation interacts and the eye becomes directed towards the centre of gravity of the pair (Findlay, 1982; Ottes, Van Gisbergen, & Eggermont, 1984). Studies of saccades to larger extended targets and target clusters show that the centre of gravity effect is very prevalent (McGowan, Kowler, Sharma, & Chubb, 1998). This means that when a target is paired with a distractor, the accuracy of saccades to the target is impaired (Walker, Deubel, Schneider, & Findlay, 1997), although it has also been argued that the global effect can serve a positive function when orienting to visual objects by providing a precise representation of a central reference position for extended shapes (Vishwanath & Kowler, 2003).

In the first report of the centre of gravity phenomenon, Coren and Hoenig (1972) required subjects to saccade to a red target in the presence of black distractors. They found that saccades were affected by the presence of neighbouring distractors. Their task required subjects to locate a target in the presence of distractors and thus constituted a search task. Many studies have been made in recent years of saccades during visual search (e.g., Binello, Mannan, & Ruddock, 1995; Hooge & Erkelens, 1996, 1999; Williams, Reingold, Moscovitch, & Behrmann, 1997). The ability to locate a target with a single saccade is often found to be rather poor (Viviani & Swensson, 1982; Zelinsky, Rao, Hayhoe, & Ballard, 1997) except when the target and distractors are well isolated (Findlay, 1997). These tasks did not require high fixation accuracy, so it is not clear whether or not the off-target saccades resulted from a basic inability to suppress distractor influences.

It is frequently argued that attentional processes select the saccade target. Covert attentional processes might operate in at least three ways to achieve this. Selection on the basis of *location* might occur if a 'mental spotlight' or 'attentional pointer' could be used; selection of *objects* might occur if an object structured representation was used; selection on the basis of visual *features* might occur if, as proposed by Desimone and Duncan (1995), a process of biased competition generated a representation selectively emphasising target features. In the present report, we study saccades during a search-like task involving a two-dimensional display of near identical elements. Because of the near identity, search selection on the basis of peripherally discriminable features was not possible. Hence, the selection of the target for the next saccade must have been based on processes that select from the peripheral visual field on the basis of location or object selection. Findlay and Walker (1999) used the neutral term *spatial selection* to describe such processes in an attempt to avoid attentional terminology. Our study thus forms an investigation of the capacities of this form of selection.

Although the task was set up to investigate how scanpaths were chosen (see FB1), it also provided a useful situation to study details of saccade control, as reported in this paper. The issue of whether saccades in this free-scanning situation could be made in a way that avoided influence from distractors was a critical concern. It will be reported that most scanning saccades in the task showed high accuracy with almost no undershoot. However, accuracy decreased and an averaging effect was present for saccades to targets where a neighbouring distractor was present. Several incidental findings are also reported, particularly concerning the initial saccade following display presentation. This movement was much less accurate, frequently showing oculomotor capture, even though advance knowledge was present about the destination required. A preliminary report of some of the material has appeared in conference proceedings (Findlay, 2004).

2. Method

2.1. Participants

Eye scan records were obtained from six individuals, aged between 23 and 38 years, who had given written consent. Two further subjects were tested and discarded since substantial tracker loss occurred during the course of the recording session. The data from two of the six subjects showed large systematic offsets (1–2 deg) in parts of the visual field between target position and recorded eye position. These were attributed to eyetracker inaccuracy and these subjects were also discarded. Thus, the majority of the data presented here is from the remaining four subjects.

2.2. Displays

Subjects were presented with displays of the type shown in Fig. 1 of FB1, viewed binocularly from a distance of 60 cm. The display area was 17.2 deg × 17.2 deg. Each display consisted of a red ring and a blue ring in fixed locations at the upper left and lower right, respectively. A set of black rings occupied random positions between these locations (details of the algorithm used to position these rings is given in FB1). The number of black rings in a display could be 3, 6, 9 or 12 and will be referred to as the ring count (N_R). All rings had outer diameter of 1.2 deg and a central blank area of diameter 0.5 deg containing an alphanumeric character of height 0.4 deg. Subjects were instructed to look first at the red ring in the upper left corner of the display, then to scan the black rings, noting the number of occasions that

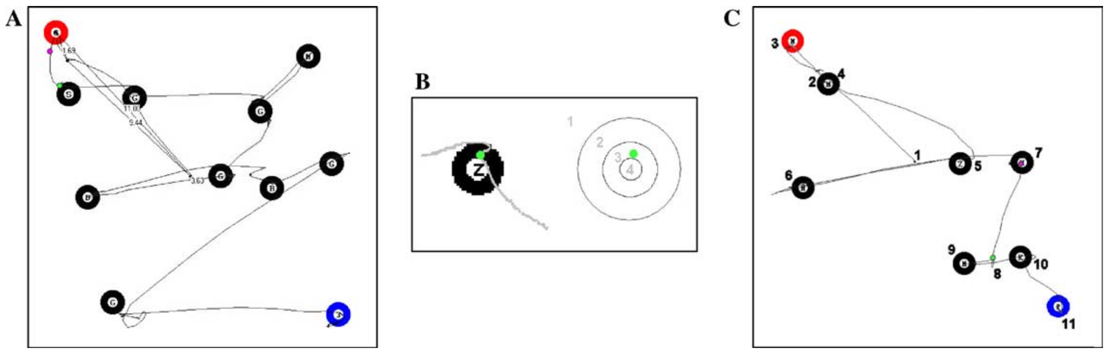

Fig. 1. Example scanpaths. The analysis software identified the start and end points of each saccade by means of small coloured circles, shown in (A) for the third saccade of the scan. Also superimposed on the display is a triangle generated by the analysis software to demonstrate how measurements were made from the X–Y record. The triangle vertices could be positioned manually by mouse pointer. In the case shown, the measures are the distance from the display centre to the centre of the red ring (11.0 deg), the amplitude of the first saccade (9.44 deg), and the distance between its landing point and the centre of the red ring (1.69 deg). The angle between the saccade axis and that to the red ring was 3.63 deg. (B) shows the alternative categorical accuracy measurement used for some purposes. One saccade's end-point is shown superimposed against the outline version of the display (with extra ring). Saccade accuracy was classified as 4 (bullseye), 3 (inner), 2 (outer) or 1 (wide). The diameters of successive rings were 0.6 deg, 1.35 deg, and 2.7 deg. (C) shows a selected scanpath with successive fixations numbered (see text).

the enclosed letter matched the target letter provided in the red ring and finally to make a YES/NO response dependent upon whether the number indicated in the blue ring at the bottom right matched this count. These instructions thus made no specific mention of eye movements and made no explicit request for a speeded response.

Following a brief practice trial set, each subject carried out a block of 80 trials, 20 with each value of ring count.

