Saccade Target Selection During Visual Search

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Five experiments are reported in which eye movements were recorded while subjects carried out a visual search task. The aim was to investigate whether an accurate initial target directed saccade could be programmed. In Experiments 1–2, subjects moved their eyes to targets defined by colour, which were presented with seven non-targets in a circular array. Accurate saccades with short latencies were common but errors sometimes occurred and search for an "oddity" target, defined exclusively by difference in colour from a homogeneous set of distractors, was particularly error prone. In Experiment 3, occasional trials contained double targets. First saccades sometimes landed at an intermediate position between the targets. In Experiments 4 and 5, targets were presented with 15 distractors in two concentric rings of 8. Targets specified by shape could be located accurately with a single saccade. Search for a colour–shape conjunction was more difficult but targets in the inner ring were located frequently with a single saccade. The results suggest that the control of the initial eye movement during both simple and conjunction searches is through a spatially parallel process. © 1997 Elsevier Science Ltd. All rights reserved

Human   Saccade   Search   Visual attention   Feature integration

INTRODUCTION

Visual search exemplifies a controlled situation in which vision is actively engaged. Sensory visual input is combined with central processes such as knowledge of the search target. Modern interest stems from the influential work of Treisman and Gelade (1980), who proposed a model of visual search drawing heavily on the distinction between parallel and serial search. This distinction has been of great heuristic value although many alternative accounts of the search process have become available (Wolfe *et al.*, 1989; Wolfe, 1994; Duncan & Humphreys, 1989) including some by Treisman herself (Treisman & Sato, 1990; Treisman, 1993). Treisman's early work on the topic coincided with a renewal of interest in visual attention (Posner *et al.*, 1978; Posner, 1980), the term used to describe a selective process whereby one location in the visual field receives enhanced processing in comparison with other regions. Posner demonstrated such enhanced processing under conditions in which the observer's eyes do not themselves move. He distinguished this *covert* form of visual attention from the *overt* attention changes, which are brought about by movements of the eyes themselves. The way in which the two forms of attention might interact in visual search will be discussed following a brief review of previous work investigating eye movements during search.

Visual targets which are difficult to discriminate show a "conspicuity area" or "visual lobe". This is a region centred on the fixation location and may be defined as the region outside which the target can no longer be detected unless scanning eye movements are made. Multiple fixations are necessary if an area larger than the conspicuity area is to be searched and predictions can be made about the dependence of search time and search time distributions on discriminability (Bloomfield, 1979). However, only rarely (Widdel, 1983) have the ideas been tested with actual eye movement recording, except in the simpler situation of searching during the systematic left to right scanning of text (Prinz, 1984; Prinz *et al.*, 1992; Rayner & Fisher, 1987; Jacobs, 1986, 1991). In the present study, targets are kept well within the conspicuity area.

A few studies have concentrated on the detailed programming of individual eye movements during search. Viviani and Swensson (1982) required subjects to locate a star-shaped target amidst 15 disk shaped distractors located between 4.1 and 12.7 deg eccentricity. When the target was at a small eccentricity it was located accurately with a single saccade whereas for targets located more peripherally, wrongly directed first saccades were common (up to 40% of occasions). In a second experiment in which all targets were located at 12.7 deg, saccade latencies were reduced and accuracy improved with evidence of a speed accuracy trade off. Viviani and Swensson noted the occurrence of erroneous saccades directed to empty space between targets. They argued, on the grounds that the subsequent fixations to such saccades were extremely short, that such saccades were "motor errors". Ottes *et al.* (1985) asked subjects to saccade to a target of one colour presented with a nearby non-target of

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a different colour. First saccades in this situation generally showed the global effect averaging phenomenon, being directed to some point in the space between the two targets. Subjects were able to delay their responses and execute an accurate first saccade but Ottes *et al.* suggested that the inaccurate saccade was the default option. Using a similar task He and Kowler (1989) showed that prior knowledge of the most likely stimulus position influenced saccade landing position and emphasized the importance of top-down control of saccade metrics. Each of these studies has found saccades directed away from the target but three different interpretations have been offered.

Williams (1966, 1967) examined eye movements during search of a set of simple geometric forms which varied in colour, shape and size. He measured search time and recorded the pattern of eye movements in a number of conditions which differed in the amount of prior specification of the features of the target. For example, the subject might be told that the target was red, or was a circle. He compared these with a baseline condition in which no advance knowledge of the target was given. He found that specification of the *colour* of the target object speeded up the search process considerably and moreover the majority of eye fixations fell on non-target items of the specified colour. Specification of the *size* of the object was much less effective; specification of the *shape* provided almost no advantage. There was a close correspondence between the ability to direct the eyes to the pre-specified items and the speed of the search. The details of Williams' findings appear to be task specific since other studies (Gould & Dill, 1969; Viviani & Swensson, 1982) have demonstrated the ability to use shape information to direct eye movements, However, Williams demonstrated that in some search tasks saccadic eye movements can be made directly to targets whereas in others non-targets are also scanned. This distinction anticipates the current distinction between serial and parallel search. Zelinsky and Sheinberg (1995) have shown more explicitly that eye movement patterns differentiate serial and parallel search tasks, although it has also been shown that the distinction between the two search types is not entirely dependent on eye movements (Treisman & Gormican, 1988; Klein & Farrell, 1989).

If a search task can be carried out pre-attentively in parallel, then it should be possible to move the eye directly to the target. On the other hand if a serial search is necessary, several attention shifts would, in general, occur before the visual axis was directed to the target. Two possibilities exist in this case. Multiple saccadic eye movements might be used. Alternatively, the target might be located with a covert attentional scan *before* the eyes are moved with a subsequent on-target saccade. In this case, the time occupied by the attention scan should be revealed as a delay in the latency of the saccade. The experiments in this paper recorded detailed patterns of eye movements during search to allow discrimination between these possibilities.

Eye movements were recorded during tasks of simple feature search (Experiments 1–4) and a colour shape feature conjunction search (Experiment 5). Subjects were instructed to direct their eyes to a target which was present on every trial. Three measures related to the initial eye movement are of interest, two concerning accuracy and the third latency. The ability to saccade to the target rather than distractors is measured as the percentage of target directed saccades and will be termed *search accuracy*. *Saccade accuracy* refers to the angular precision with which saccades are controlled. *Saccade latency* refers to the time elapsing between display onset and initiation of the first saccade.

EXPERIMENT 1

Introduction

Williams (1966, 1967) found colour to be the most effective dimension allowing selection of targets in peripheral vision. Experiment 1 investigates a search task with colour as the search dimension. As well as acting as a pilot for subsequent work, the experiment had the following aims: (i) to compare the accuracy and latency of saccades in a search situation with those when only a single target is presented; (ii) to establish whether search for a colour target can be carried out within the processing time of a single saccade; and (iii) to compare the pattern of searching when non-targets were all identical to that when non-targets varied.

Method

Subjects. Six research workers aged from 24 to 50 yr took part in the study. All had normal or corrected to normal vision and all but one had previous experience of eye movement experiments.

Procedure. The experiment used a task similar to that of Gould and Dill (1969) in which the subjects were presented with a display consisting of a central stimulus and a further peripheral target stimulus accompanied, in the search conditions, by seven non-targets in a regular ring. Subjects were instructed to move their eyes to the target as rapidly as possible.

Displays. The experiments were run on a Macintosh Quadra 700 computer with a Macintosh 21″ screen operating at 76 Hz. The computer used a program written in-house which presented on the screen a fixation target (0.6 deg black square on white background) for a fixed period (always 1 sec), then replaced this with the stimulus display and initiated eye movement recording (5 msec sampling). The program could display within a single video frame any file available in PICT format by a modification of the colour look-up table. The PICT files for this and subsequent experiments were produced using the MacDraw package. The target stimulus could occur in one of eight positions equi-spaced around an imaginary circle with non-targets occurring in the remaining seven locations. The display was viewed from a distance of 60 cm and had the following dimensions; target or non-target diameter 1.2 deg; target eccentricity (size of circle containing target and distractors) 5.7 deg. The colours

were taken from the MacDraw default palette and had the following CIE co-ordinates (measured with a Minolta meter) Red: $x = 0.608$, $y = 0.341$, $Y = 6.52$; Green: $x = 0.290$, $y = 0.540$, $Y = 4.47$.

Three separate conditions, each with 96 trials, were run in a counterbalanced order. In all conditions the target was *either* a red *or* a green circular disk. The subject was informed about the target colour which remained fixed throughout a block of trials.

1. Single target control. Only one target occurred together with the central stimulus.
2. Search—homogeneous distractors. The display consisted of eight stimuli around the perimeter, one of which was the target and the others, which were non-targets of the remaining colour (seven red disks for green targets and vice versa).
3. Search–heterogeneous distractors. The display consisted of eight stimuli around the perimeter, one target and distractors of three other colours, MacDraw default blue and yellow being added to the non-target red or green. There were at least two distractors in each colour.

