Saccade target selection in visual search: Accuracy improves when more distractors are present

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We report four experiments with search displays of Gabor patches. Our aim was to study the accuracy of gaze control in search tasks. In Experiment 1, a target was presented with a single distractor Gabor of a different spatial frequency on the same axis. Subjects could locate the target with the first saccade if the distractor was more distant, but when the distractor was between the fixation point and the target, the first saccade landed much closer to the distractor. In Experiment 2, the number of display items was increased to 16 in a double ring configuration. With this configuration, first saccades were accurately directed to the target, even when there was an intervening distractor in exactly the same configuration as in Experiment 1. Experiment 3 suggested that the improvement in accuracy was not due to distractor homogeneity but rather may be attributable to the increased first saccade latency with the ring configuration. In the final experiment, latency was shown to covary with saccade accuracy. The results are related to a general framework whereby the presence of distractors operates to hold fixation for a longer period of time, thus allowing a greater period of visual processing and more accurate eye movements.

Keywords: saccade, visual search, oculomotor control, spatial frequency, accuracy, global effect

Introduction

Studies in human vision are increasingly addressing the dynamic nature of visual activity (Ballard, Hayhoe, Pook & Rao, 1997; Findlay, 1998; Gilchrist, North & Hood, 2001). Under most situations in which vision is employed, saccadic eye movements are used to scan the visual scene actively at a rate of three or four movements each second. The task of visual search has proved to be a very productive paradigm to investigate active vision (Findlay & Gilchrist, 2001). A frequently studied task requires visual search of displays of a set of discrete items that are either the target (the item being searched for) or distractors (items with different properties). Early work in this area (Treisman & Gelade, 1980) used a global level of analysis (total time to carry out the search task) and identified an important distinction between search tasks that can be carried out with ‘pre-attentive’ visual processes and those that require attention. In certain tasks (e.g. searching for a red target in a display where all the distractors are green), search is accomplished very rapidly no matter how many distractors are present. The target appears to ‘pop out’ of the display effortlessly, suggesting that the segregation of target and distractors is made by low-level processes operating in parallel across the entire visual field.

Other tasks require more effort and an indicator of this is that search becomes more difficult as the number of distractors present increases. Such tasks are said to require attention and in practice the searcher usually will scan his or her eyes around the displays. Although one tradition (Treisman & Gelade, 1980; Wolfe, 1994) has emphasised covert attention, i.e. the recognised ability to attend ‘out of the corner of the eye’ (Posner, 1980), greater emphasis has been placed recently on active eye scanning (Zelinsky, 1996; Findlay, 1997; Zelinsky, Rao, Hayhoe & Ballard, 1997; Hooge & Erkelens, 1999; McSorley & Findlay, 2001; Eckstein, Beutter & Stone, 2001; Beutter, Eckstein & Stone, 2003; Gilchrist, Heywood & Findlay, 2003). Arguments have been advanced (Findlay & Gilchrist, 2001) that covert attention plays little part provided free scanning is possible except by providing a brief period of improved processing of visual information at the destination of forthcoming saccades (Kowler, Anderson, Dosher & Blaser, 1995; Deubel & Schneider, 1996). Work on eye scanning in studies of human visual search has proceeded in parallel with exciting developments in understanding visual search in primates, both at the behavioural level (Motter & Belky, 1998a; Motter & Belky, 1998b) and that of neurophysiology (Schall & Hanes, 1993; Bichot & Schall, 1999; Hasegawa, Matsumoto & Mikami, 2000; McPeek & Keller, 2002). A general finding has been that, in pre-attentive searches, the target can usually be located with a single saccadic eye movement, whereas in effortful search, several saccades are generally needed.

The aim of the current paper was to explore the dynamic nature of the eye movement system through the use of a visual search paradigm. Active search for targets defined by their spatial frequency was examined. It is
widely accepted that the visual system processes visual information via parallel channels which are differentially responsive to spatial frequencies (DeValois & DeValois, 1988; Graham, 1989). Furthermore, it has been shown with visual search tasks that spatial frequency can be considered a visual primitive (Moraglia, 1989; Sagi, 1990; Carrasco, McLean, Katz & Freider, 1998). However a previous study suggested that the saccadic system might show a less differentiated response. Findlay, Brogan & Wenban-Smith (1993) required participants to make saccadic eye movements to targets consisting of checkerboard patches. When two checkerboard patches of different grain size (hence different spatial frequency content) were presented on an axis to the right or left of fixation, saccades tended to land at a position intermediate between the landing positions to single targets. The saccades thus showed the well-known 'global' or 'centre of gravity' effect (Coren & Hoenig, 1972; Findlay, 1982; Deubel, Wolf & Hauske, 1984; Ottes, Van Gisbergen & Eggermont, 1984; Melcher & Kowler, 1999). The task in the Findlay et al. experiment was designed to encourage accurate saccades by requiring identification of fine detail at the target locations. However no explicit search instructions were given. In our first experiment, we report the results of a search task for a target defined by its spatial frequency content with a similar target configuration to that of Findlay et al. We find that the target could not be accurately located with a single saccade but rather a global effect emerged similar to that reported by Findlay et al. We then tested various other display configurations and found that a target defined by spatial frequency can be located with a single eye movement when there are a large number of distractors. We show that this is not due to grouping (Bravo & Nakayama, 1992) or similarity (Duncan & Humphreys, 1989). We interpret the result in terms of oculomotor constraints, and demonstrate how the result provides insight into the operation of the saccadic system.

General Method

Stimuli

The displays were generated with custom purpose software using a VSG graphics card (Cambridge Research Ltd., UK) and presented on a gamma corrected EIZO 21” monochrome monitor, with a refresh rate of 69 Hz, a pixel size of 0.36 mm and a mean luminance of 33.2 cd/m². The stimuli were Gabor patches with centre spatial frequencies of 1, 2 and 4 cpd. The patches had a standard deviation of 0.44 deg. They were presented at a viewing distance of 1m. and 90% contrast. Figure 1 gives an overview of the different display configurations used in the experiments. The displays consist of a target patch coupled with a number of distractor patches. The distractor patches had a spatial frequency content centred on 2 cpd in all cases. The target was a single Gabor, centred at either 1 cpd or 4 cpd.