2.3. Eye movement recording

The subject's head was stabilised with a dental bitebar. Their right eye movements were recorded with a dual-Purkinje eye tracker (Fourward Technologies) with the eye position record sampled every 5 ms. This instrument can deliver a record with resolution and accuracy of a few minutes of arc. Accuracy can be impaired using the DPI tracker for a variety of reasons (spurious IR reflections from eyelids or eyelashes; fixation disparities, which may be large when the non-dominant eye is tracked: head displacement on the bitebar). As noted, two subjects had records where the scans did not superimpose precisely on the stimulus pattern. In the case of the remaining four subjects, the scan record (as shown in Figs. 2, 6 and 8a of FB1 and Fig. 1 of the present paper) appeared precise over the whole display area. A check of fixation position on the red ring (following any corrective saccades) showed, for these subjects, an average deviation of under 1 deg (JP 0.39 deg; LW 0.40 deg; PB 0.66 deg and SL 0.35 deg) and this accuracy was maintained throughout the recording. One of the main findings of this paper is that highly *accurate* saccades can occur, implicitly providing an additional confirmation of instrument accuracy. However, as with any record of eye movements, it is important to recognise that additional error may be contributed by the recording instrument.

2.4. Analysis of recordings

We used interactive software to analyse the recordings. The eyetracker data could be displayed in the form of a plot of horizontal and vertical eye positions against time (examples in Fig. 7), with the saccade start and end points detected by an automatic algorithm. The algorithm compared successive points in the sampled data record. A saccade was detected if two successive pairs of points showed a difference above a pre-set threshold (set to approximately 50 deg/s). A backwards search was then carried out over a fixed number of samples (set to 4) to find the point in the prior record at which a lower threshold (approx 20 deg/s) was first exceeded. Determination of the end-point of the saccade used an algorithm to avoid problems associated with the lens slip artefact found in Purkinje eye-tracking records (Deubel & Bridgeman, 1995). For the saccade end to be triggered, the differences between three successive sample pairs were all required to be below a pre-set threshold (usually set at around 5 deg/s) with the saccade end being registered at the commencement of this sequence. The algorithms could be over-ridden by manual intervention although this was only occasionally used[1]

[1] Occasionally small saccades (under 1 deg in amplitude) were not detected by the software's automatic algorithm, although were clearly visible in the eyetracker record. The software also occasionally grouped two saccades together when the intervening fixation showed high drift. An example can be seen in Fig. 7. The manual over-ride was used in these cases to distinguish the two saccades.

The data could also be displayed in the form of an X–Y plot (as shown in Fig. 1), superimposed onto the relevant bitmap of the stimulus display for the trial. This bitmap could display the start and end points of successive saccades in the scanpath. It was possible on this display to mark locations manually (using a mouse click) and to use this to measure distances between two marked locations or angles between three marked locations. For some purposes, measurements were taken from a display in which the stimulus bitmaps were replaced with outline bitmaps as shown in Fig. 1B, allowing a categorical measure of saccade endpoint accuracy.

3. Results

3.1. Summary of scanning data

The previous paper (FB1) presents a detailed analysis of scanpaths. This shows that, in general, a scanpath is selected with each ring scanned once only and several factors are involved in the choice of which ring to scan next. Rings were omitted only very rarely (under 1%). Backtracking occurred on about 25% of trials but most usually consisted of a single rescan of the immediately preceding item. The average saccade size was 8.92 deg for trials with ring count 3, 6.41 deg for ring count 6, 5.42 deg for ring count 9 and 4.34 deg for ring count 12.

3.2. Accuracy of scanning saccades within the black ring set

Fig. 1C shows a recorded scanpath, selected to illustrate certain features. Successive fixations are numbered. Fixation 1 is the initial central fixation on the appearance of the display. The first saccade takes the eye to Fixation 2, showing oculomotor capture by a black ring on the path to the red target. Fixation 3 falls on the red ring, followed by a refixation (4) of the black ring responsible for the capture. The next saccade shows considerable curvature, landing accurately on a black ring (5). The following saccade also lands accurately on a black ring at point 6, with the lens slip artefact in the Purkinje tracker recorder being responsible for the section of the trace to the left of the ring. The following saccade lands accurately on the black ring (No. 7). Initially, it reproduces almost exactly the trajectory of the previous (5 > 6) saccade but then skips over the black ring to reach point 7. The following saccade is the only one not to land on a black ring, but lands at a point (8) almost midway between two black rings. The start and end of this saccade are marked with small circles, generated by the eyetracking analysis software. The following saccades go to the rings on the left (9) and right (10) before the final saccade taking fixation to the blue ring (11). This record is a good representative example showing first, that most saccades land accurately on a target item and second, an instance of an inaccurate saccade possibly affected by a neighbouring distractor.

The trigonometric measuring procedure (Fig. 1A) was used to measure each saccade made in scanning through the black ring sets (approximately 680 per individual subject). The following subcategories were used: the first saccade following fixation on the red ring (FB1 Category 1: 285 cases); all scanning saccades through the black rings (FB1 Category 2: 2349 cases); the subset of saccades to targets when no neighbouring distractor was present (1681 cases). A definition of neighbouring was used based on previous work and discussed in relation to Fig. 4 below. The saccade target was defined as the black ring closest to the saccade end-point. Only if no other ring was present in the critical sector region (see Fig. 4B) was the saccade included in the 'no neighbouring distractor' subset.

Three measures were accordingly taken to characterise saccade accuracy. The vector between the saccade end-point and the target centre was decomposed into an on-axis component along the axis from the saccade start point to the saccade target centre and an off-axis orthogonal component perpendicular to this axis. The mean (signed) on-axis component measures any systematic saccade undershoot/overshoot. The two measures formed by the standard deviations of the on-axis and the orthogonal components describe the variability in landing positions. These measures will be termed saccade *precision*. Fig. 2 plots each measure as a function of saccade size. For this purpose saccades were categorised into 1 deg wide bins, with the 2 deg bin containing all saccades of size between 1.5 deg and 2.49 deg, and correspondingly for other sizes.

Fig. 2 shows a number of features of interest. Measures for the whole data set (2349 saccades) showed less accurate targeting than those for scanning saccades amongst the black targets with no distractors present. This reduction in saccade accuracy when distractors are present is examined more closely in the following section. Saccades made while scanning within the set of black rings showed impressively high accuracy when no distractor was present close to the saccade target. Individual subjects performed similarly. In these, no distractor cases the measures of accuracy were as follows: undershoot: JP 0.12 deg, LW 0.23 deg, PB 0.16 deg, SL 0.04 deg, on-axis variability: JP 0.40 deg, LW 0.41 deg, PB 0.45 deg, SL 0.31 deg, off-axis variability: JP 0.32 deg, LW 0.34 deg, PB 0.32 deg, SL 0.27 deg. Saccades from the red ring when no distractor was present were only present in a limited size range. They showed similar precision to the subsequent scanning saccades amongst the black rings, but in contrast showed surprisingly large undershoot.