Eye movement recording. The subject's eye movements were recorded using a method similar to that described by Collewijn *et al.* (1975). The subject wore a contact lens-type search coil and was positioned at the centre of two large Helmholtz field coils run at 54 kHz (horizontal) and 108 kHz (vertical). The induced currents in the eye coils measured eye position in space in a way which minimised head movement artefact. An experienced technician administered conjunctival anaesthetic (oxybuprocaine) and inserted the eye coil.

Prior to recording, subjects viewed a calibration display consisting of nine points in a square array which were fixated sequentially. In some sessions, further calibrations were taken at the end of the recording sessions which showed that eye position could be reliably measured with an accuracy of 10 min arc or better. A semi-automated procedure was used to analyse the eye movement data. A computer algorithm detected the first saccade using a velocity criterion. Each record was checked individually and it was possible for the operator to over-ride the automatic routine. Such over-ride was rarely needed. In subsequent data analysis, saccades with latency outside the range 100–700 msec were rejected from further analysis and trials were also rejected if the fixation location at the start of the trial was more than 1 deg from the centre. Such rejections were rare with the proportion of trials lost being less than 0.5%.

Results

Directional analysis. Since all targets are at the same distance, the saccade direction measurement is critical for search accuracy. This was analysed using the following categories:

1. On target. Saccade direction in a sector within 15 deg of the target centre.

2. Inaccurate. Saccade direction falls in the sectors of 15 deg width between that for the target and those for neighbouring non-targets.
3. Neighbouring non-target. Saccade direction within 15 deg of the centre of one of the two non-targets on each side of the target
4. Remote. Saccade direction falls in the remaining 240 deg sector of visual space.

Search accuracy. Search accuracy in this experiment was very high although it did decline slightly across the three conditions. In each condition 480 trials were analysed. In the single target condition, 471 (98.4%) saccades were on-target, five were inaccurate, one directed to a neighbouring non-target, one in the remote category and two rejected (anticipations or non-scorable record). In the search condition with homogeneous distractors, 469 (98.1%) saccades were on-target, seven inaccurate, two neighbouring, one remote and one rejection. In the search condition with heterogeneous distractors, 452 (95.1%) saccades were on-target, 17 were inaccurate, nine neighbouring and two remote with no rejections. A record (from a subsequent experiment) of saccade end-points to the homogeneous distractor display can be seen in Fig. 2.

Saccade accuracy. An analysis was made of the distribution of angular deviations of the direction of the saccade from the target centre, including only saccades for which this deviation had a value of less than 15 deg (saccades classified as on-target). The mean within-subject standard deviation of this distribution for the three conditions was as follows:

Single target	4.22 deg	(range: 3.44–5.51 deg)
Homogeneous distractors	4.69 deg	(range: 3.19–6.09 deg)
Heterogeneous distractors	5.09 deg	(range: 4.03–6.39 deg)

This measure may slightly underestimate the precision which is intrinsic to the saccadic system since it will be inflated by any systematic offset of the mean saccade direction from the target centre.

Saccade latencies. The mean latencies in the three conditions were as follows: single targets, 250 msec; search with homogeneous distractors, 257 msec; search with heterogeneous distractors, 266 msec. The differences between the means were not significant on an analysis of variance ($F(2, 10) = 2.267$, n.s.).

Discussion of Experiment 1

The performance shown in Experiment 1 is impressive. In the homogeneous distractor condition, only 0.5% of first saccades are directed at a non-target and in the heterogeneous distractor condition the percentage of misdirected saccades is under 2%. Moreover this accuracy is achieved with no cost in the time needed to program the saccade. This provides an impressive confirmation that search for a pre-specified colour target can be carried out in parallel.

The slight difference in search accuracy between the condition with homogeneous distractors and that with heterogeneous distractors is consistent with much of the literature on visual search using reaction time measures. Duncan and Humphreys (1989) argued on theoretical grounds for the importance of intra-distractor effects in visual search, and their prediction was confirmed in an experiment by Duncan (1989) in which colour was the search dimension. Experiment 2 investigates further the contribution made by the pop-out signal occurring when a target is presented with homogeneous distractors.

EXPERIMENT 2

As argued by Bravo and Nakayama (1992), many search tasks can be carried out using either top-down, or bottom-up information, or some combination. Experiment 2 extended the range of conditions used in Experiment 1 by varying the way in which information was made available about the search target.

Method

Subjects. Six subjects were used, four having participated in Experiment 1.

Procedure. Stimuli were presented in blocks of 64. There were three tasks as follows, each involving search for a target amidst seven non-targets as in Experiment 1.

1. Search task. Red or green targets pre-specified. Replication of the homogeneous distractor condition of Experiment 1 but without a central matching stimulus.
2. Match task. No pre-specified search target. Red or green targets specified on each trial by a central matching stimulus.

3. Oddity task. No central stimulus. Either green with seven red non-targets or red with seven green non-targets.

The experiment was carried out in a single session. The red and green targets used in this experiment were matched for luminance using heterochromatic flicker photometry (using an option from the VSearch package of Enns *et al.*, 1990). CIE co-ordinates were Red: $x = 0.587$, $y = 0.338$, $Y = 5.28$. Green: $x = 0.287$, $y = 0.503$, $Y = 4.01$. An additional minor change made in this and subsequent experiments was the removal of the fine line contour surrounding objects characteristic of the MacDraw default option.

Other details of procedure and eye movement recording were as in Experiment 1.

Results

Search accuracy. Table 1 shows the first saccade directions, categorized as in Experiment 1.

The oddity task led to the worst performance with the average number of first saccades to target overall being only 75%. A high proportion of the errors made in the task were directed to neighbouring targets (Fig. 1). The mean amplitude of on-target saccades was 5.34 deg and that of saccades directed to non-targets was 4.70 deg. The data from each individual subject showed smaller amplitudes for non-target saccades than for target-directed saccades.

Saccade latencies. The mean latencies in the different conditions of Experiment 2 were as follows. Search task, 195 msec (red targets 188 msec, green targets 210 msec), match task 270 msec, oddity task 211 msec. Each subject showed the same ordering of latencies.

TABLE 1. Accuracy of first saccades in Experiment 2

Subject	AH	BK	TH	JF	KF	RW	Mean % in each category
Match task							
On-target	86.7	93.8	78.1	71.1	82.0	81.2	82.2
Inaccurate	5.5	2.3	8.6	15.6	11.7	12.5	9.3
Neighbouring	7.0	2.3	6.2	9.4	2.3	4.7	5.3
Other	0.8	1.6	5.5	3.9	3.9	1.6	2.9
Rejected (anticipations etc.)	–	–	1.6	–	–	–	0.3
Search task							
On-target	99.2	99.2	87.5	96.1	81.2	78.9	90.3
Inaccurate	–	0.8	6.3	3.1	12.5	14.8	6.3
Neighbouring	–	–	1.6	0.8	2.3	3.1	1.3
Other	–	–	2.3	–	2.3	2.3	1.2
Rejected (anticipations etc.)	0.8	–	2.3	–	1.6	0.8	0.9
Oddity task							
On-target	73.4	78.1	84.4	73.4	87.5	51.6	74.7
Inaccurate	17.2	4.7	3.1	9.4	7.8	20.3	10.5
Neighbouring	6.3	10.9	9.4	12.5	1.6	17.2	9.6
Other	3.1	6.3	3.1	4.7	–	10.9	4.7
Rejected (anticipations etc.)	–	–	–	–	3.1	–	0.5

The table shows the percentages of saccades for each subject landing in the different sectors and the average across subjects.

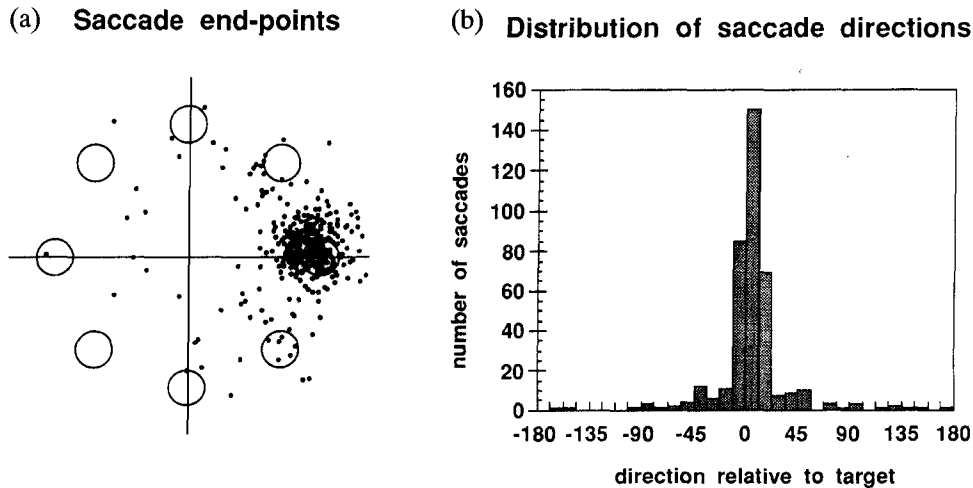(a) **Saccade end-points** (b) **Distribution of saccade directions**

FIGURE 1. Distribution of saccade end-points for saccades in the "oddity task" of Experiment 2. In this task, the target was defined as having a different colour from a set of identically coloured distractors. In (a), each point shows the end point of a saccade (results cumulated over all six subjects and eight target positions) plotted relative to the target location. The oddity target appeared with equal frequency in all eight positions and a rotational transformation has been applied to the data to give the normalised plot. (b) Shows the same data in the form of a histogram of saccade directions, plotted relative to the target. The plot shows subsidiary peaks coinciding with the neighbouring targets at ±45 deg.

