



Saccade selection in visual search: evidence for spatial frequency specific between-item interactions

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Abstract

We present two experiments in which subjects were required to make a saccade to a target amongst distractors. Targets were oriented Gabor patches. Analysis of errors, when subjects fail to make a saccade to the target, showed two interesting features. First, most error saccades were directed towards a distractor and not to the blank space between distractors. This suggests that although the location of the target may not be encoded correctly, the locations of the items in the display are encoded. Second, when the display items were all of the same spatial frequency, a long-range effect occurred whereby the likelihood of an error saccade in a specific direction decreased systematically as the distance from the target increases. This systematic influence of the target location extended over practically the whole display. The long-range effect appeared whenever all display items had the same spatial frequency and showed little dependence on the spatial frequency of the display items. However, when the items had different spatial frequencies the long-range effects were absent. © 1999 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Visual search is a process which requires the co-ordination of information about target identity with that about target location. The commonly used reaction time measure of visual search time does not allow this co-ordination to be examined in detail. An alternative approach which has been adopted in a number of recent studies is to examine the pattern of eye movements when subjects are engaged in a visual search task (e.g. Binello, Mannan & Ruddock, 1995; Findlay, 1997; Williams, Reingold, Moscovitch & Behrmann, 1997; Zelinsky & Sheinberg, 1997).

Eye movement studies allow the investigation of the extent to which attention is attracted to display distractor items that share some similarity with the target. Zelinsky (1996) found that the probability of fixating a non-target display item did not depend on its similarity to the target, and suggested that saccades to non-targets in search were not guided but made rather

randomly to items in the display. In contrast, Findlay (1997) did find evidence for some guidance of first saccades to items similar to the target and an earlier finding by Williams (1967) showed evidence for guidance by colour, but not size or shape. A possible resolution of the difference (Findlay & Gilchrist, 1998) relates to the different display arrangements used. In Zelinsky's study, targets were positioned more arbitrarily than in the displays used by Findlay, where eight display items were presented equidistant from the fixation point. If target selection for saccades is partly based on item proximity (Findlay, 1980), then any effect of target features may have been swamped in Zelinsky's experiment.

Display configuration also influences the likelihood that saccades will land on display items, rather than in the space between them. Findlay (1997) showed in a simple colour search task that the great majority of saccades were directed to the target item but a small number were misdirected, particularly to neighbouring items. Nevertheless, saccades were more likely to fall on, or very close to, items in the display rather than on intermediate locations between the items. With more

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complex display configurations (Viviani & Swenson, 1982; Findlay 1997, Experiment 5), a greater proportion of the saccades are directed to the empty space between display items. It was also found by Findlay (1997) that if, on occasional trials, two target items appeared in close proximity, saccades frequently landed at an intermediate position, a finding similar to the centre of gravity global effect (Findlay, 1982).

The two experiments reported here extend these findings and investigate further the spatial distribution of saccades in search. We used as display items Gabor patches of known spatial frequency because a number of studies have investigated spatial interactions between items using such stimuli. For example, Field, Hayes and Hess (1993) investigated the ability of observers to detect paths of collinear Gabor patches in a field of randomly oriented patches. They found that these effects were sensitive to the orientation difference among the elements in the path and that detection fell to chance when the elements had orientation differences above 60° . These effects appeared to be little affected by element separation (over the range tested)—still being present with element separations over seven times the wavelength of the individual elements. Using a similar paradigm Kovács and Julesz (1993) showed that if the path forms a complete circle then detection is further improved. In addition, the ring structure that resulted could selectively enhance the detection of a single Gabor patch. This enhancement occurred when the ring structure was up to two wavelengths away from the contour at a location outside the ring and up to eight wavelengths away from the contour when the patch was within the ring. A number of other studies have investigated the effects of flanking Gabor patches on detection of a single patch. Polat and Sagi (1993, 1994) found that when the flanking patches were very close to the patch to be detected, between 0 and 1 wavelength, then detection thresholds were increased. However, between 2 and 6 wavelengths a facilitation effect occurred and detection thresholds were reduced. This effect was maximised when the items had the same orientation and the same spatial frequency. Adini and Sagi (1992) asked subjects to make orientation judgements about two Gabor patches concurrently, and compared performance with judgements made about one patch. They found that the range over which these two judgements could be concurrently performed was affected when the items had different spatial frequencies, the interaction distance was reduced by approximately a factor of two and by a spatial frequency difference of less than two octaves.

We were interested to know whether these long-range interactions would influence the active visual behaviour shown in a task of visual search and the experiments were designed to test this. In Experiment 1 subjects had to make a saccade to a vertical Gabor patch amongst a

set of horizontal Gabor patch distractors. The targets and distractors all had the same spatial frequency on each trial and could be 1, 2 or 4 c/deg. These spatial frequencies were carefully chosen to be maximally detectable in the periphery. Experiment 2 was identical to Experiment 1 except that the display contained mixed spatial frequency items.