Both accuracy and precision for saccades in the no distractor subset were high. Contrary to our expecta-

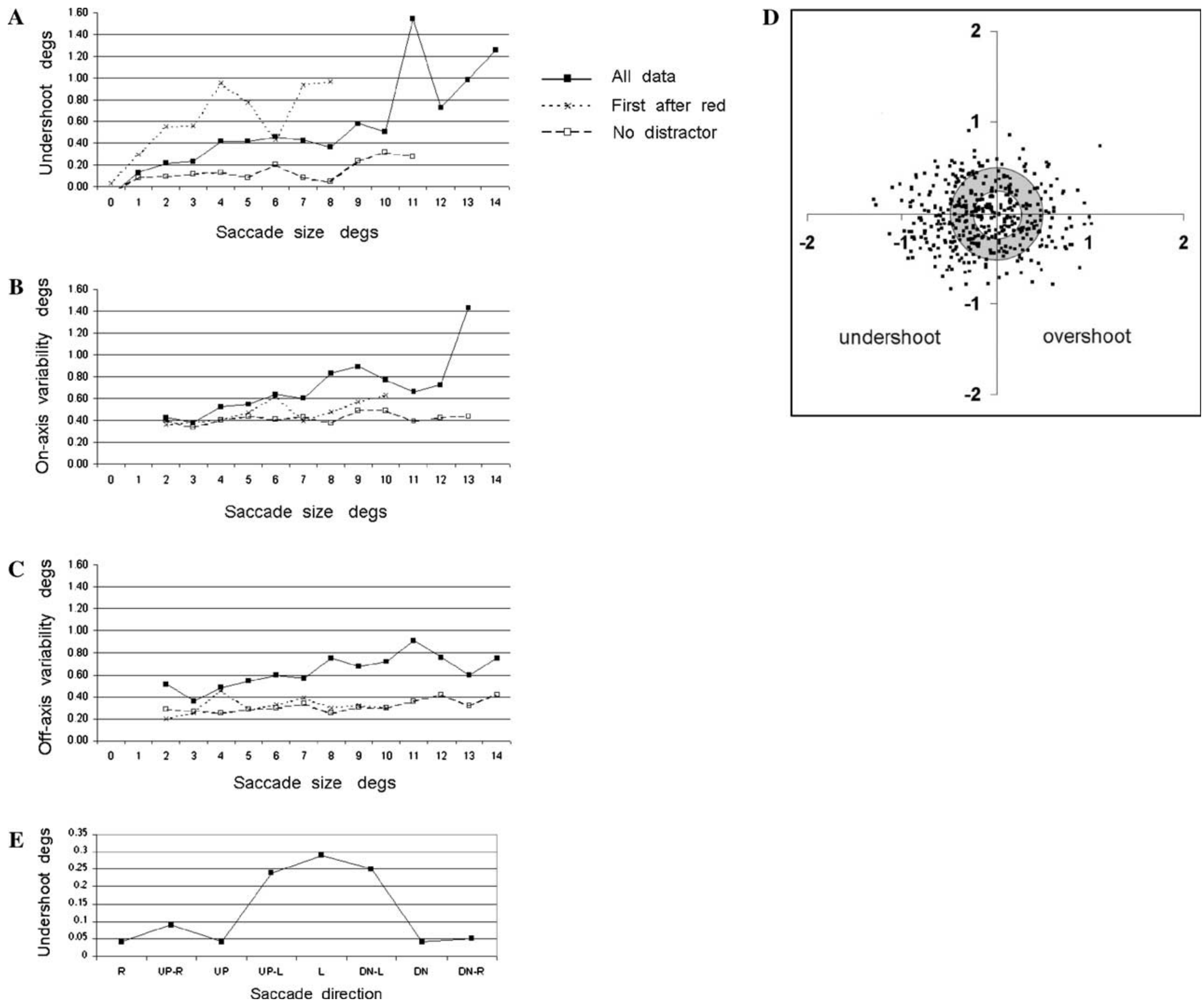

Fig. 2. (A–C) Measures of saccade accuracy, plotted against saccade size. The filled traces show saccades. The dotted traces show the first saccade to leave the red target. The dashed traces show saccades during the scan through the black targets, including only cases where no distractor target occurred near to the saccade target. (D) Record showing landing positions relative to target location for one subject (PB). The plot shows the landing positions of all saccades in the scanpath among the black rings with no interfering distractor. Scales are in degs. The directions of the saccades have been normalised to the left > right axis on the plot. Saccadic accuracy is high, with only slightly greater on-axis variability than in the perpendicular direction, and an overall small tendency to undershoot. (E) Plot showing saccade undershoot for saccades in different directions.

tion, both measures of precision were almost unaffected by the size of the saccade, over the range examined (2–14 deg). The variability along the axis was marginally greater than the variability perpendicular to it, seen also in a sample plot of saccade end points from one individual (PB) shown in Fig. 2D. This figure plots the end points of all saccades with no distractor present in the critical sector as defined below.

Since very few reports of saccade accuracy in the two-dimensional scanning situation have been made, we carried out some further analyses. We categorised saccades into eight directional segments, each subtending ± 22.5 deg around each of the eight major axes (right, left, up, down and the intermediate obliques). For the restricted subset (scanning saccades amongst black rings without distractors), an interesting and unexpected pattern emerged for the undershoot measure, as shown in Fig. 2E. Over more than half the range of saccade directions, the average undershoot was extremely small. The cases where larger undershoot occurred are those in which saccades are being made 'against the flow', in the opposite direction to the general pattern of saccades.

We checked for evidence of any speed-accuracy relationship by dividing the range of prior fixation durations into three categories: 50–150; 151–250; above 251 ms. Table 1 shows the mean scores for the various accuracy measures for saccades in each category, analysing scanning saccades amongst the black rings with no interfering distractor. Any effect is very weak and in the direction opposite to a speed-accuracy trade-off.

Inaccurate saccades were usually followed by a small corrective saccade. The records from two subjects, JP and LW, were analysed in detail and showed quite similar characteristics. Corrective saccades were made after

Table 1
Analysis of saccade accuracy measures in relation to the duration of the prior fixation

	Undershoot (degs)	On-axis variability (degs)	Off-axis variability (degs)	Number of contributing saccades
50–150 ms	0.11 (0.08)	0.39 (0.08)	0.36 (0.02)	514
150–250 ms	0.09 (0.06)	0.39 (0.06)	0.31 (0.06)	797
>250 ms	0.15 (0.09)	0.42 (0.04)	0.41(0.17)	274

The values are the averages of the mean undershoot and variability shown by each subject, together with the standard deviations between subjects of these values.

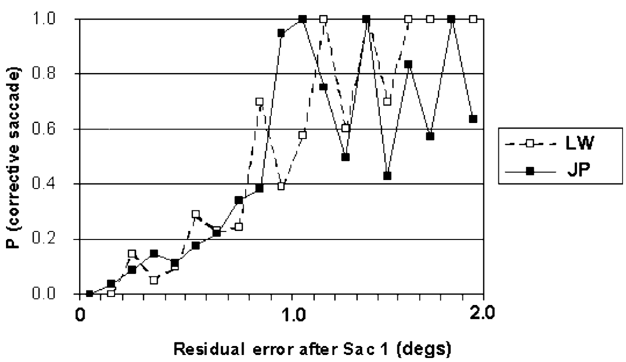

Fig. 3. Probability of a corrective saccade being generated whilst scanning the black ring set, plotted against the distance of the primary saccade landing position from the target centre.

about one-third of the primary saccades (40% for JP; 27% for LW) and showed a systematic increase in occurrence frequency as the landing position became more distant from the target as shown in Fig. 3.