Discussion of Experiment 2

The search task of Experiment 2 provided a similar task to that used in Experiment 1 (homogeneous distractors condition) but differed in that no central matching stimulus was present in Experiment 2. Three out of four subjects who performed both experiments showed similar accuracy in each, while RW showed somewhat inferior performance in Experiment 2. Saccade latencies in the search condition of Experiment 2 were systematically reduced by about 60 msec in comparison with Experiment 1. A likely reason for the latency reduction is the absence of the central match stimulus in the search condition of Experiment 2. The offset of a fixation point is known to have a substantial effect on saccade latencies as first shown by Saslow (1967). Recent work on this topic (Reuter-Lorenz & Fendrich, 1992; Walker et al., 1995) has established that the effect is an automatic one, in part relating to the disappearance of visual material at the point of fixation and in part due to a temporal warning signal-like effect. An unexplained finding was that searching for red targets, for all subjects, resulted in shorter latencies than searching for green targets.

The match task produced inferior search accuracy to the search task, indicating that prior knowledge of the search target is used effectively. The saccade latencies in the match task were prolonged by about 80 msec over those in the search task, but were only slightly increased over those in the homogeneous distractor condition of Experiment 1, suggesting that the major part of the latency difference between search and match tasks is an automatic increase resulting from the continued presence of stimulation at the point of fixation.

The oddity task proved more difficult than anticipated. Subjects reported that the task seemed straightforward, but analysis of the eye movement data showed that only

on about 75% of trials was a correct first saccade made to the target. The tendency of wrongly directed first saccades to be directed to neighbouring non-targets shows that information from the display can affect the saccade end-point without being sufficiently precise to elicit a correct response. In addition to errors generated in such a way, the match and oddity tasks have frequent switches of target feature between trials. As shown by Maljkovic and Nakayama (1994), such switching leads to degraded performance because of automatic carry-over effects.

Cohen and Ivry (1991), arguing from effects of target spacing on search rates, suggested that part of the signal arising from a target is only coarsely localised. A coarsely localised signal is a feature of saccadic eye movements to simple targets. When two targets are presented simultaneously in neighbouring positions, the first saccade is directed towards some "centre of gravity" position (Findlay, 1982; Findlay et al., 1993), probably reflecting the use of distributed coding in the saccadic system (Lee et al., 1988; Findlay, 1987; Glimcher & Sparks, 1993). Experiment 3 investigates further the existence of such a coarsely localised signal.

EXPERIMENT 3

Experiment 3 used a search task similar to that of Experiment 1, but on occasional trials, two targets were presented. The subjects were informed that two targets would occasionally occur and instructed that in such cases they should saccade to one or the other.

Method

Subjects. Five of the subjects tested in Experiment 1 gave useable data.

Stimuli. Single target displays were identical to those in the homogeneous distractor condition of Experiments 1
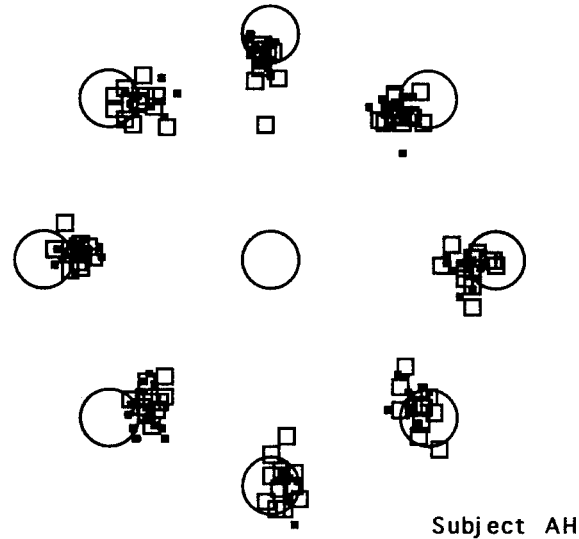
FIGURE 2. Example of saccadic responses from one subject on the single target trials of Experiment 3. Each symbol shows the end point of a single saccade (open squares: red targets; filled squares: green targets). All saccades were directed towards the appropriate target location.

and 2. Double target displays contained two targets and were of two types, having the two targets either in adjacent positions, or in separated positions having one intervening non-target. In each block of 64 trials, 48 trials had single targets, 8 trials had double targets in adjacent positions and 8 trials had double targets in separated positions. Four subjects performed four blocks, in two of which the targets were green and in the other two the targets were red. Subject FN was only available for two blocks.

Results

Figure 2 shows an example of the saccade end-points in *single* target trials for a typical subject. These saccades

all go to the appropriate target location and would be categorised as on-target.

Figures 3 and 4 show the distributions of saccade end-points relative to the targets.

Figure 5 shows, for the two double target conditions, the distribution of saccade directions plotted as a function of saccade latency.

Saccade latencies. The latencies of saccades in the double target task were as follows (the figures shown are medians because subject FN showed exceptionally long latencies). Single targets, 243 msec (red 242 msec, green 244 msec), double adjacent targets, 245 msec, double separated targets, 263 msec.
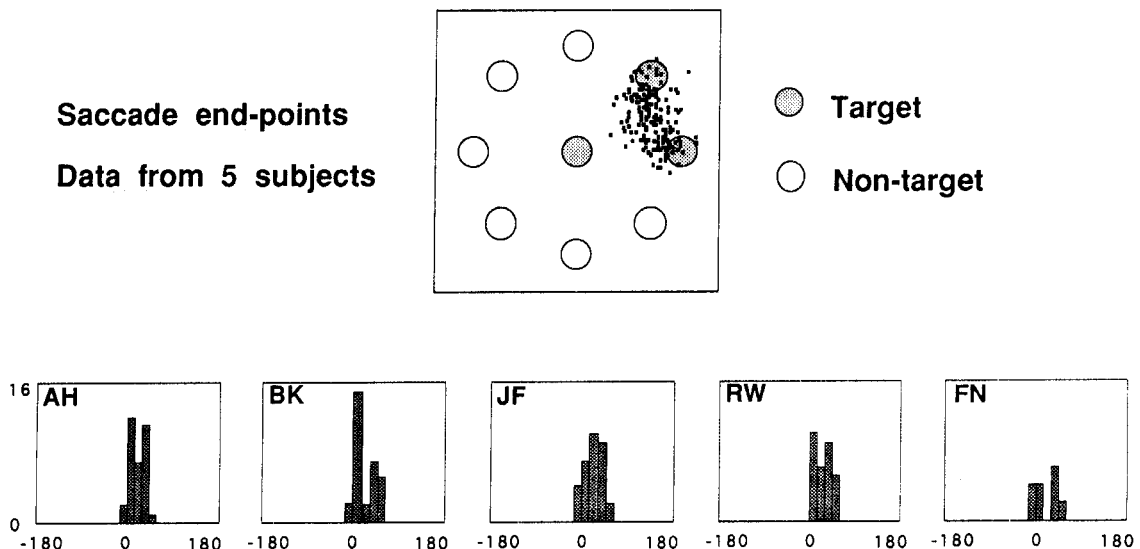

FIGURE 3. Saccade end-points from all five subjects for the double adjacent trials of Experiment 3. The points are normalised relative to a target pair in the right and upper right positions. The lower plots show, for each individual subject, the histogram of saccade directions. In these histograms, 0 and 45 deg correspond to the target positions.