Procedure

Each trial started with a central fixation cross presented for 500 ms. plus an added foreperiod of between 0 and 500 ms. This was followed by the experimental display which was presented for 1s. With the onset of the experimental display the central fixation cross was removed from display. In all experiments subjects were required to indicate the location of the predefined target by making a saccade which was as quick and as accurate as possible. Subjects were asked to saccade to the low (1 cpd) or high spatial frequency patch (4 cpd) (described as the fatter or thinner lines) separately in counterbalanced blocks.
Eye Movement Recording and Analysis

Two-dimensional recordings of the right eye were made using a Fourward Technologies Dual Purkinje Image Eyetracker (Crane & Steele, 1985). The displays were viewed binocularly and head movements were minimised with a chin rest and two forehead rests. The subjects head was held steady by a strap from the forehead rest around the back of the head. For the duration of the experimental display the eyetracker position outputs were recorded at 200 Hz by a separate computer using in house written acquisition software. Each block of trials was preceded by a calibration procedure for which the subject was required to saccade to nine small crosses positioned in a square array separated horizontally and vertically by 6 deg. The eye movement data were analysed off line by a semi-automatic procedure using an algorithm to detect the beginning and end of the saccade. The algorithm detected the first instance of two successive samples differing by more than a threshold magnitude (equivalent to registering a criterion velocity set at about 50 deg/sec). A backward search procedure with a lower criterion threshold (equivalent to 20 deg/sec) then located the exact beginning of the saccade. On occasional trials (<1%), this algorithm was triggered by small movements at the fixation that preceded the first saccade; in such cases the saccade onset was selected manually. Saccades with latencies of less than 100 ms or greater than 450 ms were automatically excluded. Furthermore saccades which had an initial starting position greater than 1 deg from the central fixation cross were also excluded. The saccade landing position was taken as that at which four successive samples differed by less than an end criterion threshold (equivalent to a velocity of less than 3 deg/s). This produced two measures for each saccade that were analysed further: the time from display onset to the initiation of the saccade or saccade latency and the distance of the saccade from initial starting point to the saccade landing position or saccade amplitude.

Experiment 1

Gabor patches were shown at 3 deg or 6 deg from the centre (see Figure 1A–D) either to the right or left. If the target appeared at 3 deg then the distractor was shown at 6 deg and vice versa. On some trials, the target patches were presented with no distractor in order to provide a baseline from which the influence of the distracting patch could be calculated. Therefore there were four stimulus presentation conditions: target only, shown at 3 deg (3t) or 6 deg (6t); the target at 3 deg with a distractor shown at 6 deg (3t6d); the target at 6 deg and the distractor at 3 deg (6t3d). These were shown on the left and right hand side of the screen giving eight conditions overall. There were 80 trials per target spatial frequency therefore 10 trials per condition.

Six subjects, of whom four were female, took part in the experiment. This included one of the authors. Their age range was 25 to 59 years. All had normal vision, were naïve as to the purpose of the experiment and had a range of experience in eye movement experiments.

Results

We defined an accuracy measure as follows. On-target saccades to a target at 3 deg were defined using a criterion that saccade amplitude was greater than 1 deg and less than 4.5 deg. For a target at 6 deg, the amplitude criterion required the saccade amplitude to be greater than 4 deg but less than 7.5 deg. These slightly overlapping zones are employed because of the tendency for the saccades to be hypometric and are comparable to those used in a previous study (Findlay, 1997). Results of this analysis are shown in Table 1. Overall 904 saccades were analysed of which 677 (74.9%) were classified as on-target. Low spatial frequency targets were found to elicit 449 saccades of which 337 (75.1%) were on-target; and the high spatial frequency target was found to elicit 455 saccades of which 339 (74.5%) were on-target. A 3-way repeated measures ANOVA was carried out with side of target, spatial frequency and accuracy as factors.

Table 1. Saccade Accuracy (On-target Saccades/Total Saccades) and Average Saccade Latencies in ms (with Standard Deviations) of First Saccades from Experiment 1.

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<td>15</td>
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</table>

Results from the low spatial frequency target are shown in the three leftmost columns while results from the high spatial frequency target are shown in the three rightmost columns. Saccades were classified as being on-target using the accuracy classification described in the text. The variations in the total number of saccades results from tracker loss.
presentation (left or right), spatial frequency (low or high), and target-distractor conditions (3t, 3t6d, 6t, 6t3d). Target configuration had a significant effect on accuracy with 6t3d showing a dramatic reduction in saccade accuracy (11 accurate saccades out of 113 for the low spatial target and 3 accurate saccades out of 114 for the high spatial frequency target; see Table 1) as compared to the other conditions: $F(1, 5) = 753.8; p < 0.05$. There were no other effects of any significance.

The mean latencies for first saccades are also shown in Table 1. A repeated measures ANOVA revealed no effect of side of presentation so the data were collapsed across this dimension. Spatial frequency of the target did not show a significant effect but there was a trend: $F(1, 11) = 3.7; p = 0.08$, for high spatial frequencies targets to elicit a slightly longer latency than low spatial frequency targets. There was no significant effect of condition: $F (1, 11) = 1.8; p > 0.05$; and no interactions were significant: all $F < 1$. However, it is clear from Table 1 that on-target saccade latencies when the target was in the far position (6t3d) were substantially longer than those landing “off-target”.