3.3. Effects of distractors

We consider next the accuracy of saccades to targets with nearby distractors and consider particularly whether the 'centre-of-gravity' or 'global effect' phenomenon, known to occur in target-elicited saccades, occurs also in scanning saccades.

We first made use of a finding from a study by Walker et al. (1997). In this study, it was found that a simultaneously appearing distractor affected the metrics of a planned saccade only if it appeared within a quite sharply

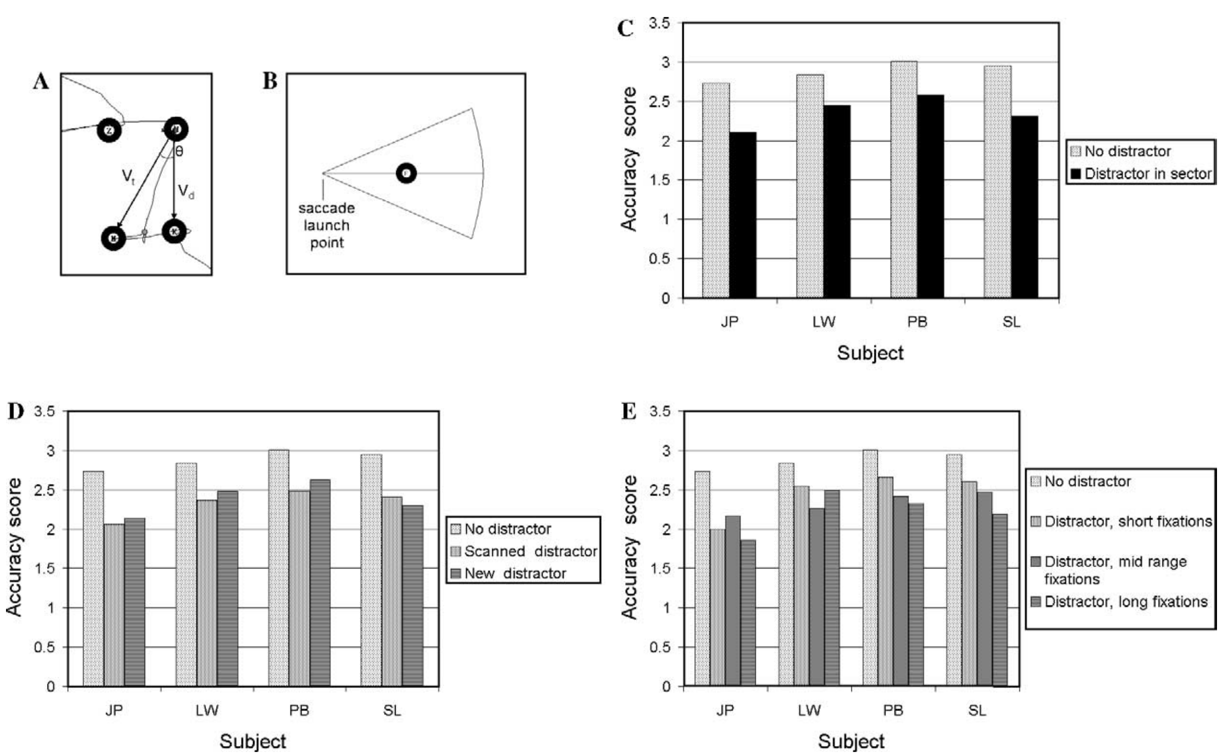

Fig. 4. Measures of the influence of distractors on saccade accuracy. (A) The three measures used to locate the nearest distractor were distance from the saccade launch point to the target, V_t, distance from the saccade launch point to the nearest other ring, V_d, and angle between these two vectors, θ. (B) The critical sector for assessing distractor influence was defined by $-22.5° < \theta < 22.5°$ and $V_d/V_t < 2$. (C) Accuracy scores for cases with and without a distractor in the critical sector. (D) Accuracy scores comparing the effects of a previously scanned distractor with an item not yet scanned. (E) Dependence of accuracy score on the duration of the prior fixation.

defined and narrow sector around the axis of the planned movement. Distractors outside this sector had no influence on saccade accuracy although they did affect latency (the remote distractor effect). For each saccade we measured the distance, V_t, from the launch site to the saccade target, the distance, V_d, from the launch site to the nearest distractor to the target, and the angle between these vectors, θ (see Fig. 4A). The saccade target was defined as the black ring closest to the saccade end point (only very rarely was a measurement with the procedure described in Fig. 1A necessary). We then coded saccades depending on whether or not a second black ring was present whose centre was in a sector (as shown in Fig. 4B) extended from the saccade launch point to twice the distance to the target, and having total width of 45 deg, the width of the sector established by Walker et al. (1997).

Fig. 4C compares the accuracy scores when no distractor was present in the critical sector with those when a distractor was present. This confirms that the presence of a distractor within the critical sector results in saccades with lower average accuracy. The inaccurate saccades when distractors were present predominantly landed between target and distractor. In about 75% of cases overall, the deviation of the saccade axis was towards the distractor. A more detailed analysis was made whereby the proportion of inaccurate saccades (categories 1 and 2) was measured when a distractor was located at various positions relative to the target. This analysis is shown in Fig. 5.

The analysis confirmed that distractors in the critical sector as previously defined affect saccade accuracy whereas those outside do so to a much smaller extent. There is a suggestion also that slightly off-axis distractors have a greater effect than ones on axis. In particular, the low value (0.25) for the on-axis sector closest to the launch point shows accurate targeting for saccades that jump over an intervening distractor (measure based on 33 cases).

Two other analyses were made using the categorised scores. The first tested whether a distractor that had already been scanned resulted in a reduced effect on saccade accuracy. The results are shown in Fig. 4D. Finally, in Fig. 4E, evidence is presented to assess whether a speed-accuracy trade-off occurred in the accuracy scores with a distractor present. The accuracy score is tabulated against the duration of the previous fixation, using a categorisation scheme that divided the duration range into roughly balanced categories. The data refute any suggestion of a positive speed-accuracy trade-off. For each subject, accuracy after long fixations is poorer than after short.