Saccade end-points
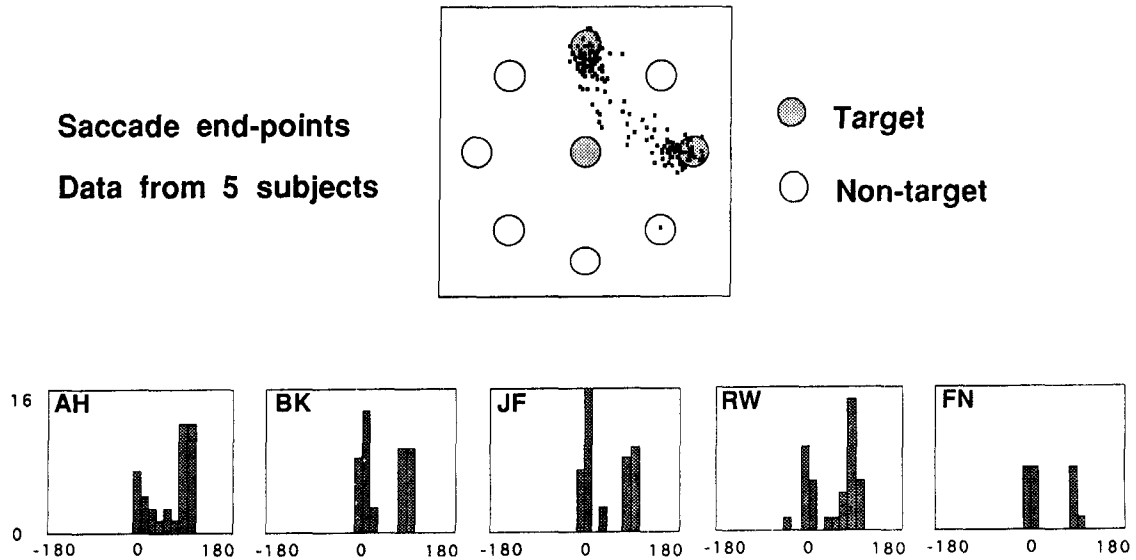
Data from 5 subjects

◉ Target

○ Non-target

FIGURE 4. Saccade end-points from all subjects for the double separated trials in Experiment 3. Plots as in Fig. 3.
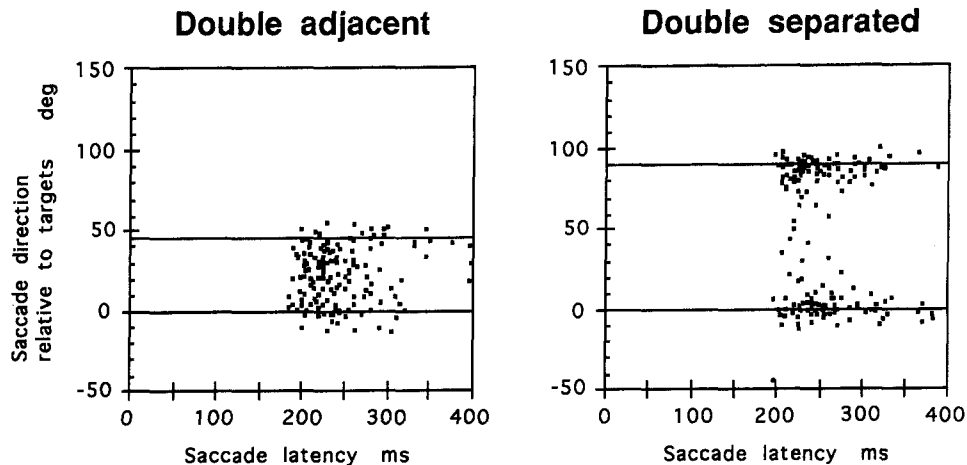

FIGURE 5. Plots showing the dependence of saccade amplitude on saccade latency in Experiment 3. In the double separated condition, only saccades with latencies less than about 270 msec show evidence of spatial averaging. In the double adjacent condition, averaging occurs over a larger range of latencies.

Discussion of Experiment 3

Results from the single target trials are similar to those found in earlier experiments in showing accurate saccades and generally fast responses. The latencies of subject FN were about 500 msec and thus considerably longer than those of the other subjects and those she herself produced in Experiment 1.

The chief interest in the experiment comes from the double target results. When double targets occur in adjacent positions, saccades are frequently directed to intermediate positions (Fig. 3). The distribution histograms for three subjects (AH, BK and RW) show bimodal distributions of saccade direction, with location of the peaks in each case being in the bins extending from the target centre *towards* the second target, rather than at the centre of each target. The asymmetry of these distributions shows that, even for on-target saccades, the second target has some effect. Each of these subjects also

produced saccades directed to the bin centred midway between the two targets. Subject JF shows a unimodal distribution of saccades with the peak centred between the targets. The results from these subjects confirm the earlier finding suggesting that a coarse localisation signal is influential in the saccade programming, although it is also clear that a fully integrated signal is not the only determinant.

When double targets occur in separated positions, the majority of the saccades were directed at the individual targets with little indication of a bias in direction towards the second target. However, four subjects produced occasional saccades directed to an intermediate position between the two targets. These intermediate saccades had smaller amplitude than the saccades directed towards the target (Fig. 4). No saccade fell on the intermediate non-target, although one short latency saccade from subject RW fell on a neighbouring non-target.

The absence of saccades to intermediate positions shown by subject FN, coupled with the long latencies shown by this subject, is suggestive of a speed–accuracy trade-off. Further confirmation of such a trade-off is shown in Fig. 5 which plots saccade direction against saccade latency for the remaining subjects. In the case of double separated targets, clear evidence of a trade-off is present. In the case of double adjacent targets, there was much less evidence of a speed–accuracy relationship, with some saccades to intermediate directions having long latencies.

Shape and feature conjunction search tasks

Experiments 1–3 were concerned with tasks where the search target was defined by a single feature, target colour. In the great majority of cases, the first saccade was generated rapidly and was directed towards the target. This behaviour is consistent with the notion that the relevant information is processed rapidly in parallel at all eight target locations. The following experiments are concerned with search for colour–form conjunctions.

A pilot experiment (carried out by Kalpana Sheth as a project for a B.Sc degree at Durham University) examined saccades in a colour–shape conjunction task using similar eight-element displays to those of Experiments 1–3. The percentage of on-target first saccades was about 70% with mean latencies slightly over 300 msec. These results suggested that with a display consisting of eight stimuli, saccades could be quite accurately directed to a conjunction target. Experiments 4 and 5 follow-up the finding.

EXPERIMENT 4

Experiment 4 examined performance on a shape search task. In view of the high level of performance obtained in the pilot experiment just described, it was decided to increase the number of elements in the display by the addition of an outer ring of target elements, as shown in Fig. 6.

Method

Subjects. Four subjects were used, all having participated in at least one earlier experiment.

Displays. The displays were of the type shown in Fig. 6, each consisting of 16 elements, positioned at either 5.7 or 10.2 deg, one of which was the target. The elements were black on a white background and the target could appear in all 16 possible positions. The four shapes used were constructed to have identical surface area. Some shape confusion between square and triangle was noted in the pilot experiment, hence the circle and cross were used as targets.

Procedure. Each subject was run in four blocks of 64 trials each. In two of these the target was a cross and in the remaining two the target was a circle. Other details were as in previous experiments.

Results

The accuracy of responses to the circle targets and the cross targets was very similar. Responses to the two types of targets were therefore pooled. Search accuracy was analysed using a classification similar to that used in the earlier experiments. The introduction of a second array adds a further possible case to the error categories, the *wrong distance* error. Such errors were scored as follows. For the target at 5.7 deg, all saccades with amplitude less than 8.5 deg were accepted as on-target, while for targets at 10.2 deg, all saccades with amplitudes greater than 7.0 deg were accepted. These rather lax criteria were felt appropriate in view of the relatively low accuracy achieved by the saccadic system, even under optimal conditions.

Search accuracy in this experiment was high. In all, 1024 trials were analysed, half having the target in the near position and half in the far position. The distribution
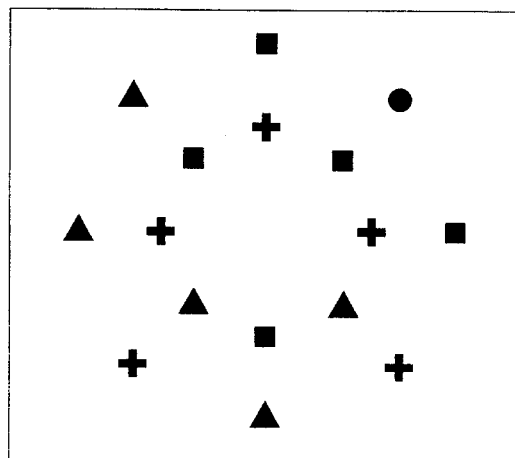

FIGURE 6. Example of the type of stimulus display used in Experiments 4 and 5. The display shown is from Experiment 4 with a circle target. The target appeared with equal frequency in each of the 16 positions, located at eccentricities of 5.7 and 10.2 deg. Experiment 5 used a similar display with alternate items coloured red and green. Three non-targets had the same shape as the target in the opposite colour.