As noted in the introduction saccades tend to land at an intermediate position between two stimuli when they are presented on the same axis (Coren & Hoenig, 1972; Findlay, 1982; Deubel, Wolf & Hauske, 1984; Ottes, Van Gisbergen & Eggermont, 1984; Melcher & Kowler, 1999). In order to assess distractor influence on target driven saccade amplitudes the global effect percentage (GEP) was calculated using the following formula.

\[
\text{GEP} = 100 \times \left( \frac{A - A_n}{A_f - A_n} \right),
\]

where $A_n$ is the average saccade amplitude to targets presented alone at 3 deg, $A_f$ is the average saccade amplitude to targets presented alone at 6 deg, and $A$ is the amplitude of saccades evoked by target-distractor pairs. Thus the GEP measures the relative influences of the near and far stimuli. The effect of this equation on saccade amplitudes is illustrated in Figure 2. Here we have plotted the data from one subject showing saccade direction in terms of its angular deviation and saccade amplitude. The unfilled symbols show the raw data for each trial and the filled symbols plotted on the abscissa show the average saccade amplitude for each condition. The GEP computation employed here is a measure of the influence that each Gabor patch has on saccade amplitude regardless of which Gabor patch is the target and the distractor. The average amplitudes elicited by each target alone, i.e., 3t or 6t, are treated respectively as the 0% and 100% points on a percentage scale. If a saccade elicited when two-items are shown is largely influenced by the near one then its GEP tends towards 0%. On the other hand if the saccade amplitude tends towards far patch then its GEP tends towards 100%. To illustrate with the case of the subject shown in Figure 2: the average saccade amplitude found when the target was shown alone in the near position was 2.30 deg and in the far position was 4.60 deg; while the average saccade amplitude found when two-items were shown with the target in the near position (3t6d) was 2.31 deg and in the far position was 2.80 deg. Thus the saccade amplitude in the 3t6d condition was almost the same as the average when the target is shown alone in the near position thus its GEP is 0.4% (the calculation is: $0.4 = (2.31 - 2.30)/(4.60 - 2.30) \times 100$); while the average saccade amplitude found in the 6t3d condition was some way between the average saccade amplitudes found in either target alone condition and thus the GEP here was 21.7% (the calculation is: $21.7 = (2.80 - 2.30)/(4.60 - 2.30) \times 100$).

Figure 3 shows the GEP for target-distractor pairs over all subjects. It can be seen that saccade amplitudes were affected when the target was coupled with a distractor. When the target was shown at 3 deg while the distractor was shown at 6 deg on average saccade amplitude is “pulled” across toward the distractor, showing a GEP of 11.6 % (Low spatial frequency: 10.6%; High spatial frequency: 12.5%). When the target is shown at 6 deg while the distractor is shown at 3 deg, the average GEP is 24.3% (Low spatial frequency: 31.4%; High spatial frequency: 17.2%). The extent of the global effect with this configuration is similar to that found in the study by Findlay et al (1993) using checkerboard patches as stimuli.

**Discussion**

Unsurprisingly, when only a single target was presented, the eye made an immediate saccade to the target in nearly all cases. However, the saccades showed systematic...
Figure 3. Mean global effect percentage in Experiment 1 by target - distractor pairing separately by spatial frequency. Error bars are standard deviations.

The results from Experiment 1 show visual search with the eye is hampered by the intervening presence of a distractor of a different spatial frequency content. This finding seems inconsistent with results showing that spatial frequency is a visual primitive and can generate pop-out in search tasks using reaction time measures (Moraglia, 1989; Sagi, 1990; Carrasco, McLean, Katz & Freider, 1998). We suspected our result could be due to the way that the stimuli were arranged along the horizontal meridian. In Experiment 2, we used a display with 16 possible target locations: an equal number arranged equidistant on two imaginary concentric rings. The target appeared in one of the positions while the remaining fifteen were taken by distractors. Thus in eight cases a distractor was present between the fixation spot and the target.

Sixteen Gabor patches were arranged into two rings of eight patches each (see Figure 1G). These had a radius of $2.5^\circ$ and $5^\circ$ (a reduction from $3^\circ$ and $6^\circ$ due to unforeseen display restrictions on the vertical axis) respectively and were presented so that each ring was centred on fixation. The target could appear in anyone of the 16 locations. The remaining 15 positions were taken up by Gabor patches with the distracting spatial frequency content. Thus there were 16 conditions corresponding to the possible target locations. There were 160 trials per block therefore 10 trials per condition.

Six new subjects, three of whom were female, took part in the experiment. Their age range was 19 to 27 years. All had normal vision, were naive as to the purpose of the experiment and had a range of experience in eye movement experiments. Subjects were required to make a saccade to the predefined target as quickly and accurately as possible. Subjects searched for the low and the high spatial frequency target in two separate counterbalanced blocks.

**Results**

Saccades were classified as “on-target” if they landed within a sector 15 degrees either side of the target and met an amplitude criteria proportional to that employed in Experiment 1. On-target saccades to a target at $2.5^\circ$ were defined using a criterion that saccade amplitude was greater than $1^\circ$ and less than $3.75^\circ$. For a target at $5^\circ$, the amplitude criterion required the saccade amplitude to be greater than $3.33^\circ$ but less than $6.25^\circ$. Overall 1763 saccades were analysed of which 1451 (82.3%) were classified as on-target. Performance was good with the target landing position being $89.5%$. When the target was of a lower spatial frequency targets elicited 860 saccades of which 770 (89.5%) were on-target; and the high spatial frequency target elicited 903 saccades of which 681 (75.4%) were on-target. When the target was of a lower spatial frequency 390 out of 427 (91.3%) were correctly directed to the closer distance while 380 of 433 (87.8%) saccades were correctly directed when the target was shown at the farther distance; and when the higher spatial frequency was the target 370 of 451 (82%) of saccades were correctly directed to the inner ring while 311 of 452 (68.8%) of saccades were correctly directed when the target was at the nearer edge of the target (cf Findlay et al., 1993). In the two-item case, on-target saccades were made when the target was at the near, $3^\circ$ position although a small effect of the distractor on saccade amplitude occurred. However, when a far, $6^\circ$, target was accompanied by a distractor at $3^\circ$, very few first saccades met the criterion for accuracy to land on the target.