2. General method

2.1. Displays

The displays were generated using purpose written software for a VSG graphics card (Cambridge Research Ltd., UK) and presented on a gamma corrected high resolution EIZO 21" monochrome monitor. The displays consisted of a ring of eight equally spaced elements, the ring having a radius of 8° , leading to a centre-to-centre element separation of 6.1° . The targets and distractors were Gabor patches with contrast close to 100% and the spatial envelope of the patch had a standard deviation of 1° . The patches had spatial frequencies of 1, 2 or 4 c/deg and background brightness was 6.9 cd/m^2 . These spatial frequencies were chosen on the basis of a preliminary experiment, which showed that at an eccentricity of 8° the peak of the contrast sensitivity function was at a spatial frequency of 2 c/deg. In both experiments the target was a vertical Gabor patch and all the distractors were horizontally oriented. The eight items (one target, seven distractors) were spaced uniformly around a circle, so the angular direction of the saccade provides a meaningful measure of the spatial characteristic of the first saccade. The target could appear in any one of the eight positions with equal probability. Viewing distance was 0.6 m.

2.2. Procedure

Each trial commenced with a fixation cross presented for 1.5 s. This was followed by the display, which was presented for 1 s. The task of the subject was simply to saccade to the vertical target. Instructions required subjects to do this as quickly but as accurately as possible.

2.3. 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 using a chin rest and two forehead rests. During a trial eye position was sampled at 200 Hz by a separate computer using purpose written software. Each block of trials was preceded and succeeded by a

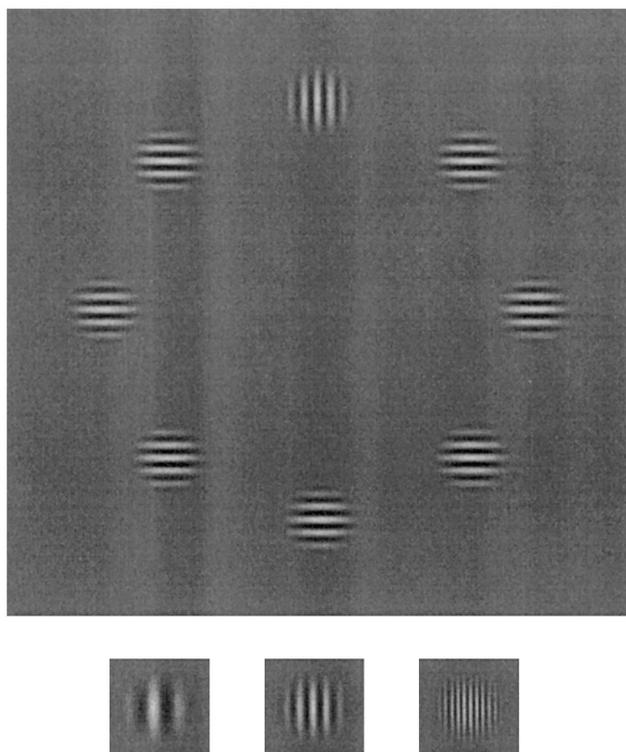


Fig. 1. The upper large panel shows an example display from Experiment 1 of the 2 c/deg display condition. The target is the vertical Gabor patch at the 12 o'clock position. The three smaller lower panels show example target elements for the three other conditions: from left to right 1, 2 and 4 c/deg.

calibration procedure for which the subject was required to saccade to nine small crosses that were sequentially presented in a square array of positions separated by 6° horizontally and vertically.

The eye-movement data were analysed off line by a semi-automatic procedure that detected the first incidence of two successive samples registering a velocity over 25 deg/s. On occasional trials (less than 5%), this algorithm detected small movements at the fixation that preceded the first saccade, in such cases the saccade onset position was selected manually. In addition, saccades with latencies of less than 100 ms were excluded as were saccades that occurred after the duration of the trial (1000 ms). The saccade landing position was taken as the eye position 80 ms after the onset of the saccade. This avoids artefacts that result from lens displacement (Deubel & Bridgeman, 1995). 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 *saccade direction*. The saccade direction is coded in a radial manner to measure saccade direction from the central fixation point. The amplitude of the saccade was also available but was not analysed in detail. Amplitudes corresponded approximately with target eccentricity.

3. Experiment 1

3.1. Method

3.1.1. Subjects

There were six subjects including two of the authors. All had normal or corrected to normal vision and had a range of experience in eye-movement experiments.

3.1.2. Procedure

Subjects participated in a practice block of 16 trials followed by two experimental blocks of 72 trials. This generated 48 trials per condition. The subject's task was to saccade to the vertical target, presented in a ring with seven horizontal distractor items.

3.1.3. Displays

The spatial frequency of all the items in a single trial was the same. From trial to trial the spatial frequency of the displays was varied randomly. The three spatial frequencies were 1, 2 and 4 c/deg. Subjects were thus searching for a pre-defined orientation but with an unpredictable (one of three) spatial frequency. An example display is shown in Fig. 1.