3.4. Accuracy of the first saccade

The instructions asked participants to look first at the red ring on the top left of the display. It was, however,

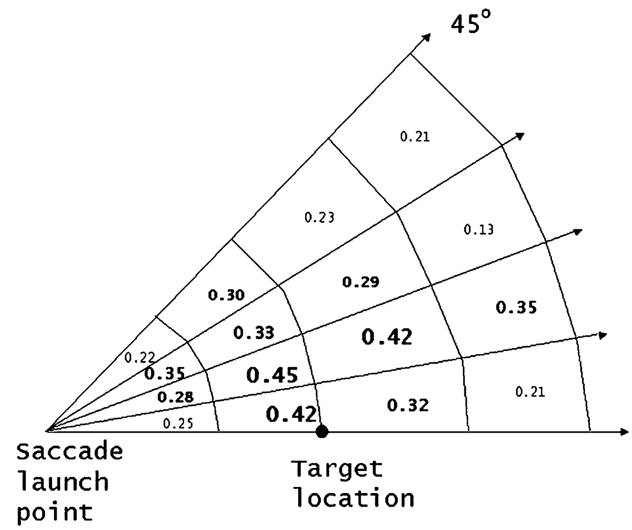

Fig. 5. Probability estimate of an inaccurate saccade (accuracy category 1 or 2) when a distractor ring was present related to the relative positions of target and distractor. The baseline probability of an inaccurate saccade was around 0.2 when no distractor was present in the critical sector. The radial axes of the plot represent relative distances from the saccade launch point to distractor and target (V_d/V_t in Fig. 4A). For the inner four cells, the distractor distance was less than one-half the target distance, for the next four, the distractor distance was between one-half of the target distance and the target distance, etc. The angles of the 11.25 deg sectors correspond to the actual angles in the display. The probability measures shown are obtained from the average of the probability scores for the four individual subjects, excluding three instances, all from cells in the innermost sector, with less than four saccades. The average number of contributing saccades per subject in each cell for the four radial distances working outward was 8, 18, 25, and 19.

quite rare that a single saccade was made to this target. Much more frequently, an oculomotor capture occurred with the first saccade made to a black ring, or with the first saccade landing in empty space between display elements (either two black rings or black and red). The landing positions of the first saccades of two subjects are shown in Fig. 6.

The subjects chosen span the range of accuracies for the first saccade. JP's initial saccades had short latency (average 136 ms) while those of LW had average latency 174 ms. Although LW has considerably more first saccades landing on the red ring target, the number is still relatively small and it is evident that oculomotor capture is a frequent occurrence. Capture is most likely when a black ring is close to the planned trajectory of the saccade, but also occurs occasionally when a black ring is in an entirely different direction but close to the fixation point.

Most often the saccade following the first fixation went to the red ring, or close to it. However, for every individual there were cases where more than one fixation occurred before the red ring was reached and for some this pattern was quite common (19 cases out of 50 for

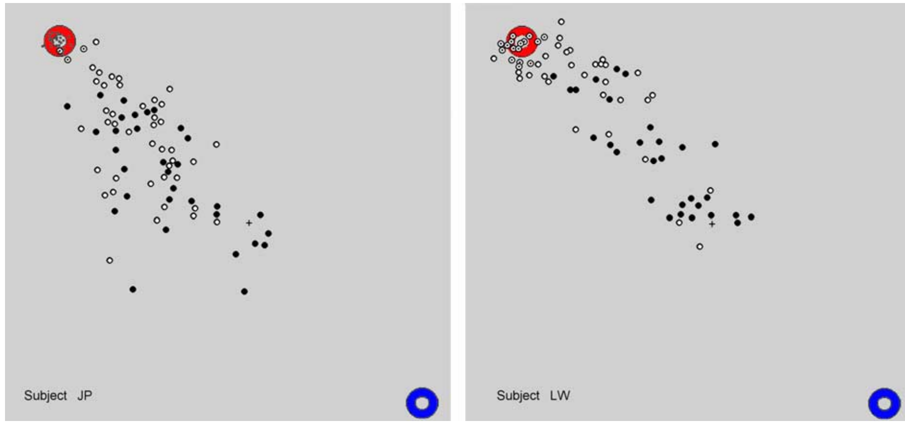

Fig. 6. Landing positions of first saccades shown for two subjects. First saccades that landed on the target red ring (allowing 0.5 deg tolerance) are shown with a circle containing an inner dot. Filled black circles show first saccades that landed on a black ring (with 0.5 deg tolerance). Open black circles show the position of first saccades that landed on an empty region of the display between rings (either two black rings or one black, one red). For subject JP, the small dots in the upper left ring show typical gaze positions when the red ring target had been reached after one or two further saccades.

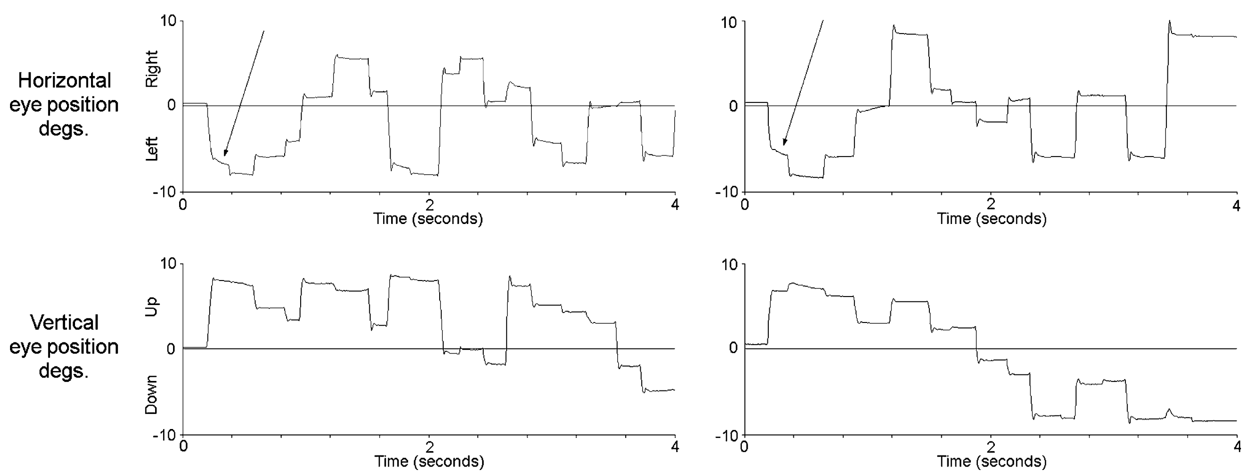

Fig. 7. Records of eye scans (Subject LW) showing horizontal (upper) and vertical (lower) components of eye rotation. These records show instances of oculomotor capture with the red ring target only reached after two saccades. The fixation following the first saccade, marked by an arrow, shows strong horizontal drift in each case.

BR, 16/66 for JP, 15/42 for LS, 6/62 for LW, 1/14 for PB[2] and 15/47 for SL). In addition to these instances of multiple large saccades before reaching the red ring, instances occurred (10–20% of occasions) where an initial incorrect saccade landing close to a black ring was followed by a small corrective movement. No similar corrective movements were observed when the eye landed in a space between rings.

[2] The small numbers in the case of PB arise because this individual adopted a strategy whereby fixation at the start of the trial was close to the red ring, possibly as a result of an anticipatory saccade shortly before the display occurred and recording started. Hence, in the majority of cases for this subject, the red ring was reached directly with a single quite small saccade. Other individuals complied with the fixation instructions.

Table 2
Median duration in millisecond of the first fixation in cases of oculomotor capture

	Median duration of fixation on black ring (ms)	Median duration of fixation between rings (ms)
BR	107	100
JP	95	65
LS	70	50
LW	112	125
SL	105	50

3.5. *Fixation following the first saccade*

Several features were noted in the early part of the scan sequence. As described above, the first saccade often failed to reach the red ring target and the fixation following these inaccurate first saccades was generally very short, sometimes as low as 15 ms. The distribution of these durations was highly skewed with occasional much longer fixations (above 200 ms). The median is reported in Table 2 and demonstrates that short fixations occurred for all subjects. Subject PB, as noted above, failed to follow the instructions and was often fixating close to the red ring when the trial started. Here data are not included in this section.