The failure of saccades in the two-item case to reach the far target seems linked to the well-known ‘global effect’ phenomenon (Findlay, 1982) and a ‘near distractor effect’. In a variety of tasks it has been found that when two stimuli are presented simultaneously in neighbouring positions, then the first orienting saccade to these stimuli lands at an intermediate location between the stimuli, generally closer to the nearer of the two. Figure 3 demonstrates that the global effect occurred in the two-item searches. The data show a typical global effect with the $3t6d$ and $6t3d$ saccades landing somewhat beyond the $3t$ landing position when a $3t$ target is presented alone. Furthermore, the GEP shows that the near Gabor patch has a larger impact on processing regardless of any general hypometria. Walker et al (1997) and Chou, Sommer & Schiller (1999) identified this as a ‘near distractor effect’.

**Experiment 2**

The results from Experiment 1 show visual search with the eye is hampered by the intervening presence of a distractor of a different spatial frequency content. This finding seems inconsistent with results showing that
farther distance. However, a two-way ANOVA with spatial frequency and distance as factors revealed there to be no significant difference between these conditions (Spatial frequency: F (1,5) = 3.6; p > 0.05; Distance: F (1,5) = 3.5; p > 0.05; Spatial frequency x Distance: F (1,5) = 3.5; p > 0.05).

Since no single targets were presented in this experiment, it is not possible to obtain an accurate GEP measure. However if a very conservative method is employed by which the centroid of the different Gabor patches (near and far) is used in the GEP calculation, the mean GEP value (standard deviations shown in brackets) for the near target case was -3.4% (13.5%) for the low spatial frequency target and 5.9% (13.4%) for the high spatial frequency target. The mean GEP for the far target case was 79.5% (21.8%) for the low spatial frequency target and 73.6% (18.4%) for the high spatial frequency target. The mean GEP’s by target-distractor position and radial position are shown in Figure 4.

![Figure 4](https://jov.arvojournals.org/pdfaccess.ashx?url=/data/journals/jov/933554/)

**Figure 4. Mean global effect percentage for each spatial frequency target at each position across subject.**

The mean latencies for correctly directed saccades were as follows: Low spatial frequency target at 2.5 deg, 240.6 ms; low spatial frequency target at 5 deg, 251.2 ms; high spatial frequency target at 2.5 deg, 231.4 ms, high spatial frequency target at 5 deg, 252.4 ms. These were found not to differ significantly depending upon on spatial frequency (F < 1) but did differ significantly depending upon distance of target: F (1,5) = 16.4; p<0.05. Thus latencies were found to be longer when the target was in the farther position. The interaction between spatial frequency and distance was not significant: F(1,5) = 4.0; p>0.05.

**Discussion**

The results contrast remarkably with those of Experiment 1. Target selection in saccade programming during a 16-item visual search task for a target defined by spatial frequency is no longer heavily disrupted by the presence of distractors with a different spatial frequency content. Thus the apparent lack of support for spatial frequency as a visual primitive for search with the eye found in Experiment 1 was due to the nature of the visual display. It would appear that the increase in the number of distracting items has actually eased search difficulty.

Intuitively it should be the case when searching for visual stimuli that things become more easy to find the less number of items which have to be searched. However, it is well documented that search can be relatively easy regardless of the number of distractors (Treisman & Gelade, 1980). Furthermore, situations have been noted where search becomes easier as the number of distractors increases (Duncan & Humphreys, 1989; Bravo & Nakayama, 1992). This has been suggested to be a function of reducing heterogeneity amongst distractors and concomitantly increasing heterogeneity between distractors and targets, or it may be due to grouping processes of the distractors into homogenous wholes which increases the discriminability of the target. Thus it may be the case that grouping or similarity of the target and / or distractors eases the search difficulty and allows accurate eye movements to be programmed.

However, it is notable that the increase in number of distractors also led to differences in the latencies of the first saccades. In the two-item case, when only a single distractor accompanied target onset, latencies were found to be shorter in comparison to the 16-item case, when 15 distractors were present. For example, when presented at the far eccentricity, low spatial frequency targets elicited a saccade with average latency of 196.5 ms in Experiment 1 when one distractor was present and 251.2 ms in Experiment 2; while in equivalent conditions high spatial frequency targets the average saccade latency was 208.3 ms and 252.4 ms respectively (these latency values include all saccades regardless of their accuracy). This shows an increase of 40 - 50 ms. Thus the presence of the distractor items affects the temporal aspect of the eye movement programming. It has been shown previously that if saccadic latencies are increased, the global effect may be reduced. An early report (Findlay, 1981) noted this effect within the natural range of latencies occurring in an experiment. Specific instructions to delay initiation of the movement also leads to more accurate saccades (Ottes, Van Gisbergen & Eggermont, 1985; Coeffe & O’Regan, 1987; Chou et al, 1999). In the next two experiments the grouping / similarity and saccade latency explanations for the differences found in first saccade accuracy between Experiment 1 and Experiment 2 are examined in turn.
Experiment 3

To examine the issue of grouping or similarity four experiments were carried out in which the heterogeneity of the distractors was manipulated across four dimensions. If the search task is made easier by homogeneity or grouping, e.g. through lateral inhibition processes, then increasing distractor heterogeneity should disrupt search performance.

The heterogeneity of the distractors was manipulated independently across four dimensions in four separately executed conditions. First, the $x$-$y$ position of the distractors was randomly jittered by up to 20 pixels (0.41 deg) in either direction to break up any grouping by position. Second, the orientation of each distractor was randomly chosen from one of six ranging from 0 – 180 deg in steps of 30 deg. Third, the target contrast was changed to 50% and the contrast of each distractor was randomly chosen from one of seven contrast values (20%, 30%, 40%, 50%, 60%, 70% and 80%). Fourth, the spatial frequency of each distractor was subjected to random variation. If the target was a 1 cpd Gabor patch then the distractor could be 2 cpd or one of seven values above this in log10 steps of 0.07. Alternatively if the target was 4 cpd then the distractor could be 2 cpd or one of seven values below this in log10 steps of 0.07.

Three subjects, two new naïve female subjects and one male (one of the authors) subject with an age range of 21 – 59, took part in this experiment. The experiment was as Experiment 2 but the distractors were randomly changed on one of the four dimensions in one of four separate experiments (one for each dimension). Subjects were asked to indicate the position of the target by moving their eyes to its location as quickly and as accurately as possible. As with Experiment 2 the subject searched for a low and a high spatial frequency target in two separate blocks.