TABLE 2. Accuracy of first saccades in Experiment 5

Subject	TH	JF	BK	RW	Mean % in each category (TH, JF, BK)
		Target in near position			
On-target	59.4	67.9 (5.5)	64.1 (39.8)	21.1 (2.3)	64.0
Inaccurate	10.9	8.6	6.2	10.2	8.6
Neighbouring	7.0	7.0	5.5	12.5	6.5
Other	21.1	15.6	17.2	53.9	18.0
Wrong distance	–	0.8	7.0	–	2.6
Rejected (anticipations etc.)	1.6	–	–	2.3	0.5
		Target in far position			
On-target	16.4	40.6 (10.2)	21.1 (6.3)	2.3 (1.5)	26.0
Inaccurate	0.8	1.6	3.1	–	1.8
Neighbouring	0.8	0.8	0.8	0.8	0.8
Other	19.5	2.3	3.1	–	8.3
Wrong distance	62.5	54.7	71.9	92.2	61.0
Rejected (anticipations etc.)	–	–	–	4.7	

The table shows the percentages of saccades for each subject landing in the different sectors and the average across subjects. The figures in parentheses show the percentages of saccades scored as correct which had amplitudes in the intermediate region (7.0–8.5 deg). In this region, saccades in the target direction were scored as correct for both target distances. The figures for subject TH are, in part, estimates because of the recording problem (see text).

of saccade end-points was as follows. Target in near position: saccades on target 418 (81.6%), inaccurate 35, neighbouring 21, remote 14, wrong distance 13, rejected 11. Targets in far position: on-target 429 (83.8%), inaccurate 25, neighbouring 4, remote 4, wrong distance 37, rejection 13. The distribution of errors for the individual subjects all showed similar patterns except that subject TH showed a unexpectedly high number of inaccurate saccades (48) with correspondingly fewer on-target saccades.

The mean latencies of first saccades were as follows. Circle target: near 236 msec, far 246 msec. Cross target: near 228 msec, far 236 msec.

Discussion of Experiment 4

The achievement of accurately directed saccades to a target defined by shape contrasts strongly with the finding of Williams (1967). Williams found that, when subjects were presented with displays containing a variety of shapes, providing subjects with prior information about target shape led to very little benefit either in overall search times or in the ability to restrict fixations to targets of the appropriate shape. Whilst there are a number of differences between the two experiments, a likely cause of the different result is the display spacing. The displays of Williams were relatively cluttered, whereas those used in Experiment 4 were designed to minimise any lateral sensory masking.

There was little difference between the ability to direct saccades onto the targets in the near positions and those in the far positions. Saccades in the right direction but at the wrong distance were quite rare, with wrongly directed saccades showing only a slight bias to be directed to non-targets in the inner ring.

EXPERIMENT 5

In Experiment 5 the requirement was to search for a conjunction of colour (red or green) and shape (cross or circle).

Method

Subjects. Four subjects were used, all having participated in at least one earlier experiment.

Displays. The displays each consisted of 16 elements, positioned as in Experiment 4, one of which was the target. The non-targets always included *three* with the same shape as the target (cross/circle) in the non-target colour. The remaining elements were chosen from the three remaining shapes (circle/cross, square and triangle) so that each shape appeared at least three times. The elements were red or green on a white background and the target could appear in all 16 possible positions. Red and green stimuli were alternated in the display so that no adjacent targets had the same colour.

Procedure. Each subject was given four blocks of 64 trials. Targets were the four pairings of red/green and cross/circle. Other details were as in previous experiments.

Results

A slight technical problem arose with the data from one subject (TH). Because of a faulty zero setting in the eye movement recorder, the record of the vertical component of eye movements showed a saturation non-linearity for all positions greater than about 2 deg below the fixation point. It was still possible to measure the latency of the first saccade, and to estimate the initial direction of the saccade trajectory as well as (for oblique saccades) its approximate amplitude. These estimates have been used in the results presented below.
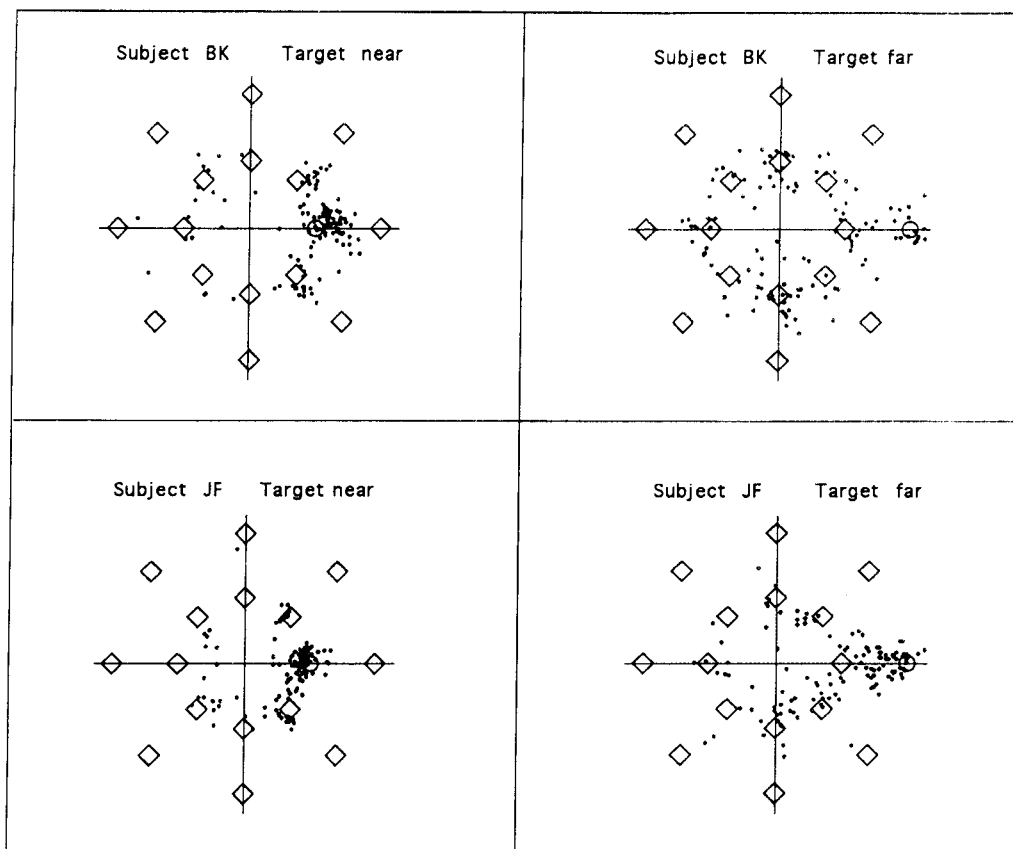
Search accuracy. Table 2 shows the distribution of

FIGURE 7. Distribution of first saccade end-points for two subjects in Experiment 5. Stimulus locations are marked schematically with the diamond symbol, except for the target reference location which is marked with a circle. The data have been subjected to a rotational transformation so that the left-hand plots cumulate all saccades when targets were in the eight locations of the inner ring and show end-points normalised relative to a target in the near right position. The right-hand plots cumulate all saccades when the target was in the outer ring, normalised in a similar manner relative to a target in the far right position.

saccade directions, classified in the same way as for Experiment 4. With the exception of RW, subjects made frequent first saccades to targets at all eight positions in the inner ring (TH, worst case positions received 50% of first saccades, best 81%; JF, worst position 44%, best 88%; BK, worst position 38%, best 81%). There was very little indication of any systematic positional bias that might reflect a preferred scanning order.

Saccade latencies. Mean latencies were as follows. Circle targets: near 220 msec, far 232 msec. Crosses: near 225 msec, far 236 msec. For targets in the near position, on-target saccades had a mean latency of 228 msec, inaccurate 222 msec and erroneous saccades 218 msec. For targets in the far position, the figures were on-target 253 msec, inaccurate 260 msec and erroneous saccades 227 msec.

The increased latencies to targets in the far position appeared to arise from a sub-group of saccades with considerably increased latency, rather than a general shift in the latency distribution.

Misdirected first saccades. The erroneous first saccades provide potentially revealing information about the processing which has occurred. The misdirected saccades were further analysed in two ways; firstly to bring out the spatial factors involved in the programming and secondly

to investigate the non-target characteristics which may have influenced the programming.

Figure 7 shows the distribution of saccade end points relative to the target location for two subjects. The data from subject TH could not readily be analysed in this manner (see note above) and the data from RW was less informative because of the marked positional biases shown by this subject.

TABLE 3. Destinations of erroneous first saccades using, for this analysis, the stimulus nearest the saccade end point. Erroneous first saccades are divided into those directed to stimuli having the same colour as the target, those having the same shape as the target, and those having neither feature in common with the target.