4. Results and discussion

These data are summarised in Tables 1 and 2. The first analysis classified saccades as correct if they landed closer to the target than to a distractor, i.e. if their direction was within 22.5° of the target centre. Of the 857 saccades analysed 563 saccades landed in the target sector (66% correct). Performance was equally good for 1 c/deg (201 saccades, 70% correct) and 2 c/deg (199, 70% correct) displays; but was somewhat worse for 4 c/deg displays (163 saccades, 57% correct). There were large differences in subjects' overall performance level, ranging from 90% correct to 30% correct, however the pattern of most errors with the 4 c/deg displays was shown by five of the six subjects.

Table 1

The mean first-saccade latencies from Experiment 1 in milliseconds, averaged across the six subjects (a correct saccade is one that is in the target direction $\pm 22.5^\circ$)

Saccade latencies (ms)				
Spatial frequency	1 c/deg	2 c/deg	4 c/deg	Overall
Correct	274	264	280	272
Incorrect	283	281	296	287
Overall	278	273	288	280

Table 2
The number of correct first saccades from Experiment 1, the data are presented for each condition (in columns) and for each subject (in rows), percentage first saccades to target ($\pm 22.5^\circ$) are shown in brackets

Saccade accuracy (<i>N</i>)				
Spatial frequency	1 c/deg	2 c/deg	4 c/deg	Overall
RH	19/47 (40%)	16/48 (33%)	8/48 (17%)	43/143 (30%)
KH	16/47 (34%)	22/47 (47%)	26/46 (57%)	64/140 (46%)
FN	45/48 (94%)	42/47 (89%)	30/48 (63%)	117/143 (82%)
JF	32/48 (67%)	30/48 (63%)	26/48 (54%)	88/144 (61%)
IG	46/48 (96%)	45/48 (94%)	38/48 (79%)	129/144 (90%)
SH	43/48 (90%)	44/48 (92%)	35/47 (74%)	122/143 (85%)
Overall	201/286 (70%)	199/286 (70%)	163/285 (57%)	563/857 (66%)

Saccade latencies are shown in Table 1. Incorrect saccades were slower (287 ms) overall than correct saccades (272 ms)— $F(1, 5) = 9.67$, $P < 0.05$. For both correctly and incorrectly directed saccades, the shortest mean saccade latencies were for 2 c/deg displays (273 ms) compared with 1 c/deg (278 ms) or 4 c/deg (288 ms) displays. These spatial frequency effects on saccade latencies, although reflecting a strong trend were not significant— $F(2, 10) = 2.98$, N.S. ($P = 0.099$). Although present, the spatial frequency effect on both saccade accuracy and latency were small. The 4 c/deg display led to saccades that both were less accurate and had longer latencies; the differences with this spatial frequency do not result from a speed accuracy trade off.

A more detailed analysis of the landing position of the error saccades was carried out. Here saccades were further classified on the basis of which of 32 equally sized sectors, in relation to the target, saccades landed in. The resulting sectors and the labels used to refer to them are summarised in Fig. 2. The positive and negative sectors (clockwise and anticlockwise from the target) were combined and the results of this analysis are presented in Table 3. The results pooled across the three conditions are presented in Fig. 3. Inspection of Table 3 reveals that the pattern in these data is consistent across the three spatial frequencies. The results, pooled across all three conditions are shown in Fig. 3. There are two main points of interest. First, the majority of saccades are directed to a distractor and not between the items; this results in the periodic modulation of saccade landing position that matches the location of the distractor items. Error saccades are 2.6 times more likely to land in the sector that is in the middle of a distractor than in the sector that is midway between two items. Error saccades that are not directed to the target are in general directed accurately to one of the distractors. Second, the landing positions of saccades, even when they are not directed towards the target are systematically affected by the location of the target. The further away the distractor is from the target the

less error saccades are directed to it. Model fitting (see Appendix A) shows a systematic, reliable decrease in % error with angular degree from target of $1.60 \times 10^{-3} \%$

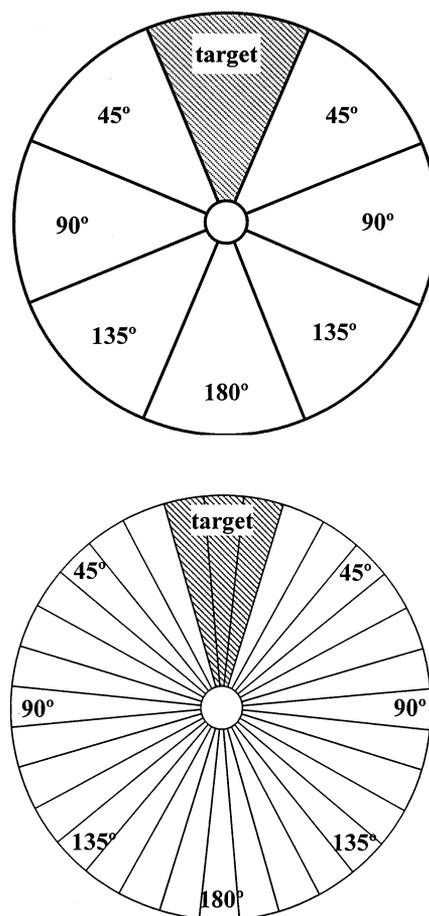


Fig. 2. The two methods for classifying saccade direction. The upper panel shows how the display was divided to classify saccades as correct: those that landed in the shaded 45° sector containing the target were designated correct. Those that landed outside the 45° shaded region were counted as incorrect. The lower panel shows the display further divided into 32 sectors (each of 11.25°) for a more fine grained analysis of landing positions. The shaded area, the sectors containing the centre of the target and the sectors either side, is not plotted in Figs. 3 and 5 but does appear in Tables 3 and 6.