Results

Saccades were classified in terms of angular distance from target as “on-target” if they landed within 15 degrees of the target. Furthermore the same amplitude criteria as employed in Experiment 2 was used here. On-target saccades to a target at 2.5 deg were defined using a criterion that saccade amplitude was greater than 1 deg and less than 3.75 deg. For a target at 5 deg, the amplitude criterion required the saccade amplitude to be greater than 3.33 deg but less than 6.25 deg . Overall 881, 831, 837 and 769 saccades were analysed from the Position Jitter, Orientation, Contrast and Spatial frequency experiments respectively. Of these 825 (93.6%), 803 (96.6%), 768 (91.8%), 695 (90.4%) were classified as on-target.

Table 2. Saccadic Accuracy (On-target Saccades / Total Saccades) in Each of the Four Conditions of Experiment 3 Shown Separately by Subject, Spatial Frequency of Target and Whether the Target was Shown on the Inner Ring or the Outer Ring.

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<td>Kf</td>
<td>67/75</td>
<td>65/65</td>
<td>69/70</td>
<td>65/65</td>
</tr>
<tr>
<td>Totals</td>
<td>208/228</td>
<td>203/211</td>
<td>211/219</td>
<td>203/209</td>
</tr>
</tbody>
</table>

The variable numbers of total saccades result from trials with tracker loss.
order to examine whether the distracting patches had an influence on target directed saccades GEPs were computed and are shown in Figure 5. It can be seen from this figure that the presence of the near patch had little effect on the saccade landing positions.

The mean latencies for correctly directed saccades are shown in Table 3. It can be seen that there is very little difference between the experimental conditions and spatial position of the target although for targets in the near position the latencies are on average 20 – 30ms longer than those found in Experiment 2.

**Table 3. Mean Latencies for each Condition of Experiment 3 Analysed by the Spatial Position of the Target.**

<table>
<thead>
<tr>
<th>Jitter</th>
<th>Orientation</th>
<th>Contrast</th>
<th>Spatial frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>inner</td>
<td>outer</td>
<td>inner</td>
</tr>
<tr>
<td>Low</td>
<td>261.2</td>
<td>259.3</td>
<td>265.4</td>
</tr>
<tr>
<td>High</td>
<td>256.5</td>
<td>263.7</td>
<td>260.2</td>
</tr>
</tbody>
</table>

**Discussion**

The results show that subjects are able to accurately direct a saccade on the basis of a spatial frequency difference despite an increase in distractor heterogeneity. This suggests that improvement in search performance when more distractors accompany the target is not due to mechanisms which operate on the basis of distractor grouping (Bravo & Nakayama, 1992) or similarity (Duncan & Humphreys, 1989).

![Figure 5](https://jov.arvojournals.org/pdfaccess.ashx?url=/data/journals/jov/933554/)  
Figure 5. Mean global effect percentages by spatial position of the target separately for the two spatial frequencies of the target. The GEP for each dimension is shown separately.
Experiment 4

The second possible explanation posited to account for first saccade accuracy differences found between Experiments 1 and 2 was that of latency. The latency difference between Experiments 1 and 2 was found to be substantial (approximately 40 - 50 ms) and appears attributable to the display configuration used. We suggest this is a manifestation of the effect studied by Walker, Deubel, Schneider & Findlay (1997). Walker et al. showed that the initiation of a saccade to a visual target is delayed when a visual stimulus appears simultaneously with the target in a different part of the visual field. This effect appears automatic. In the Walker et al. experiments, participants had advance knowledge of the direction in which the target would appear, but nevertheless the onset of the remote stimulus could not apparently be ignored. Walker et al. showed that this ‘remote distractor effect’ (RDE) occurred with distractor onset at any location in the contralateral visual field and also at locations in the ipsilateral field outside a sector of width about 20 degree each side of the saccade axis. Neighbouring distractors within this central sector no longer affected saccade latency but instead the metrics of the saccade were affected (see General Discussion).

It thus seems possible that the distant stimuli in the 16-item displays of Experiment 2 acted as remote distractors, thus producing an automatic increase in latency. We thus carried out a further experiment to try to find if the similar latency and accuracy differences could be found to co-occur within an experimental block. We returned to the 2-item displays of Experiment 1 but included additional 4-item displays. We predicted that the two further distractors presented contralaterally to the target-distractor pair should act as remote distractors thus increasing the saccade latencies elicited. As a consequence of this it would be expected that saccades should be directed more accurately than when only a target-distractor pair was shown.

As with Experiment 1, the target Gabor patch could appear at 3 deg or 6 deg on either left or right. 3t6d and 6t3d conditions had a single distractor on the ipsilateral side with the target as in Experiment 1. Four new conditions were added. 3tall had a distractor presented at 6 deg ipsilaterally with the target and distractors at both 3 and 6 deg contralaterally to the target. 6tall had a distractor presented at 3 deg ipsilaterally and distractors at both 3 and 6 deg contralaterally to the target (see Figure 1). Control stimuli were also presented with single target patches alone. This led to 12 different displays and blocks had 10 trials per condition, giving 120 trials in total per block.

Seven subjects, of whom four were female, took part in the experiment. This included one of the authors. The remaining subjects were naïve as to the purpose of the experiment and had not taken part in any of the previous experiments. Their age range was 25 to 59 years. All had normal vision and a range of experience in eye movement experiments. Subjects were required to make a saccade to the predefined target, which was as quick and as accurate as possible. Subjects searched for the low and the high spatial frequency target in two separate counterbalanced blocks.

Results

As in previous cases, the accuracy of saccade landing positions was initially classified according to their amplitude. As with Experiment 1 the amplitude criterion for an on-target saccade to a target at 3° was that the saccade had an amplitude greater than 1° and less than 4.5°. For a target at 6°, the amplitude criterion required the saccade amplitude to be greater than 4° but less than 7.5°. Results of this analysis are shown in Table 4 in which a comparison of the columns 6t3d and 6tall for both low and high spatial frequency targets suggest that accuracy improves as the number of distractors increase from one to three.