A further very striking feature of these first fixations is that the eye was not stable but showed an unexpected and systematic large drift. Two example records are shown in Fig. 7, which also shows also that in spite of the drift, saccades and fixations can be clearly identified. To our awareness, this large drift has not been previously reported and thus we checked it in some detail. Table 3 shows, for the subjects whose eye movement record was reliable, values of the drift on the initial fixation prior to the first saccades, that between the second and third saccade, and that between fourth and fifth saccades. The latter was chosen to give a representative measure of activity during the scanning sequence. The measure shown is the average drift over all cases when the drift is in the preponderant direction, together with a figure in parentheses showing what percentage of cases have the drift in this direction (drift in the non-preponderant direction on Fixation 2 had average magnitude of between 0.04 and 0.18 deg with the highest value 0.43 deg). The records from Subjects BR and LS were more noisy than those from the other three subjects and the values of drift, particularly in Fixation 1, may be overestimates.

All subjects show considerably higher drift on Fixation 2 than for the other fixations and in all but one, the horizontal component of drift is particularly elevated. Fixation 2 also shows the greatest consistency in drift direction. On performing the analysis, it appeared that the high drift occurred particularly on trials where the first saccade was large. This observation was checked by repeating the analysis (horizontal drift only), including only trials where the initial saccade size was less than 5 deg. The average horizontal drift in degrees per second, calculated in the same way as in Table 3, in these cases was: BR −2.28 (67%); JP −1.43 (80%); LS −3.39 (57%); LW −1.21 (77%); SL −0.86 (59%). In each case, the drift velocity, while large, is less than in the complete data set. This suggests that high drift values are associated with a large preceding saccade towards the target, rather than a large distance still to be covered.

Table 3
Average values of the horizontal and vertical components of drift on the first, second, and fifth, fixations of the scanning sequence

	Fixation 1	Fixation 2	Fixation 5
Horizontal drift			
BR	−1.64 (56%)	−3.61 (79%)	+1.67 (63%)
JP	−0.46 (65%)	−2.83 (88%)	+1.04 (75%)
LS	−0.94 (87%)	−4.09 (97%)	−1.47 (52%)
LW	−0.42 (72%)	−3.77 (94%)	+1.14 (79%)
SL	+0.46 (70%)	−3.78 (88%)	−1.20 (86%)
Vertical drift			
BR	−0.94 (70%)	−1.59 (75%)	+0.71 (64%)
JP	−0.67 (73%)	−1.83 (77%)	+0.61 (55%)
LS	−1.22 (88%)	−4.17 (97%)	−1.42 (50%)[a]
LW	−0.34 (54%)	−1.27 (95%)	−0.43 (63%)
SL	−0.50 (86%)	−1.45 (94%)	+0.37 (62%)

Values are in deg/s, with negative figures indicating leftward or upward drift and positive figures downward or rightward. The averages are taken over all cases when the direction of the drift was that of the preponderant direction shown on the fixation. The number in parentheses shows the percentage of trials where drift in this direction occurred. Thus, the top left entry in the table shows that, for the initial fixation of subject JP, on 56% of occasions leftward drift was measured and this had an average rate of 1.64 deg/s.

[a] Upward drift average velocity 0.63 deg/s.

4. Discussion

The main findings of the study were as follows:

1. The accuracy and precision of the saccades forming the scanpath through the black ring sequence was generally very high although reduced when a second neighbouring item was present (see point 3). If no neighbouring item was present, the precision of saccade amplitudes, assessed as the standard deviation of the targeting error, had an on-axis component of about 0.4 deg and an off-axis component of just under 0.3 deg. Unexpectedly, precision was almost independent of the size of the saccade. None of the accuracy measures were affected by the duration of the previous fixation.
2. Undershoot was extremely small. With no distractor present, average undershoots were less than 0.05 deg for saccades directed in octants to the right, downward and down-right (the majority of saccades were in these three octants). A slightly higher value, averaging 0.18 deg, was found for saccades directed in the remaining directions.
3. Accuracy was reduced when a second target item was present in a neighbouring location. Under these circumstances, saccades tended show a centre of gravity or global effect, landing at an intermediate location between the target elements. The degree of proximity of the targets for this effect to be manifest was broadly consistent with the critical sector of ±22.5 deg either side of the axis from fixation to target identified in previous studies of the global effect. However, there was evidence for influence of distractors within a somewhat wider sector when these were at roughly the same distance from fixation as the target. Also, it appeared that saccades could be successfully programmed to skip over a close distractor on the same axis as the target.

4. A distractor that has previously been scanned was as effective in generating global effect inaccuracy as one that had not previously been scanned, even though previously scanned distractors rarely received a second fixation (FB1).
5. Inaccurate global effect saccades appeared more likely when the previous fixation was long than when it was short. The data thus showed a negative speed-accuracy trade-off.
6. The first saccade following display onset was very rarely directed at the requested red ring but normally landed either on a black ring or in a blank region of the display between rings.
7. Following misdirected first saccades, the subsequent fixation was very brief (averaging 95 ms when on a black ring; 68 ms when in a blank region). This fixation also showed unusually high drift (average drift velocity 3.6 deg/s horizontally, 2.1 deg/s vertically) in the direction of the red ring.

We shall discuss these points in order.

The first point to note is the impressive accuracy with which saccades through the black rings were executed. First, undershoot was very small (no more than between 1% and 2% of saccade size) and much lower than the values of 5–10% generally found with saccades elicited to sudden onset targets. The saccadic precision was also high with the standard deviation of saccade landing position showing values of 0.3–0.4 deg for all saccade sizes. As a percentage of the saccade amplitude, the precision ranged from 10% for 3–4 deg movements down to around 3% for large (10–14 deg) saccades. The accuracy measures show more precise saccades than those previously observed to sudden onset targets. Our finding of similar precision measures on the two orthogonal axes contrasts with results from target-elicited saccades (Van Opstal & Van Gisbergen, 1989) where considerably greater variability occurrred along the saccade axis. The displays used were designed so that accurate foveation would be required and thus it is possible that this requirement contributed to the high accuracy. However, in previous work (Findlay & Kapoula, 1992), we found no difference between saccade targeting accuracy in a condition requiring accurate foveation and one without such a requirement, although considerably more small corrective saccades were found in the accurate foveation condition. This earlier study was restricted to movements along the horizontal axis.