Table 3
The spatial distribution of first saccades from Experiment 1^a

Spatial distribution of errors				
Sector	Spatial frequency			Overall
	1 c/deg	2 c/deg	4 c/deg	
0	143	132	106	381
11.25	49	59	51	159
22.5	10	10	11	31
33.75	8	9	12	29
45	15	12	17	44
56.25	4	9	7	20
67.5	6	7	2	15
78.75	9	4	8	21
90	7	16	17	40
101.25	0	3	8	11
112.5	3	1	3	7
123.75	5	3	5	13
135	11	8	10	29
146.25	4	5	11	20
157.5	1	0	3	4
168.75	4	3	9	16
180	7	5	5	17

^a The body of the table shows the landing position of first saccades coded in relation to the position of the target. The display area was divided into 32 sectors in relation to the target (see Fig. 2) and the number of saccades across the six subjects in each sector recorded. The sectors that correspond to the centre of display elements are shown in bold. Note that there is only one 180° sector (opposite the target) and one 0° sector (on target).

errors/deg², which is equivalent to 0.072 % errors/deg per item. This pattern in the error saccade directions continues across almost the whole array of distractors and is not just restricted to the local area close to the target.

In summary we have found: (1) The pattern of eye movements is similar for all spatial frequencies tested, with only a small decrease in accuracy and increase in latency with the 4 c/deg displays; (2) when errors do occur they are not generally directed to the space between the items but to distractor items that are present. This is true at all distractor locations; (3) when errors occur their direction is systematically affected by the location of the target across almost the full range of locations, this suggests that there were very long-range interactive effects of the target on the remainder of the display in the current experiment.

These results suggest that two kinds of information combine to guide the saccadic system in the search task. The first codes the presence of items, irrespective of whether they are target or distractor. This location code has high spatial accuracy and results in the fine-grained periodic nature of the function in Fig. 3. The second signal codes the presence of the target characteristics and in general leads to an accurate on-target saccade.

However the influence of this second signal appears to spread widely so that more saccades are made to distractor locations closer to the target than to those further away.

Two possible explanations of the result are possible. The first is that the pattern of data reflects possible long-range effect consequent on the appearance of a target in a particular location and that these influences spread across all the display items. However, a somewhat different account might be given by considering the mutual facilitatory effects that might occur between the distractor items. As discussed in the introduction, long range interactions between Gabor patches have been demonstrated in psychophysical experiments at threshold (Polat & Sagi, 1993). If such interactions operated for suprathreshold stimuli, they could operate in a mutually reinforcing way so that the strength of the signal coding a horizontal patch was stronger for distractors surrounded by two horizontal patches than for those adjacent to the target where only one of the neighbouring patches was horizontal. Such mutual facilitation could result in a gradient in the strength of a non-target signal with increasing distance from the target. This position is similar to and extends the explanation for distractor grouping effects in reaction-time search discussed by Duncan and Humphreys (1989); this similarity is discussed in more detail in Section 7 of this paper.

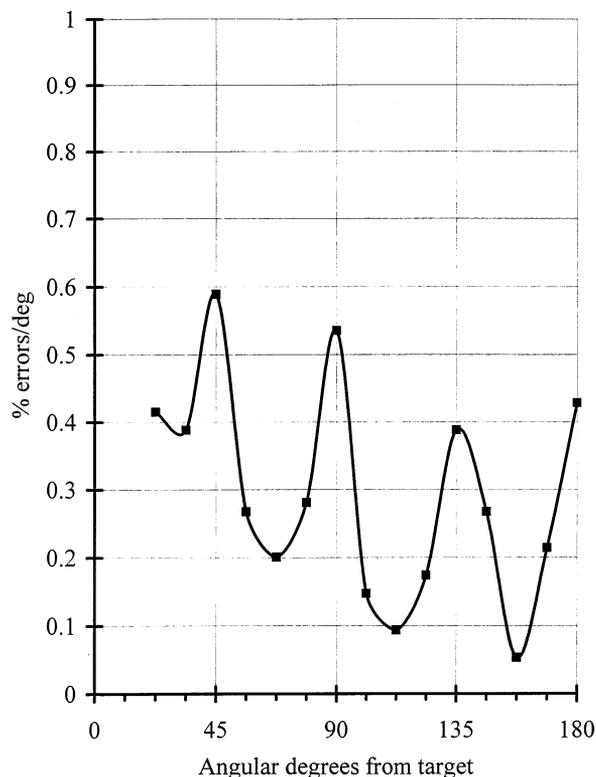


Fig. 3. The spatial distribution of error saccades in Experiment 1 plotted against their angular distance from the centre of the target (total number of observations = 317).