	Same shape	Same colour	Other
Subject			
BK	64	31	5
JF	53	38	9
TH	34	54	13
RW	34	46	20

The table shows the distribution, expressed as a percentage, for each of the four subjects tested. If erroneous saccades had been directed randomly to the non-targets of the inner ring, the expected distribution would be: same shape, 23%; same colour, 43%; other, 34%.

Table 3 analyses the stimuli which received fixation following erroneous first saccades. It is apparent that erroneously directed saccades are not distributed randomly and are more likely to be directed to a non-target with one feature in common with the target.

Scanning sequences. When the target was not located with the first saccade, a series of saccades occurred and, almost without exception, the eye reached the target within the 1 sec display time. A detailed analysis of the characteristics of these saccades is outside the scope of this paper but an interesting feature was the occurrence of regular scanpaths, repeating on three or more of the trials with each particular display.

Discussion of Experiment 5

Subject RW produced results on this task which were very different from the other three subjects, showing very low search accuracy. The major influence in his case was a strong positional bias to saccade to the near left target with a short latency saccade. The other subjects confirmed the finding of the pilot experiment that, in a colour–shape conjunction search, the first saccade may be directed to the target on a high proportion of occasions. For all three subjects, the ability to saccade directly to the target was much greater when the target was in the inner ring, although all showed some ability to saccade to targets in the outer ring also. Subjects TH and JF had latencies which were only slightly increased (8 msec for TH and 23 msec for JF) from those of Experiment 4. Subject BK did not participate in Experiment 5 but a comparison of his latencies with those in the search condition of Experiment 3 shows a latency increase of 32 msec. As in Experiment 4, all subjects showed increased latencies for targets in the far position.

It is evident that items in the outer ring are much less effective in attracting saccades. Pashler (1987) has suggested that parallel processing can occur only over a limited number of items in colour shape conjunction searches. However, targets in the outer ring are disadvantaged simply by reason of their increased eccentricity and thus the poor performance might be attributable to purely sensory factors. In an attempt to decide between these possibilities, a follow-up experiment (carried out by Karin Troidl) used displays similar to those of Experiment 5, but with all targets in the outer ring enlarged using a linear scaling factor. Search performance was found to be almost identical with that shown in Experiment 5, suggesting that it is the presence of the intervening targets, rather than the reduced sensory discriminability, which results in the performance decrement.

GENERAL DISCUSSION

Summary of results

In Experiments 1 and 2 a target defined by colour was generally located with a single saccade. Confirming earlier findings (Duncan, 1989), locating such a target amidst homogeneous distractors was slightly more efficient than amidst heterogeneous distractors. When the target was specified within the display itself (matching and oddity tasks), errors were more frequent than when the target colour was known in advance and search for an oddity target (defined solely by sensory pop-out) proved particularly error prone.

Erroneous saccades in the oddity task fell predominantly on neighbouring non-targets, suggesting that some of the signals involved in search and saccade control may be coarsely localised. Coarse localisation was further demonstrated in Experiment 3 by the presence of saccades falling at intermediate locations in displays containing two targets (Figs 3 and 4). There was also evidence of the saccade end-points being influenced by inhibition or suppression from a representation of an intermediate non-target (Fig. 4).

Experiments 4 and 5 investigated shape search and colour/shape conjunction search, respectively, in a 16 element search display. Searching for a shape-defined target amidst distractors of four different shapes was easy, with over 80% of first saccades going directly to the target. In the conjunction search task, three subjects were able to locate targets with a single saccade on 60–70% of occasions in the inner ring and on 16–40% in the outer ring. Erroneous first saccades were likely to be directed to a non-target in the inner ring (Fig. 7) and also to a non-target sharing one feature with the target (Table 3). The latency of the first saccades was generally in the 200–300 msec range.

Search accuracy and saccade accuracy

In all cases, a high proportion of first saccades were directed to the target. Whilst not a particularly surprising finding, it has only been shown clearly in one previous study of visual search (Viviani & Swensson, 1982) and contrasts in particular with the findings of Williams (1966, 1967). In Williams' tasks, subjects made many inaccurate first saccades. Williams used a greater range of colours and shapes so the difference may depend on the degree of target–nontarget discriminability. A second possible reason for the difference is the nature of the displays used, which in Williams' case contained a greater number of elements and had a greater density of elements. As has been noted (Bouma, 1978; Cohen & Ivry, 1991; Palmer et al., 1993), discrimination in dense or cluttered displays is degraded because of lateral masking. The displays used were designed to minimise such lateral masking effects.

In Experiment 2, prior knowledge proved more effective than intrinsic display factors in producing accurate saccades. In the oddity task of this experiment, the target was defined as being a "singleton", different in colour from all the distractors. Inaccurate saccades occurred frequently (Fig. 1), even though the situation generated strong perceptual pop-out. The extent to which isolated feature differences can capture attention has been the subject of recent debate (e.g. Bravo & Nakayama, 1992; Folk & Annett, 1994). One factor which is important is the display density. The displays used in

Experiment 2 were quite sparse and a colour singleton in a more closely spaced display might be a more effective target.

Even with separated targets, "averaging" saccades (Findlay, 1982) were found in Experiment 3 when an occasional double target trial was presented. A suggested explanation for averaging is that it is a reflection of spatial processing using large receptive fields in the superior colliculus (Findlay, 1987; Lee et al., 1988; Glimcher & Sparks, 1993). Whilst the superior colliculus is unlikely to be the site of target vs non-target discrimination on the basis of colour, it may act as a final common path for saccades, receiving signals from cortical centres (Ottes et al., 1987)

Figure 4 shows saccade end-points to displays where two targets were separated by a non-target. A number of saccades in this situation showed averaging for direction but had reduced amplitudes, leading to a clearly demarcated region around the non-target in which no saccades fell. Current work on the neurophysiology of target selection in cortical regions (Chelazzi et al., 1993; Schall & Hanes, 1993; Schiller & Lee, 1994) has found both enhancement of cell firing when a cell is coding a target property and suppression when the cell is not. Such a combination of inhibition and excitation provides a mechanism for target selection and would also be capable of explaining the distribution of saccade end-points, as shown in Fig. 4.

It is likely that such a pattern of inhibition and excitation takes time to build up. Figure 4 shows one saccade with very short latency landing on a non-target. In other cases also, misdirected saccades show a tendency to land on neighbouring non-targets (Figs 1 and 7). In these cases, the target signal interacts *additively* with a signal from a non-target. Such additive interaction has been noted in studies of saccades to a target in the presence of a single non-target (Ottes et al., 1985; He & Kowler, 1989) with saccades often landing at intermediate locations between the target and non-target positions. Further work is needed to disentangle those situations where excitatory and those where inhibitory influences dominate.

The latency of the first saccade

In cognitive psychology, it is customary to expect a tight link between task difficulty and chronometric measures. Thus, in studies of search using manual reaction time, it is generally assumed that the reaction time reflects the information processing load involved in the task. In the saccadic situation more caution is needed in interpreting latencies since they are influenced by both low level and cognitive factors. When a new stimulus appears, some form of "compulsion to orient" dictates the release of the eye movement and a saccade may be produced with a latency which is independent of programming difficulty (cf. Findlay & Kapoula, 1992).

A dramatic decrease in latency, known as the "gap effect", is found when stimulation at fixation disappears shortly before a saccade target appears (Saslow, 1967).

The effect may be accounted for by the two low level effects of temporal alerting and fixation disengagement (Reuter-Lorenz & Fendrich, 1992, Walker et al., 1995). Concerning the latter, it appears that one process (fixation) holds the eye in place whilst visual information is analysed and a second process (move) initiates a sequential sampling of new regions of visual space (Findlay, 1992; Munoz & Wurtz, 1992). The processes work competitively and are influenced by events at the fixation point. These effects were manifest in the contrast between the long latencies in tasks where the central stimulus remained on, and the much shorter latencies in those where it was removed.

Cognitive factors affect saccade latencies, as shown by a long tradition of work relating the length of a fixation to the amount of information processing of the fixated material at the fovea (Gould, 1973, Rayner, 1995). As well as foveal processing, visual material in the periphery is processed during fixation. In some cases, this processing increases fixation durations (Nazir & Jacobs, 1991). In others, processing of peripheral material is carried out in parallel with that of central material. Lévy-Schoen (1981) asked subjects to scan two symbols at different locations in peripheral vision. Using a gaze contingent display, the more distant symbol could be modified either before, or after, the subject's fixation on the nearer symbol. Peripheral information from the symbol was processed if available, since the duration of the subsequent fixation on the symbol was reduced and the overall discrimination was speeded. However the availability of the information did *not* influence the duration of the *preceding* fixation, that is the one where the symbol was seen in the periphery. This suggests that the peripheral information is processed in a parallel stream to the central information processing stream and only the central processing stream influences saccade latency.