Difference in accuracy between saccades to sudden onset targets and those to continuously visible ones was also observed by Lemij and Collewijn (1989). Their observations were of saccades in the range 10–40 deg made between self-luminous targets in an otherwise dark room. We believe our observation is the first to show such good accuracy for smaller saccades made in normal scanning in two dimensions. Similar accuracy was observed by Kowler and Blaser (1995) for horizontally directed saccades and by Vishwanath and Kowler (2003) for scanning in a three-saccade sequence. Both these studies used saccades with a very restricted range of amplitudes and required a predetermined scan order. Epelboim et al. (1995) recorded saccades in a three-dimensional tapping task that in some ways resembled the present task but without any requirement to fixate accurately. They reported that fixation errors following an initial gaze shift were around 15% of the magnitude of the movement. McConkie, Kerr, Reddix, and Zola (1988) carried out a careful systematic study of saccades made during text reading. In this situation, saccades appear to be targeted at some location within a word. Landing positions depend on the saccade launch site and the length of the word. However, for a fixed value of these variables, the variability of landing positions shows an optimal value of about 1.3 character spaces, equivalent to about 0.3 deg and thus comparable with the precision we observed. A final comparison of interest is with the scanning of monkeys in the search task studied by Motter and Belky (1998). Motter and Belky report that 20–30% of saccades land more than 1 deg from the intended target centre. This is rather higher than the figures we observed (25% overall; 17% with no distractor present). The displays used by Motter and Belky had somewhat more closely spaced elements and also their targets were elongated bars.

Optimal accuracy was obtained only when the saccade target was relatively isolated. If two potential targets were present in nearby locations fairly close to the axis of the planned saccade, then targeting accuracy deteriorated and saccades showed a tendency to land at a location influenced by the centre of gravity of the target pair. This pattern is similar to the global effect (Findlay, 1982) found when observers are asked to make a saccade toward two targets which onset in neighbouring positions in the visual periphery. The effect with onset targets has been frequently reported although Findlay and Kapoula (1992) were unable to find any substantial global effect when they studied the saccades to the second pair of targets in a three-target sequence. Hence, we believe our demonstration may be the first that a similar effect occurs with free scanning saccades. It is often assumed that saccadic targeting is accurate although Vishwanath and Kowler (2003) have reported that both sudden-onset and free scanning saccades land near the centre of gravity of extended targets. Our data allow an estimate of the dimensions of the region where averaging occurs. As shown in Fig. 5, global averaging occurs mainly when the distracting item is within a sector around the saccade axis of total width about 45 deg, similar to the region found in the study by Walker et al. (1997). Since our conclusion on this point comes from a naturalistic study, it will need further investigation from carefully designed experiments allowing formal inferential testing.

Although the effect we have found is similar to the global effect, two significant differences are noteworthy. In the situation with sudden onset targets, the global effect is stronger when saccade latencies are shorter (Findlay, 1981; Godijn & Theeuwes, 2002; Ottes, Van Gisbergen, & Eggermont, 1985). The converse relationship was observed here with scanning saccades. Global effect type interference occurred for all values of prior fixation duration but was somewhat stronger when the prior fixation was long. Another surprising result was that previously scanned targets were as effective as those not forming part of the prior scanning sequence in exerting the global effect. Since the two sets of targets are clearly differentiated in the target choice decision (FB1), this implies that the global averaging is made by a different representation from that where targets are selected. This contrasts with the finding of Watanabe (2001) who showed that for saccades to onset targets, inhibition of return affected the averaging metrics.

The limitations found in making saccades to targets in the presence of distractors appear to have implications for attentional selection. As discussed in the introduction, it is commonly believed that attentional processes are involved in saccadic selection. Our task eliminated the possibility of selection on the basis of a biased competition approach based on features (Desimone & Duncan, 1995) but would have allowed either spotlight-like location selection or object-based selection to operate. The pervasive influence of neighbouring distractors that was found suggests that neither of these processes operated with any higher resolution than that intrinsically present in the saccadic system (Walker et al., 1997). Other work not involving eye movements has suggested that the processes of covert attention have low resolution (Intriligator & Cavanagh, 2001). Our findings indicate that, when the possibility of selection through biased competition is eliminated, saccadic target selection operates at a low spatial resolution although it should be noted that operation at low spatial resolution is not incompatible with high accuracy for saccades to single targets (Findlay, 1987). Kowler, Anderson, Dosher, and Blaser (1995, p. 1898) considered that averaging errors 'would be disastrous if they occurred during normal scanning.' Our results suggest that biased competition must be the process that normally prevents the disaster.

In contrast to the high accuracy of the scanning saccades, the first saccade made after the display appeared was very rarely directed to its target, even though this saccade could be pre-planned since the initial red ring always occupied the same display location. We have termed this oculomotor capture because of its similarities to the finding of Theeuwes, Kramer, Hahn, and Irwin (1998), who gave subjects a search task where a new object could appear at the same time that the search target was defined. Subjects' eyes frequently were misdirected to the new object. In the study of Theeuwes et al., subjects did not know in advance the location of the search target. In a recent development of this work, Van Zoest, Donk, and Theeuwes (2004) have shown that oculomotor capture can be triggered by the onset of prominent distractors in a multi-element display. Our data (Fig. 6) show that capture can occur even when there is advance knowledge of the location of the saccade target. Capture was generally made by a black ring close to the trajectory that a saccade to the red ring would have taken. However, capture was occasionally found from stimuli in very different directions in the visual field but close to fixation.

The fixation following capture was generally very short. Similar short duration fixations following an erroneous first saccade in a search task have been noted previously (Findlay, Brown, & Gilchrist, 2001; McPeek, Skavenski, & Nakayama, 2000). The interpretation offered by McPeek et al. is that two saccades are programmed concurrently. The first saccade is triggered by stimulation from a distractor, whereas the second is based on stimulation from the target. They supported this position by demonstrating that the second saccade in the sequence was a pre-programmed saccade to the target location since changing the target location during the execution of the first saccade did not in general affect the second. Similar ideas have been elaborated by Godijn and Theeuwes (2002) and McSorley and Findlay (2003). Our data can be interpreted under this broad framework although suggest that the idea of two independently programmed saccades may need modification. Quite frequently, an erroneous first saccade was not followed by a single saccade to the red ring target, but by a multiple saccade sequence. Such multiple saccades might suggest that, rather than saccades being planned entirely in terms of target location, a broad route through visual space to the target might be activated with saccades being triggered along this route in a somewhat ad hoc manner.

Such a suggestion might also provide an account of the finding of substantial drift during the first fixation following oculomotor capture. Kowler and Steinman (1979) observed systematic drift in the direction of a saccade to a target with known location, but its magnitude was about 1 order of magnitude below that observed in the present study. To our knowledge, drifts of this magnitude have not been previously reported during free scanning although they are common in situations of anticipatory pursuit (Barnes, Schmid, & Jarrett, 2002). The drift we observed had larger horizontal component than vertical. Since we recorded monocularly, we cannot rule out the possible involvement of the vergence system but there seems no reason why our displays would elicit systematic convergence. We believe it more likely that the drift results from incomplete activation of the fixation cell/pause cell system that normally maintains stable fixation.

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References

Barnes, G. R., Schmid, A. M., & Jarrett, C. B. (2002). The role of expectancy and volition in smooth pursuit eye movements. *Progress in Brain Research, 140*, 239–254.