Polat and Sagi (1993) demonstrated that the reinforcement effect of neighbouring patches was both orientation and spatial frequency specific. This suggested a test of the explanation of the long-range effects in terms of mutual facilitation. If the explanation is correct, then the long-range effects should only occur in displays in which all elements had the same spatial frequency. Experiment 2 tests this by examining a search task similar to that of Experiment 1 except that the spatial frequency of the display elements was varied.

5. Experiment 2

Experiment 1 showed that the code for the location of the target had an influence over a wide spatial area and that this effect occurred with all the spatial frequencies tested. In Experiment 2 we investigated whether this spatial influence would be disrupted by changes in spatial frequency between the items.

5.1. Method

5.1.1. Subjects

There were six subjects, all had normal or corrected to normal vision and had a range of experience in eye-movement experiments (three subjects served in Experiment 1).

5.1.2. Procedure

Subjects participated in three experimental blocks of 72 trials. In each block, each display contained two spatial frequencies. On any given trial the target could be of either spatial frequency. A practice block of 16 trials preceded each block. The block order was counter balanced across subjects. On all blocks the subject's task was as before, to saccade to the vertical target.

5.1.3. Displays

In a given block each display contained Gabor patches of two of the three spatial frequencies. These could be 1 and 2 c/deg displays, 1 and 4 c/deg displays or 2 and 4 c/deg displays. In a single display the spatial frequency alternated around the circular display from one spatial frequency to the other, in order to maximise the potential disruption to the mechanisms mediating the interactions between neighbouring items. The target appeared with equal probability at all eight locations and could be of either spatial frequency. Subjects were thus required to search for a predefined orientation (vertical) but with an unknown (one of two) spatial frequency. An example display is shown in Fig. 4.

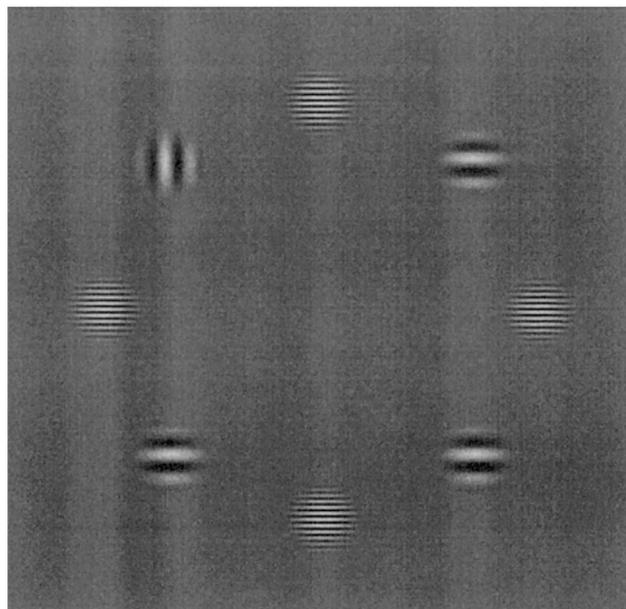


Fig. 4. An example display from Experiment 2. The target is the vertical Gabor patch.

6. Results and discussion

These data are summarised in Tables 4 and 5. Overall accuracy was good. Of the 1146 saccades collected 524 were on target (46% correct). However, performance is generally poorer than in Experiment 1 and two subjects (EM and JF) performed at or near to chance in some conditions. For the 1 and 2 c/deg displays, performance was identical when the target was 1 c/deg (53.4% correct) or 2 c/deg (53.2% correct). For 1 and 4 c/deg displays, 1 c/deg targets were located more efficiently (46.9%) than 4 c/deg targets (38.0% correct) and in 2 and 4 c/deg displays, performance was better for 2 c/deg (49.5% correct) than for 4 c/deg targets (33.5%). Thus in two of the three display types, first saccades were more likely to be directly to the target if the target was the lower spatial frequency.

A very weak, but apparently systematic, trend was noted that error saccades were more likely to be directed to the higher spatial frequency distractors. Of the 622 errors, 334 were to the higher spatial frequency distractors (53.7%). This pattern was consistent for 1 and 2 c/deg displays (51.4%); 2 and 4 c/deg displays (54.0%) and 1 and 4 c/deg displays (55.2%). A similar effect has been observed by Groner, von Mühlhelen and Groner (1997).

Overall saccade latency was 292 ms, correct saccades were faster (289 ms) than incorrect saccades (295 ms) although this effect was not statistically significant— $F(1, 5) = 0.56$, N.S. ($P = 0.489$). There was a tendency for saccades to the high spatial frequency targets in any given condition to be slower (296 ms) than those to low spatial frequency targets (288 ms)— $F(1, 5) = 5.40$, $P =$

Table 4
The mean first-saccade latencies from Experiment 2 in ms^a

Saccade latencies (ms)							
Display	1 and 2 c/deg		1 and 4 c/deg		2 and 4 c/deg		Overall
	1 c/deg	2 c/deg	1 c/deg	4 c/deg	2 c/deg	4 c/deg	
Correct	267	265	300	291	298	311	289
Incorrect	270	279	295	302	298	326	295
Overall	269	272	298	297	298	318	292

^a The data are an average across the six subjects. A correct saccade is one that is in the target direction, $\pm 22.5^\circ$.