Table 4. Saccadic Accuracy [On-target Saccades (Total Saccades)].

<table>
<thead>
<tr>
<th></th>
<th>3t</th>
<th>6t</th>
<th>3t6d</th>
<th>6t3d</th>
<th>3tall</th>
<th>6tall</th>
<th>all</th>
</tr>
</thead>
<tbody>
<tr>
<td>low</td>
<td>125</td>
<td>110</td>
<td>122</td>
<td>34</td>
<td>114</td>
<td>57</td>
<td>562</td>
</tr>
<tr>
<td></td>
<td>(127)</td>
<td>(128)</td>
<td>(127)</td>
<td>(127)</td>
<td>(116)</td>
<td>(118)</td>
<td>(743)</td>
</tr>
<tr>
<td>high</td>
<td>120</td>
<td>109</td>
<td>120</td>
<td>11</td>
<td>101</td>
<td>38</td>
<td>499</td>
</tr>
<tr>
<td></td>
<td>(122)</td>
<td>(130)</td>
<td>(131)</td>
<td>(128)</td>
<td>(105)</td>
<td>(119)</td>
<td>(735)</td>
</tr>
<tr>
<td>all</td>
<td>245</td>
<td>219</td>
<td>242</td>
<td>45</td>
<td>215</td>
<td>95</td>
<td>1061</td>
</tr>
<tr>
<td></td>
<td>(249)</td>
<td>(258)</td>
<td>(258)</td>
<td>(255)</td>
<td>(221)</td>
<td>(237)</td>
<td>(1478)</td>
</tr>
</tbody>
</table>

In order to examine whether the distracting patches had an influence on target directed saccades GEPs were computed and are shown in Figure 6. It can be seen from...
this figure that the presence of a distractor shown in the near position ipsilateral with the target had a large effect on the saccade landing positions (6t3d) however, when accompanied by two further contralateral distractors this effect lessened considerably (6tal).

Mean saccade latencies for each condition are shown in Figure 7. As we are interested in saccade latencies independent of their actual accuracy, no amplitude criteria was applied. A repeated measures ANOVA with spatial frequency, side and target-distractor pairing as factors was carried out. It was found that spatial frequency of the target and side of presentation had no significant effect on saccade latencies (F < 1) while the target-distractor pairing did: F (1, 6) = 113.8, p < 0.01. The interaction was found not to be significant: F (1, 6) = 3.9, p > 0.05. Figure 7 shows that longer saccade latencies occur when more than one distractor is shown. It was hypothesised that increased fixation time prior to saccade onset was the reason for improved accuracy when distractor number increased. The analysis supports this proposal.

There may be concern over the differences found between the GEPs and latencies reported here and those reported in Experiment 1 for the same 2-item conditions. The GEP found here were found to be greater showing more influence of the Gabor patch shown in the far position than found in Experiment 1. This could either be a secondary consequence of the addition of the 4-item displays within the block or result from the use of different subjects. In order to examine whether the results from the 2-item conditions in both experiments are indeed from the same underlying distribution the GEP found in each experiment was plotted by latency (Figure 8). The results from Experiment 1 are shown as diamonds; those from the 2-item displays reported in Experiment 4 are shown as squares; and those from the 4-item displays reported in Experiment 4 are shown as triangles. It can be seen that the data from the 2-item displays in both experiments overlap considerably while the data from the 4-item form a distinct distribution. This suggests that although the GEP means found for the 2-item displays in Experiment 1 and 4 differ, they may nonetheless derive from the same underlying distribution.

**Discussion**

The introduction of contralateral distracting stimuli was found to increase first saccade latencies in comparison to target alone and single distractor conditions. Thus the contralateral stimuli led to the predicted latency increase (the remote distractor effect, RDE). The change in global effect across condition shows that when three distractors were present saccade accuracy improved relative to that when a single distractor was present.

These results suggest that the contradictory results from Experiments 1 and 2 are at least in part a consequence of the saccade latency differences. It was found in Experiment 1 that saccades land closer to the distractor when the target is shown in the far position and a distractor is present between it and the current fixation position, however, when fifteen distractors were present this effect was almost eliminated.

Taken together, the experiments show that when a greater number of stimuli are presented they act to increase the resulting accuracy of that saccade. Figure 9a shows the GEP found in all experiments presented here. It can be seen that as the number of stimuli presented increased so the global effect percentages shift toward 0.
when the target is presented at the near position and shift toward 100 when the target is presented at the far position. The effect appears for targets with both low and high spatial frequencies, although the reduction in accuracy is somewhat stronger in the latter case. This may be an effect of integration times being greater for higher spatial frequencies reflecting the operation of transient and sustained channels (Breitmeyer, 1975; Watson & Nachmias, 1977; Gish, Shulman, Sheehy & Leibowitz, 1986). However, it may also be due to the two targets almost certainly being of unequal power as they were both shown at the same absolute contrast.

We have shown that first saccade accuracy improves with increasing number of stimuli and we have suggested that this is in part linked to the increase in the first saccade latency. In order examine this the GEP and latencies recorded in all experiments are presented in Figure 9b. The graph is arranged so that each line shows the GEP and latency for each target spatial frequency and its position. The points on the line show the GEP and latency for each experiment. The points are arranged so that as they run from left to right the number of elements in the display increases. It would be expected that as latency increases so would the accuracy of the saccade. However, while there is clearly a trend for this the increase in accuracy with latency is not monotonic. This may be due to individual differences as different subjects were used in each experiment or it may be due to the remote distractor effect saturating beyond a certain distractor number or saccade latency or it may be due to other factors operating as the number of the display items increase.

### General Discussion

Research using target/present absent responses (Moraglia, 1989; Sagi, 1990; Carrasco, McLean, Katz & Freider, 1998) has suggested that spatial frequency is a visual primitive allowing accurate visual search to occur. We might thus have expected that saccades could readily be directed to a target defined by spatial frequency but our results show that the situation is more complex. For target selection with saccades, accuracy depends upon saccade latency and spatial frequency differences are only effective in visual search if there is sufficient time available. This contrasts with the finding that eye control in a black/white discrimination task could be achieved with saccades of very short latency (Findlay & Gilchrist, 1997).