Becker, W. (1989). Metrics. In R. H. Wurtz & M. E. Goldberg (Eds.), *The Neurobiology of Saccadic Eye Movements* (pp. 13–67). Amsterdam: Elsevier.

Binello, A., Mannan, S., & Ruddock, K. H. (1995). The characteristics of eye movements made during visual search with multi-element stimuli. *Spatial Vision, 9*, 343–362.

Coren, S., & Hoenig, P. (1972). Effect of non-target stimuli on the length of voluntary saccades. *Perceptual and Motor Skills, 34*, 499–508.

Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective attention. *Annual Review of Neuroscience, 18*, 193–222.

Deubel, H., & Bridgeman, B. (1995). 4th Purkinje image signals reveal eye lens deviations and retinal image distortions during saccades. *Vision Research, 35*, 529–538.

Epelboim, J., Steinman, R. M., Kowler, E., Edwards, M., Pizlo, Z., Erkelens, C., & Collewijn, H. (1995). The function of visual search and memory in sequential looking tasks. *Vision Research, 35*, 3401–3422.

Findlay, J. M. (1981). Local and global influences on saccadic eye movements. In D. F. Fisher, R. A. Monty, & J. W. Senders (Eds.), *Eye Movements, Cognition and Visual Perception* (pp. 171–179). Hillsdale, NJ: Lawrence Erlbaum.

Findlay, J. M. (1982). Global processing for saccadic eye movements. *Vision Research, 22*, 1033–1045.

Findlay, J. M. (1987). Visual computation and saccadic eye movements. *Spatial Vision, 2*, 175–189.

Findlay, J. M. (1997). Saccade target selection in visual search. *Vision Research, 37*, 617–631.

Findlay, J. M. (2004). Eye scanning and visual search. In J. M. Henderson & F. Ferreira (Eds.), *The Interface of Language, Vision and Action: Eye Movements and the Visual World*. New York: Psychology Press.

Findlay, J.M., Brown, V. (accompanying paper). Eye scanning of multi-element displays. I. Scanpath planning. *Vision Research*.

Findlay, J. M., Brown, V., & Gilchrist, I. D. (2001). Saccade target selection in visual search: the effect of information from the previous fixation. *Vision Research, 41*, 87–95.

Findlay, J. M., & Kapoula, Z. (1992). Scrutinization, spatial attention and the spatial properties of saccadic eye movements. *Quarterly Journal of Experimental Psychology A, 45*, 633–647.

Findlay, J. M., & Walker, R. (1999). A model of saccadic eye movement generation based on parallel processing and competitive inhibition. *Behavioral and Brain Sciences, 22*, 661–721.

Godijn, R., & Theeuwes, J. (2002). Programming of endogenous and exogenous saccades: Evidence for a competitive integration model. *Journal of Experimental Psychology. Human Perception and Performance, 28*, 1039–1054.

Hooge, I. T. C., & Erkelens, C. J. (1996). Control of fixation duration in a simple search task. *Perception and Psychophysics, 58*, 969–976.

Hooge, I. T. C., & Erkelens, C. J. (1999). Peripheral vision and oculomotor control during visual search. *Vision Research, 39*, 1567–1575.

Intriligator, J., & Cavanagh, P. (2001). The spatial resolution of visual attention. *Cognitive Psychology, 43*, 171–216.

Kapoula, Z., & Robinson, D. A. (1986). Saccadic undershoot is not inevitable: Saccades can be accurate. *Vision Research, 26*, 735–743.

Kowler, E., Anderson, E., Dosher, B., & Blaser, E. (1995). The role of attention in the programming of saccades. *Vision Research, 35*, 1897–1916.

Kowler, E., & Blaser, E. (1995). The accuracy and precision of saccades to small and large targets. *Vision Research, 35*, 1741–1754.

Kowler, E., & Steinman, R. M. (1979). The effect of expectations on slow oculomotor control. I Periodic target steps. *Vision Research, 19*, 619–632.

Lemij, H. G., & Collewijn, H. (1989). Differences in accuracy of human saccades between stationary and jumping targets. *Vision Research, 29*, 1737–1748.

McConkie, G. W., Kerr, P. W., Reddix, M. D., & Zola, D. (1988). Eye movement control during reading: I. The location of initial eye fixations on words. *Vision Research, 28*, 1107–1118.

McGowan, J. W., Kowler, E., Sharma, A., & Chubb, C. (1998). Saccadic localization of random dot targets. *Vision Research, 38*, 895–909.

McPeek, R. M., Skavenski, A. A., & Nakayama, K. (2000). Concurrent processing of saccades in visual search. *Vision Research, 40*, 2499–2516.

McSorley, E., & Findlay, J. M. (2003). Saccade target selection in isual search: Accuracy improves when more distractors are present. *Journal of Vision, 3*, 877–892, http://journalofvision.org/3/11/20/.

Motter, B. C., & Belky, E. J. (1998). The guidance of eye movements during active visual search. *Vision Research, 38*, 1805–1818.

Ottes, F. P., Van Gisbergen, J. A. M., & Eggermont, J. J. (1984). Metrics of saccadic responses to double stimuli: Two different modes. *Vision Research, 24*, 1169–1179.

Ottes, F. P., Van Gisbergen, J. A. M., & Eggermont, J. J. (1985). Latency dependence of colour-based target vs nontarget discrimination by the saccadic system. *Vision Research, 25*, 849–862.

Theeuwes, J., Kramer, A. F., Hahn, S., & Irwin, D. E. (1998). Our eyes do not always go where we want them to go: Capture of the eyes by new objects. *Psychological Science, 9*, 379–385.

Van Opstal, A. J., & Van Gisbergen, J. A. M. (1989). Scatter in the metrics of saccades and properties of the collicular motor map. *Vision Research, 29*, 1183–1196.

Van Zoest, W., Donk, M., & Theeuwes, J. (2004). The role of stimulus-driven and goal-driven control in saccadic selection. *Journal of Experimental Psychology, Human Perception and Performance, 30*, 746–759.

Vishwanath, D., & Kowler, E. (2003). Localization of shapes: Eye movements and perception compared. *Vision Research, 43*, 1637–1653.

Viviani, P., & Swensson, R. G. (1982). Saccadic eye movements to peripherally discriminated visual targets. *Journal of Experimental Psychology, Human Perception and Performance, 8*, 113–126.

Walker, R., Deubel, H., Schneider, W. X., & Findlay, J. M. (1997). The effect of remote distractors on saccade programming: Evidence for an extended fixation zone. *Journal of Neurophysiology, 78*, 1108–1119.

Watanabe, K. (2001). Inhibition of return and averaging saccades. *Experimental Brain Research, 138*, 330–342.

Williams, D. E., Reingold, E. M., Moscovitch, M., & Behrmann, M. (1997). Patterns of eye movements during parallel and serial visual search tasks. *Canadian Journal of Experimental Psychology-Revue Canadienne de Psychologie Experimentale, 51*, 151–164.

Zelinsky, G. J., Rao, R. P. N., Hayhoe, M. M., & Ballard, D. H. (1997). Eye movements reveal the spatiotemporal dynamics of visual search. *Psychological Science, 8*, 448–453.