0.068. There were no significant latency effects for display type (1 and 2 c/deg, 1 and 4 c/deg or 2 and 4 c/deg displays)— $F(2, 10) = 2.93$, $P = 0.100$, and no two or three way interactions between these factors. This suggests that subjects maintained a relatively fixed and constant saccade latency time in this task, so task difficulty here had an impact primarily on first saccade accuracy.

Table 6 and Fig. 5 show the distribution of error saccades in this experiment. Inspection of Table 6 shows once again a pattern, across all the conditions, for saccades to be directed towards items in the display rather than space between them. In this experiment error saccades are 4.9 times more likely to land in the sector that is in the middle of a distractor than in the sector that is midway between two items. Although there is some variation across conditions, none of the conditions shows the consistent systematic decrease of errors with increase in distance from the target that was found in Experiment 1. Model fitting, as performed on the data from Experiment 1, (see Appendix A) shows a smaller decrease in % error with angular degree from target, -0.609×10^{-3} % errors/deg², which is equivalent to -0.027 % errors/deg per item. This decrease

was not reliably different from 0. Fig. 5 shows these data graphically for a direct comparison between Experiment 1 and 2 (compare Figs. 3 and 5). The long-range effect appears to be severely disrupted by even a one octave difference between neighbouring items. As noted above two subjects in this experiment performed at, or close to, chance on some conditions. The conclusions hold even when these subjects are excluded from the analysis. The findings of this experiment support our explanation of the effect of target proximity in Experiment 1. The increase in the number of saccades to distractors near to the target occurs because of mutual interactions between distractors sharing similar characteristics, rather than because of any direct long-range effect of the target.

7. General discussion

In the present experiments we found evidence for interactions between Gabor patches which affected the behaviour of the saccadic system in a search task. These interactions took the following form. In a search task for a vertical target amongst horizontal distractors, saccades were directed to distractors that were close to

Table 5
The number of correct first saccades from Experiment 1^a

Saccade accuracy							
Display	1 and 2 c/deg		1 and 4 c/deg		2 and 4 c/deg		Overall
	1 c/deg	2 c/deg	1 c/deg	4 c/deg	2 c/deg	4 c/deg	
BK	19/32 (59%)	24/32 (75%)	23/32 (72%)	12/32 (38%)	18/32 (56%)	7/32 (22%)	103/192 (54%)
RH	15/30 (50%)	23/32 (72%)	19/32 (59%)	15/32 (47%)	12/32 (38%)	10/32 (31%)	94/190 (49%)
SH	32/32 (100%)	30/32 (94%)	18/32 (56%)	19/32 (59%)	27/32 (84%)	24/32 (75%)	150/192 (78%)
EM	3/31 (10%)	1/30 (3%)	5/32 (16%)	6/32 (19%)	3/32 (9%)	3/31 (10%)	21/188 (11%)
JF	6/32 (19%)	3/32 (9%)	4/32 (13%)	4/32 (13%)	6/32 (19%)	2/32 (6%)	25/192 (13%)
IG	26/32 (81%)	20/32 (63%)	21/32 (66%)	17/32 (53%)	29/32 (91%)	18/32 (56%)	131/192 (68%)
Overall	101/189 (53%)	101/190 (53%)	90/192 (47%)	73/192 (38%)	95/192 (49%)	64/191 (34%)	524/1146 (46%)

^a The data are presented for each condition (in columns) and for each subject (in rows). Percentage first saccades to target ($\pm 22.5^\circ$) is shown in brackets.

Table 6
The spatial distribution of first saccades from Experiment 2^a

Spatial distribution of errors							
Display	1 and 2 c/deg		1 and 4 c/deg		2 and 4 c/deg		Overall
	1 c/deg	2 c/deg	1 c/deg	4 c/deg	2 c/deg	4 c/deg	
0	75	67	65	41	64	47	359
11.25	25	30	26	18	25	24	148
22.5	5	8	6	6	3	7	35
33.75	7	3	10	9	8	10	47
45	17	19	18	13	20	16	103
56.25	1	6	3	7	7	4	28
67.5	1	2	1	5	2	5	16
78.75	7	6	3	9	3	9	37
90	12	11	13	18	14	15	83
101.25	3	3	7	5	4	6	28
112.5	1	1	3	4	3	1	13
123.75	5	2	8	10	4	8	37
135	18	17	9	19	20	14	97
146.25	3	4	7	3	3	3	23
157.5	0	2	3	4	1	4	14
168.75	3	4	1	10	3	9	30
180	6	5	9	10	8	10	48

^a The body of the table shows the landing position of first saccades coded in relation to the position of the target. The display area was divided into 32 sectors in relation to the target, and the number of saccades in each sector across the six subjects were recorded. The sectors that correspond to the centre of a display elements are shown in bold. Note that there is only one 180° sector (opposite the target) and one 0° sector (on target).