No foveal processing was required in the present experiments except in the match task of Experiment 2 in which a small but consistent latency increase resulted. The effects of peripheral processing in the present set of experiments were also quite small. Thus the latency differences between the most difficult task (Experiment 5) and an easy task (Experiment 1) were about 30 msec. In Experiments 4 and 5, latencies for targets in near positions were shorter by up to 40 msec than those for targets in the far position.

These findings suggest that the generation of the first saccade is a relatively automatic process, rather than one which is subject to cognitive control. However, the presence of occasional long latency saccades suggests that a form of tactical over-ride can sometimes occur. There were also occasional runs from individual subjects in which delays occur which might be more strategic. It might even be suggested that the unexpectedly *short* latencies shown by RW in Experiment 5 reflected a strategic decision that the task was one in which attempting to use peripheral vision was not worthwhile.

Implications for theories of visual search

The present study has found accurate on-target saccades to targets in at least eight possible positions in simple colour or shape search tasks, and accurate movements to about six or seven locations in a colour–shape conjunction task. In these cases, overt saccadic search is clearly not serial.

In models of search, as in the classic account of Treisman and Gelade (1980), appeal is often made to covert attentional scanning. In relating the present work to models of search, the link between such covert attentional shifts and overt eye movements must be addressed. Evidence suggests that overt eye movements are accompanied and preceded by an attentional shift (Shepherd et al., 1986; Hodgson & Müller, 1995; Schneider & Deubel, 1995). Covert attentional shifts are clearly possible but an unresolved issue is the rate at which such shifts can occur (Duncan et al., 1994; Duncan, 1995).

How might a theory of search be developed which incorporates both overt and covert attentional movements? Two extreme possibilities can be set out while recognising that intermediate positions between the extremes are also possible. The first possibility, based on the ideas of Treisman and Gelade (1980), would suggest that rapid covert shifts of attention occur to locate the target. The eye movement might be initiated once the target is found and not reflect more than a minor part of the process of attentional allocation. The second position would suggest that when the eyes are free to move, eye movements exclusively constitute the way attention is allocated. Thus the movements of the eyes reflect precisely the attentional scan and covert attention plays no role. These two possibilities may be conveniently referred to as serial or parallel processing within a fixation.

Although the first position (serial scanning by covert attention) cannot be ruled out on the basis of the present data, neither do the data provide any positive support. The data from Experiment 5 on feature conjunction search are particularly relevant, since this is a situation where serial scanning would be expected according to the classical search theory of Treisman and Gelade (1980). If a rapid serial scanning with covert attention could occur before the saccade is initiated, it is not clear why incorrect saccades would occur so frequently. Moreover, the data place constraints on the speed of any hypothetical serial scanning process since it would be necessary for a number of locations to be scanned before the target is located, given the accuracy obtained. This process must be completed in the 250 msec latency period for the saccade. Since a proportion of saccade latency (often estimated at 70 msec) is occupied by peripheral (retinal and oculomotor) processes, an estimate of about 30 msec per item (six items in 180 msec) can be derived for the speed of a hypothetical serial process of covert attentional scanning. Another comparison is between the 250 msec latency in feature conjunction search (Experiment 5) and the 200 msec latency of simple colour search (Experiments 1–2). If the additional latency is taken as the extra time required to deploy covert attention, an even faster rate (8 msec per item) is deduced.

If the increase in reaction time with display size in the standard visual search paradigm is taken to reflect the operation of the serial scanning process, then the slope of the function showing this increase gives an estimate of search rate. Experiment 1 of Treisman and Gelade (1980) pursued this logic and found a slope of 28.7 msec per item in a colour shape feature conjunction task. Whilst this figure is nicely concordant with the first search rate deduced above, caution must be exercised. This figure is an indirect measure, derived from experiments with manual responses which are in the range 400–600 msec. If only a small fraction of this time is employed in scanning through the set of search elements, it seems legitimate to ask what is occurring during the remainder of the period, particularly as the present experiments have shown that accurate saccadic responses can be made with latencies of 200–300 msec.

Several pieces of work have cast doubt on such a straightforward interpretation of search rate slopes, drawing attention to the theoretical point made by Townsend (1971) that serial and parallel processes cannot in principle be distinguished with such measures. Furthermore, other estimates of the speed of covert orienting have cast doubt on such a fast rate for the deployment of covert attention (Nakayama & Mackeben, 1989; Duncan et al., 1994). Alternative accounts of the visual search process have appeared which assign much more weight to parallel processes (Duncan & Humphreys, 1989; Treisman & Sato, 1990; Wolfe, 1994) and avoid the postulation of rapid serial scanning. Pashler (1987), following Hoffman (1978), argued for a hybrid model to explain results in colour form conjunction search. In his model about eight items can be searched for in parallel but serial search is required for displays of larger number. The results of Experiment 5 are consistent with such a model.

Parallel processing and saccade generation

Parallel processing models are well suited to providing an account of eye movement generation. Such models frequently invoke the concept of a master activation map which codes the salience of different locations in the visual field (Treisman & Sato, 1990, Wolfe, 1994). Such a map would be activated in a spatiotopic way from the various visual feature maps under the control of some additional top-down selective processes (e.g. so that red and circular items are weighted). The map would form a landscape consisting of peaks, valleys, troughs, etc.

A plausible suggestion to link such maps with eye movement generation is to equate the highest peak of the salience map with the saccade goal. Such a formulation might appear trivial in the sense of merely restating the obvious fact that saccades have a unique goal. However, it provides a perspective in which other results can be understood. As shown in Table 3, erroneous saccades are likely to be directed to a non-target sharing a feature with

the targets. Such items would receive positive weighting from the feature and thus tend themselves to form a peak in the salience map. If the process of formation of the salience map is noisy, this peak might become the main peak rather than a subsidiary one, thus accounting for the direction of the erroneous saccades.

An additional problem brought into focus by the consideration of a master salience map is that of the location of the point of highest salience in such a map. This is a non-trivial task, given that it must be accomplished by an autonomously operating neural network. It is only possible to be certain that the point of highest salience has been reached if a comparison has been made, explicitly or implicitly, with *all* other locations. Such a task is in itself a form of search task. The peak finding process can be simplified if coarse spatial coding is used (Findlay, 1987). It is interesting that coarse spatial coding appears to be a general characteristic of the operation of the saccadic system, as shown by several results in the current paper as well as earlier work with simple target elicited saccades (Findlay, 1982).

One way in which the peak location might occur is through the operation of recurrent reciprocal inhibitory cross connections within a two-dimensional map-like neural network. The envisaged cross-connections function so that activity at the input of the connection decreases activity at the termination. A network containing such reciprocal inhibitory cross-connections is inherently unstable if multiple centres of activity are present and will tend to evolve to a more stable "winner take all" state where the strongest peak dominates. Such networks have been proposed as an alternative to input filtering as a mechanism to achieve attentional selectivity (Desimone, 1992; Duncan, 1995). Future work will be needed to demonstrate whether the dynamics of such a process can mimic the classic results which suggest serial search.

REFERENCES

Bloomfield, J. R. (1979). Visual search with embedded targets: color and texture differences. *Human Factors, 21,* 317–330.

Bouma, H. (1978). Visual search and reading: eye movements and functional visual field. A tutorial review. In Requin, J. (Ed.), *Attention and performance 7* (pp. 115–147). Hillsdale, NJ: Lawrence Erlbaum.

Bravo, M. J. & Nakayama, K. (1992). The role of attention in different visual search tasks. *Perception and Psychophysics, 51,* 465–472.

Chelazzi, L., Muller, E. K., Duncan, J. & Desimone, R. (1993). A neural basis for visual search in inferior temporal cortex. *Nature, 363,* 345–347.

Cohen, A. & Ivry, R. B. (1991). Density effects in conjunction search: evidence for a coarse location mechanism of feature integration. *Journal of Experimental Psychology, Human Perception and Performance, 17,* 891–901.

Collewijn, H., van der Mark, F. & Jansen, T. C. (1975). Precise recordings of human eye movements. *Vision Research, 15,* 447–450.

Desimone, R. (1992). Neural circuits for visual attention in the primate brain. In Carpenter, G. A. & Grossberg, S. (Eds), *Neural networks for vision and image computation* (pp. 343–364). Cambridge, MA: MIT Press.

Duncan, J. (1989). Boundary conditions on parallel processing in human vision. *Perception, 18,* 457–469.

Duncan, J. (1995). Cooperating brain systems in perception and action. In Inui, T. & McClelland, J. L. (Eds), *Attention and performance XV.* Cambridge, MA: MIT Press.

Duncan, J. & Humphreys, G. W. (1989). Visual search and stimulus similarity. *Psychological Review, 96,* 433–458.

Duncan, J., Ward, R. & Shapiro, K. (1994). Direct measurement of attention switching time in human vision. *Nature, 369,* 313–315.