We have presented evidence which shows that increasing the number of stimuli in a search task can improve performance, measured as the ability to direct the eyes to the target. In a search task in which a single distracting stimulus was presented concurrently with a target stimulus (Experiment 1), subjects were unable to successfully direct the eyes to the target if the distractor lay in between current fixation position and target location (Findlay et al, 1993). Indeed saccades were largely captured by this close distractor giving a near distractor effect (Walker et al, 1997; Chou et al, 1999).
However, when the number of display items was increased to 16 (Experiment 2), then saccades were successfully directed to targets at all positions. In order to examine whether this was due to similarity or grouping mechanisms four experiments (Experiment 3) were carried out in which position, orientation, contrast and spatial frequency were jittered. These manipulations would be expected to degrade the performance by disrupting the operation of similarity or grouping mechanisms. However, good search performance was maintained.

When a larger number of stimuli were presented at once, we observed that initial saccade latencies were longer. We suggested that this increase in saccade latency might be a result of the remote distractor effect (Walker et al, 1997). It is further suggested that a consequence of this increase in saccade latency is to allow visual information to be analysed more fully and thus to allow a saccade to be generated on the basis of a better representation of the target location. This suggestion was supported by the results of a further experiment in which the number of display items was either two or four (Experiment 4). It was observed that subjects were unable to direct saccades accurately when a single distractor lay between current fixation position and the target, replicating the finding of Experiment 1. However, with four-item displays containing three distractors, two of which were contralaterally positioned thus acting as remote distractors, saccade latencies were lengthened and saccade accuracy improved. The similarity of first saccade latencies found in Experiment 2 with 16-items and Experiment 4 with 4-items suggests that accuracy may not improve monotonically with latency but rather the remote distractor effect may saturate beyond a certain number of display items. Alternatively the lack of a strong monotonic relationship between latency and accuracy may be more likely due to the use of different subjects across the four experiments. The results support the suggestion that in a search task, the point in time when a saccade is initiated can have a strong effect on its accuracy (see also Hooge & Erkelens, 1999). In the following sections we elaborate this proposal.

**Coarse to Fine Processing**

We discuss below a framework to account for the results reported in this paper. We propose that it is necessary to consider effects relating both to the processing of visual information and to eye movement control. Our proposal emphasizes the coarse to fine nature of these processes.

There is considerable evidence that the flow of visual information develops from the immediate transient signal resulting following the appearance of a display to subsequent, more sustained and filtered, information (see Lamme & Roelfsema, 2000, for an elaboration of this separation). Visual information arrives by default in this anisotropic temporal manner, although there is still discussion as to whether the visual system depends upon a coarse to fine availability of visual information in order to efficiently integrate it (Parker, Lishman & Hughes, 1992; McSorley & Findlay, 1999; McSorley & Findlay, 2002). Much evidence suggests that an initial transient visual signal associated with the onset of a stimulus is rapidly superseded by longer lasting sustained visual information which is specific to individual stimuli. This change from transient to sustained visual information has been respectively associated with the M and P pathways of the primate visual system (Lennie, 1993). Of the response characteristics of the two pathways those of interest here are that the M pathway has larger receptive fields and faster conduction velocities than the P pathways (Kaplan, Lee & Shapley, 1990). Thus the initial activation via the retino-geniculo-cortical pathway would be driven by transient visual information which is carried by larger receptive fields. Subsequent to the initial sweep of the transient signal, the P pathways develop a more sustained representation of the visual signal and one which has more potential for filtering and selective operations.

Turning to the eye movement control system, a similar coarse to fine transition can be identified. The large receptive fields associated with saccade targeting, for example in the superior colliculus, have as a consequence that visual information is initially represented by large areas of activity and thus spatially separate stimuli are treated globally by the saccadic system. The integrative effect that this has on saccade metrics has been termed the global effect (Findlay, 1982) and subsequent work has found that saccade metrics are only influenced by the characteristics of visual information which falls within a circumscribed portion of visual space (Walker et al, 1997). Through a process of competition, which takes time to progress, activation associated with each stimulus resolves such that saccades are more and more likely to be executed to individual stimuli. This mirrors the resolution occurring through filtering in the visual system by which the search target is identified.

The coarse to fine nature of both the mechanisms involved in saccade targeting and the underlying visual information which forms the basis by which the saccades are targeted suggests that the global effect operates most strongly on the transient visual signal. Thus short-latency saccades are dominated by the transient signal. However, if the saccade is delayed, modulation of the effect occurs based on the increasing influence of the sustained part of the visual signal. The point in time at which the saccade is initiated thus becomes critical in determining what aspect of the visual signal is used to determine where it is directed. Search selection will in general only be possible if the nature of the visual information supports target selection. For example, Findlay & Gilchrist (1997) showed, using a similar paradigm to that of the present paper, that a black/white discrimination could be made with short latency saccades. It seems plausible to suggest
that such a discrimination could be made on the basis of transient information alone.

**Functional Model**

In the functional model of the saccadic generation process described by Findlay & Walker (1999), the signals which drive saccadic eye movements are organised in terms of when the eyes are moved and where the eyes are directed. When the eyes are moved is determined by a fixate centre while where the eyes are moved to is determined by a move centre organized as a saliency map. Inhibitory interactions are posited to exist between these two centres. There are also further inhibitory interactions between regions of the saliency map such that the generation of a single peak of highest activation is promoted. Saccades are generated when the activity in the fixate centre decreases to below a threshold. When this occurs a saccadic eye movement is made to the current point of highest activation in the saliency map. The saliency map is dynamically updated by visual information so that the location of the saccade target is critically dependent on the point in time at which the saccade is elicited.