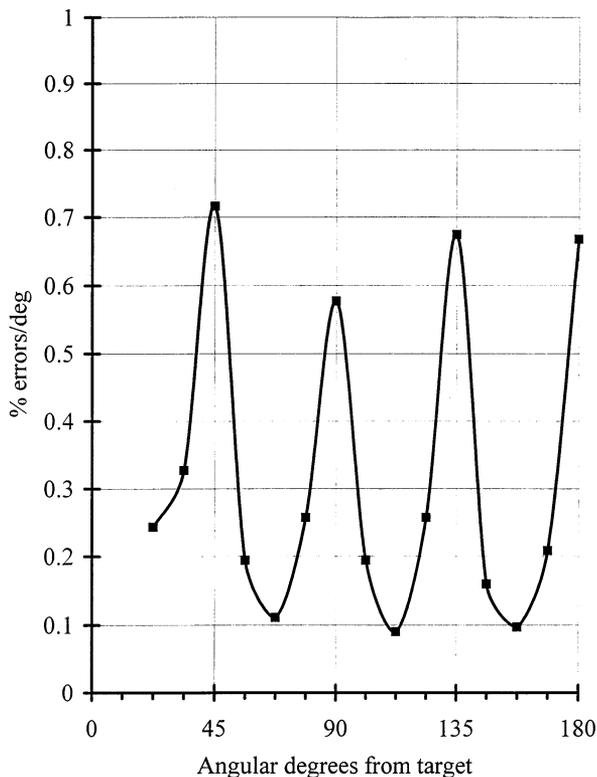


Fig. 5. The spatial distribution of error saccades in Experiment 2 plotted against their angular distance from the centre of the target (total number of observations = 639).

the target rather than ones that were further away, these interactions spread across a number of items in the circular display ring. The interactions were almost entirely eliminated by alternating the spatial frequency of the items in the display. It would appear that the interactions are disrupted by changes of spatial frequency even though these interactions were relatively independent (across two octaves) of the overall spatial frequency of the displays.

As discussed in the Section 1, a number of studies, using a range of paradigms, have reported evidence for spatial interactions between Gabor patches (Adini & Sagi, 1992; Field et al., 1993; Kovács & Julesz, 1993; Polat & Sagi, 1993, 1994). Spatial interactions of this kind could be used to account for all the results reported here. Interactions occur between Gabor patches of identical orientation but not between Gabor patches with orthogonal orientations (Field et al., 1993; Polat & Sagi, 1993). This supports the view that the interactions responsible for the long range effect in Experiment 1 do not involve the target directly (since this had an orthogonal orientation to the distractors) but occur between the distractors. One account of the generation of saccadic eye movements in a visual search task (Findlay, 1997) appeals to a spatial salience map with the eye being directed to the point of highest salience. Salience is increased at locations where the properties of the search target are coded but reduced at locations receiv-

ing input from a distractor feature (Schall, 1995). We suggest that the orientation specific interactions operate to enhance the horizontal feature signal. This leads to a gradient in the strength of this signal amongst the set of distractors with the distractor diametrically opposite to the target showing the maximum enhancement. This horizontalness signal feeds into the salience map in an inhibitory way and thus results in the presence of an oppositely directed gradient in the salience map. The salience map is assumed to be subject to random perturbations of activation, which occasionally result in the point of maximum salience being at a distractor location rather than that of the target. Because of the additional gradient such an event occurs with decreasing likelihood at distractor locations further removed from the target.

Between item interactions form a central component of the Duncan and Humphreys (1989) model of reaction-time performance in visual search. Duncan and Humphreys argued that similarity based grouping acts to facilitate or hinder search performance. If distractor items are visually similar to each other then the group and are treated as a single perceptual unit, resulting in faster target detection. When distractor items are less similar, the grouping process is ineffective and search efficiency is reduced. This framework thus predicts a

dependency of search performance on distractor similarity. The current results are consistent with this account and show moreover that a grouping process can operate rapidly enough to influence eye movement direction within the latency period.

The present study allows for the investigation of these interactions in the context of subjects making a spatial localisation response. What is clear from Figs. 3 and 5 is that the effect of these interactions is not to form a single coherent structure at the cost of losing the location of the individual patches, but rather to spread the identity information (in this case orientation) about the features of the patches, while retaining a relatively accurate code of their locations. So when a larger structure is formed via these interactions, the location of the individual items is not degraded or lost. However, the interactions can lead to long range effects extending over the full set of similarly oriented distractors.

Interactions between localised items have been shown to enhance the ability to perceive structures in a display (Field et al., 1993; Kovács, & Julesz, 1993). The current results demonstrate a further role for such interactions. The interactions assist visual search since they spread information about distractor identity which indirectly aids target localisation.