Enns, J. T., Ochs, E. P. & Rensink, R. A. (1990). VSearch. Macintosh software for experiments in visual search. *Behavior Research Methods, Instrumentation and Computers, 22,* 118–122.

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. (1992). Programming of stimulus elicited saccadic eye movements. In Rayner, K. (Ed), *Eye movements and visual cognition* (pp. 8–30). New York: Springer.

Findlay, J. M., Brogan, D. & Wenban-Smith, M. (1993). The visual signal for saccadic eye movements emphasizes visual boundaries. *Perception and Psychophysics, 53,* 633–641.

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

Folk, C. L. & Annett, S. (1994). Do locally defined feature discontinuities capture attention? *Perception and Psychophysics, 52,* 277–287.

Glimcher, P. W. & Sparks, D. L. (1993). Representation of averaging saccades in the superior colliculus of the monkey. *Experimental Brain Research, 95,* 429–435.

Gould, J. D. (1973). Eye movements during visual search and memory search. *Journal of Experimental Psychology, 98,* 184–195.

Gould, J. D. & Dill, A. (1969). Eye movement parameters and pattern discrimination. *Perception and Psychophysics, 6,* 311–320.

He, P. & Kowler, E. (1989). The role of location probability in the programming of saccades: implications for "center-of-gravity" tendencies. *Vision Research, 29,* 1165–1181.

Hodgson, T. L. & Müller, H. J. (1995). Evidence relating to premotor theories of visuospatial attention. In Findlay, J. M., Walker, R. & Kentridge, R. W. (Eds), *Eye movement research: mechanisms, processes and applications* (pp. 305–316). Amsterdam: Elsevier.

Hoffman, J. E. (1978). Search through a spatially presented visual display. *Perception and Psychophysics, 23,* 1–11.

Jacobs, A. M. (1986). Eye movements control in visual search: how direct is visual span control? *Perception and Psychophysics, 39,* 47–58.

Jacobs, A. M. (1991). Eye movements in visual search: a test of the limited cognitive effort hypothesis and an analysis of the search operating characteristic. In Schmid, R. & Zambarbieri, D. (Eds), *Oculomotor control and cognitive processes. Normal and pathological aspects* (pp. 397–410). Amsterdam: North-Holland.

Klein, R. & Farrell, M. (1989). Search performance without eye movements. *Perception and Psychophysics, 46,* 476–482.

Lee, C., Rohrer, W. H. & Sparks, D. L. (1988). Population coding of saccadic eye movements by neurons in the superior colliculus. *Nature, 332,* 357–360.

Lévy-Schoen, A. (1981). Flexible and/or rigid control of visual scanning behaviour. In Fisher, D. F., Monty, R. A. & Senders, J. W. (Eds), *Eye movements: cognition and visual perception* (pp. 299–314). Hillsdale, NJ: Lawrence Erlbaum.

Maljkovic, V. & Nakayama, K. (1994). Priming of pop-out: I. Role of features. *Memory and cognition, 22,* 657–672.

Munoz, D. P. & Wurtz, R. H. (1992). Role of the rostral superior colliculus in active visual fixation and execution of express saccades. *Journal of Neurophysiology, 67,* 1000–1002.

Nakayama, K. & Mackeben, M. (1989). Sustained and transient components of focal visual attention. *Vision Research, 29,* 1631–1647.

Nazir, T. & Jacobs, A. M. (1991). The effects of target discriminability and retinal eccentricity on saccade latencies: An analysis in terms of variable criterion theory. *Psychological Research, 53,* 287–299.

Ottes, F. P., Van Gisbergen, J. A. M. & Eggermont, J. J. (1985).

Latency dependence of colour-based target vs nontarget information by the saccadic system. *Vision Research, 25,* 849–862.

Ottes, F. P., Van Gisbergen, J. A. M. & Eggermont, J. J. (1987). Collicular involvement in a saccadic colour discrimination task. *Experimental Brain Research, 66,* 475–478.

Palmer, J., Ames, C. T. & Lindsey, D. T. (1993). Measuring the effect of attention on simple visual search. *Journal of Experimental Psychology, Human Perception and Performance, 19,* 108–130.

Pashler, H. (1987). Detecting conjunction of color and form: reassessing the serial search hypothesis. *Perception and Psychophysics, 41,* 191–201.

Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology, 32,* 3–25.

Posner, M. I., Nissen, M. J. & Ogden, M. C. (1978). Attended and unattended processing modes: the role of set for spatial location. In Pick, H. L. & Saltzman, I. J. (Eds), *Modes of perceiving and processing information* (pp. 137–157). Hillsdale, NJ: Lawrence Erlbaum.

Prinz, W. (1984). Attention and sensitivity in visual search. *Psychological Research, 45,* 355–366.

Prinz, W., Nattkempfer, D. & Ullman, T. (1992). Moment to moment control of saccadic eye movements: evidence from continuous search. In Rayner, K. (Ed), *Eye movements and visual cognition* (pp. 108–129). New York: Springer.

Rayner K. (1995). Eye movements and cognitive processes in reading, visual search, and scene perception. In Findlay, J. M., Walker, R. & Kentridge, R. W. (Eds), *Eye movement research: mechanisms, processes and applications* (pp. 3–22). Amsterdam: North Holland.

Rayner, K. & Fisher, D. L. (1987). Letter processing during eye fixation in visual search. *Perception and Psychophysics, 42,* 87–100.

Reuter-Lorenz, P. A. & Fendrich, R. (1992). Oculomotor readiness and covert orienting: Differences between central and peripheral precues. *Perception and Psychophysics, 52,* 336–344.

Saslow, M. G. (1967). Effects of components of displacement-step stimuli upon latency for saccadic eye movement. *Journal of the Optical Society of America, 57,* 1030–1033.

Schall, J. P. & Hanes, D. P. (1993). Neural basis of target selection in frontal eye field during visual search. *Nature, 366,* 467–469.

Schiller, P. H. & Lee, K. M. (1994). The effects of lateral geniculate nucleus, area V4, and middle temporal lesions on visually guided eye movements. *Visual Neuroscience, 11,* 229–241.

Schneider, W. X. & Deubel, H. (1995). Visual attention and saccadic eye movements: evidence for obligatory and selective spatial coupling. In Findlay, J. M., Walker, R. & Kentridge, R. W. (Eds), *Eye movement research: mechanisms, processes and applications* (pp. 317–324). Amsterdam: Elsevier.

Shepherd, M., Findlay, J. M. & Hockey, G. R. J. (1986). The relationship between eye movements and spatial attention. *Quarterly Journal of Experimental Psychology, 38A,* 475–491.

Townsend, J. T. (1971). A note on the identifiability of parallel and serial processes. *Perception and Psychophysics, 10,* 161–163.

Treisman, A. (1993). The perception of features and objects. In Baddeley, A. & Weiskrantz, L. (Eds), *Attention, selection, awareness and control* (pp. 5–35). Oxford: Clarendon Press.

Treisman, A. & Gelade, G. (1980). A feature integration theory of attention. *Cognitive Psychology, 12,* 97–136.

Treisman, A. & Gormican, S. (1988). Feature analysis in early vision: Evidence from search asymmetry. *Journal of Experimental Psychology, Human Perception and Performance, 10,* 12–31.

Treisman, A. & Sato, S. (1990). Conjunction search revisited. *Journal of Experimental Psychology, Human Perception and Performance, 16,* 459–478.

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., Kentridge, R. W. & Findlay, J. M. (1995). Independent contributions of the orienting of attention, fixation offset and bilateral stimulation on human saccadic latencies. *Experimental Brain Research, 103,* 294–310.

Widdel, H. (1983). A method for measuring the visual lobe area. In Groner, R., Menz, C., Fisher, D. F. & Monty, R. A. (Eds), *Eye movements and psychological functions: international views* (pp. 73–83). Hillsdale, NJ: Lawrence Erlbaum.

Williams, L. G. (1966). The effect of target specification on objects fixated during visual search. *Perception and Psychophysics, 1,* 315–318.

Williams, L. G. (1967). The effects of target specification on objects fixated during visual search. In Sanders, A. F. (Ed.), *Attention and performance I* (pp. 355–360). Amsterdam: North-Holland.

Wolfe, J. M. (1994). Guided search 2.0. A revised model of visual search. *Psychonomic Bulletin and Review, 1,* 202–228.

Wolfe, J. M., Cave, K. R. & Franzel, S. L. (1989). Guided search: an alternative to the feature integration model for visual search. *Journal of Experimental Psychology, Human Perception and Performance, 15,* 419–433.

Zelinsky, G. & Sheinberg, D. (1995). Why some search tasks take longer than others: using eye movements to redefine reaction times. In Findlay, J. M., Walker, R. & Kentridge, R. W. (Eds), *Eye movement research: mechanisms, processes and applications* (pp. 325–336). Amsterdam: North-Holland