Findlay & Walker (1999) identified a number of influences on where and when a saccade is made, three of which are of concern here. First, as mentioned previously, activation in the move centre inhibits activation in the fixate centre. Second, search selection occurs whereby saccades to particular visual features are promoted. This is assumed to operate within the visual processing pathways to allow pre-selected visual features to be emphasised in the salience map constituting the move centre. Third, the occurrence of transients associated with peripheral visual events influences both the move centre and the fixate centre. It may seem paradoxical that the influence can be felt in both centres, however to explain the remote distractor effect an influence on the fixate centre is required. This is due to the finding by Walker et al (1997) that the strength of the remote distractor effect depends upon the distance of the distractor from current fixation position not the distance of the distractor from the target. Therefore, as they point out, the existence of inhibitory interactions between the target and distractor cannot explain their results. Importantly for the present interpretation, a transient signal occurring at a location contralateral to the saccade direction will result in an increase in the latency of the saccade.

We suggest that these three influences dynamically interact with each other to determine where and when a saccade is directed. Specifically, a transient visual signal produced by both stimuli feeding directly into the move centre inhibits the fixate centre and generates a short latency saccade which is targeted globally due to receptive field properties of the saccadic system. As saccade latency increases the influence of the transient signal dissipates, the influence of the underlying visual features becomes more apparent and through competitive interactions activity in the saccadic system becomes more tightly localised around the target location. Furthermore, the influence on saccade targeting of search selection would also become more apparent over time. As a result of these constraints saccades become more tightly localised as their latency increases. The influence of the remote distractors serve to increase saccade latencies (as found in Experiment 4) and thus improve target localization.

The new feature of our results is to show that a quite small additional delay can have important consequences for a realistic perceptual task by resulting in a concomitant reduction in the global effect. Previous studies (Ottes et al, 1985; Coëffé & O’Regan, 1987) have also noted that the global effect is reduced for saccades with longer latencies but in these cases considerably longer latencies were achieved by voluntarily withholding the response. In our situation, the increased latency appears to be a consequence of the stimulus configuration. While we cannot rule out the possibility that subjects are voluntarily withholding their responses and thus allowing greater saccade accuracy, the small increase in saccade latency reported here argues against such a strategic explanation for the results.

In normal scanning, such as reading, fixations average 250–300 ms (Rayner, 1998). It is possible that this relatively sedate pace of scanning has evolved to allow target selection in a way whereby the distracting influence of competing possible targets is minimised (Findlay, Brown & Gilchrist, 1997). There appears no intrinsic neural limitation to prevent a faster rate of scanning. Indeed individual cases where a fixation pause is very brief (< 100 ms) are often found. Saccades following these responses appear to well directed and there has been considerable recent interest in the programming of these responses (McPeek, Skavenski & Nakayama, 2000; Findlay, Brown & Gilchrist, 2001, Ludwig & Gilchrist, 2002) since the phenomenon strongly suggests that two saccades can be programmed together. Quite frequently in our experiments, the misdirected first saccades in the 2-item and 4-item displays were rapidly followed by a subsequent saccade to target.

**Spatial Frequency**

Spatial frequency of the target was found to have little effect on search performance but did have an effect on the saccade amplitude calculation when distractors were present. High spatial frequency targets showed relatively less influence on the programming of a target directed saccade. This may be due to resolution issues in that the visual system may be less sensitive to the higher spatial frequency when it is shown in the far position. Alternatively, it may be due to differential delays involved in processing different spatial frequencies, that is, the higher spatial frequency may take longer to process (Breitmeyer, 1975; Gish et al, 1986; Felipe, Buades &
Artigas, 1993) and thus have less impact on the saccade which is initially programmed. It is not possible to say from the results here which of these possibilities is the case. Carrasco et al (1998) have shown that when spatial frequency patches are M-scaled to take in to account the relative sensitivity of the visual system in more eccentric positions, then differences in search performance disappears. This indicates that it is differences in sensitivity to spatial frequencies at different eccentricities which is responsible for the differences found. However, in Experiment 1, a statistical trend was found which indicates that targets with a higher spatial frequency content elicit saccades with a longer latency. This mirrors a trend reported by Gilchrist, Heywood and Findlay (1999). They asked subjects to saccade to Gabor patches which differed in orientation and found that when the spatial frequency content of the displays increased from 1 cpd to 4 cpd a small increase was observed in the saccade latencies. While the saccade latencies were not significantly different in either case it must be noted that the differential delays involved in the spatial frequency processing are small and would be largely swamped by the inherent variability of saccade latencies. Thus the trends may reflect smaller processing delay differences. Therefore any differences in search for the two spatial frequency targets maybe due to either a fall-off in the resolution of the periphery or inherent latency differences in spatial frequency processing.

Conclusions

We have reported that visual search for spatial frequency which involves localisation by an eye movement becomes progressively more accurate as the number of distractors presented with the target increases. The result occurred progressively over 2-item, 4-item and 16-item displays. The results suggest that this may in part be due to an increase in first saccade latencies. We argue that this increase allows the first saccade to be more accurately directed. We also suggest that the normal rhythm of eye scanning may operate at the optimum speed consistent with avoidance of interference from potential visual distractors.

Acknowledgements

This work was carried out with the support of BBSRC Grant 12/S10576. We would like to thank Iain Gilchrist for numerous discussions, two anonymous reviewers and Dr. Lee Stone. Commercial relationships: none.

Notes

1The use of the centroids of the Gabors as being the 0% and 100% points in the GEP calculation results in a conservative estimate of the global effect because saccades are normally hypometric. This would result in an underestimation of the global effect found when two or more stimuli are shown. This can be seen from consideration of Figure 2. Data is shown from a single subject from Experiment 1. The Gabor patches were shown at 3 and 6 degrees. The mean saccade amplitudes are less than this in all conditions with the greatest hypometria found in the 6t condition. If the centroid of the Gabor patches were used as the landing positions in the 3t and 6t conditions the GEP formula would be 100*((A – 3)/3) and the global effect percentage found in the two item cases would drop to below zero. This underestimates the GEP found in both cases but especially the 6t3d condition where a GEP of 21.7% was found. The use of the Gabor patch centroids in the GEP calculation in this experiment suggests that the GEP reported were smaller than would have been found if the target only amplitudes had been recorded.

References