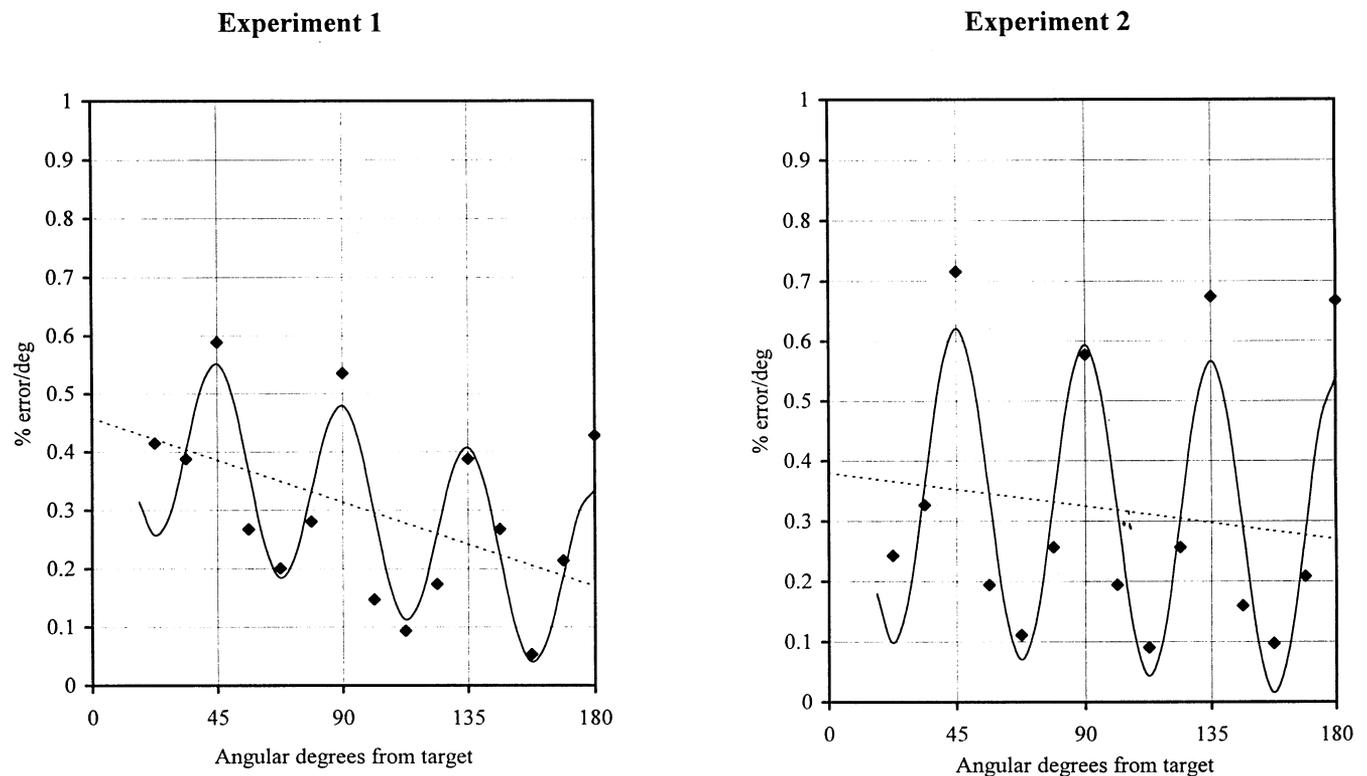


Fig. 6. The data from Experiment 1 and Experiment 2 (filled symbols) plotted with the model fitted (solid line). The dashed line in both panels shows the linear component of the model.

Table 7
The parameters from the fitted model for Experiment 1 and Experiment 2 (95% confidence intervals are shown in brackets for the three parameter estimates)

	Parameter		
	A % errors/deg	B ($\times 10^{-3}$)% errors/deg ²	C % errors/deg
Experiment 1	0.165 (0.100, 0.231)*	-1.60 (-2.59, -0.616)*	0.458 (0.348, 0.569)*
Experiment 2	0.269 (0.185, 0.352)*	-0.609 (-1.87, 0.651)	0.380 (0.239, 0.521)*

* Indicates that 0 falls outside the 95% confidence interval.

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Appendix A

In order to test for the long-range effect of the target in Experiment 1, and its absence in Experiment 2. We fitted the frequency data (as plotted in Figs. 3 and 5) with a simple three parameter model of the form:

$$F = A \cos(8\varnothing) + B\varnothing + C$$

where F is the frequency (% error/deg); \varnothing is the angular degrees from target; A is the size of the sinusoidal modulation; B is the linear slope component and C is a constant.

The model is the simple additive combination of a linear component and a sinusoidal modulating component. If any long-range effect is present it will be reflected in a significant negative slope (B). The model proved to be a good description of the data for both Experiment 1 ($r^2 = 0.756$) and Experiment 2 ($r^2 = 0.802$). However, a number of the small differences between the model and these data are systematic (see Fig. 6). For example the peaks are consistently higher than the sinusoidal function predicts, suggesting that the landing position of the saccades is more tightly tuned to the item locations than would be predicted by the model.

Table 7 below summaries the value of the three parameters for the two experiments and these data are plotted along with the model in Fig. 6.

The slope of the linear component is significant in Experiment 1, but in Experiment 2, this component does not differ significantly from a horizontal line. There is thus clear evidence for long range interactions in Experiment 1. In Experiment 2, the function has a small, non-significant, negative slope and the possibility

exists that a small long-range effect may be present in this case also.

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