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Peripheral and parafoveal cueing and masking effects on saccadic selectivity in a gaze-contingent window paradigm

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Abstract

The present study employed the gaze-contingent window paradigm to investigate parafoveal and peripheral cueing and masking effects on saccadic selectivity in a triple-conjunction visual search task. In the cueing conditions, the information shown outside the gaze-contingent window was restricted to the feature or feature pair shared between the target and a particular distractor type. In the masking conditions, no stimulus features were shown outside the window. Significant cueing and masking effects on saccadic selectivity were observed for saccades directed at items within the window, where all features were visible across experimental conditions. Cueing a particular feature or feature pair biased saccadic selectivity towards this feature or feature pair, while masking generally reduced saccadic selectivity. These findings support the concept of visual guidance being a preattentive process that operates in parallel across the display. © 2001 Published by Elsevier Science Ltd.

Keywords: Guidance; Visual Search; Gaze contingents; Cueing and masking; Saccadic selectivity; Peripheral; Parafaveal; Eye movements

1. Introduction

Visual search is one of the dominant paradigms for investigating visual attention. In the last decades, several studies have examined patterns of eye movements in visual search tasks, providing fine-grained measures that supplement global performance indicators such as response time (RT) and error rate. Such visual search experiments have made use of a variety of measures including fixation duration, saccade amplitude, number of fixations per trial, initial saccadic latency, and the distribution of saccadic endpoints. These measures were found to be sensitive to manipulations that are thought to affect the cognitive processes underlying visual search performance (e.g. Bertera & Rayner, 2000; Binello, Mannan, & Ruddock, 1995; Findlay & Gilchrist, 1998; Gould, 1967; Gould & Schaffer, 1967; Jacobs, 1987; Motter & Belky, 1998; Previc, 1996; Pomplun, Reingold, & Shen, 2001; Rayner & Fisher, 1987; Reingold, Charness, Pomplun, & Stampe, 2001; Williams & Reingold, 2001; Williams, Reingold, Moscovitch, & Behrmann, 1997; Viviani & Swensson, 1982; Zelinsky & Sheinberg, 1997).

To investigate the influence of distractor features on eye-movement patterns, several visual search studies have examined saccadic selectivity, that is, the proportion of saccades directed to each distractor type, by assigning saccadic endpoints to the closest display item. Such studies documented that the spatial distribution of saccadic endpoints was biased towards distractors sharing a particular feature such as color or shape with the target item (e.g., Williams, 1967, but see Findlay, 1997; Hooge & Erkelens, 1999; Luria & Strauss, 1975; Motter & Belky, 1998; Scialfa & Joffe, 1998; Shen, Reingold, & Pomplun, 2000; Williams & Reingold, 2001; Zelinsky, 1996).

For example, Williams and Reingold (2001) reported two visual search experiments using target and distractor items with features varying along three dimensions—color, shape, and orientation. Each experiment consisted of a single-feature (SF) and a two-feature (TF) search condition, in which the distractor items shared one or two dimensions respectively with the target item. While both experiments used the same

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colors (red and blue) and orientations (upright and rotated clockwise by 90°), the stimuli differed in the discriminability of the shape dimension. Experiment 1 employed the similar letters E and F (low discriminability), whereas Experiment 2 used the distinct letters T and C (high discriminability). In both the SF and TF search conditions, the higher shape discriminability in Experiment 2 induced greater saccadic selectivity towards distractors sharing shape with the target, as compared to Experiment 1. This finding suggests that guided visual search was flexibly adapted to take advantage of the increased informativeness of the shape dimension.

Further evidence for the flexibility of visual guidance was found by Shen et al. (2000). In their study, participants had to detect, for example, a red X (target) among green Xs (same-shape distractors) and red Os (same-color distractors). While the total number of search items was held constant, the ratio between the two distractor types was varied across trials. Saccadic selectivity towards a particular feature (color or shape) was found to increase with fewer display items sharing this feature with the target, indicating that participants tended to search along the stimulus dimension shared by fewer distractors (i.e. color with few same-color distractors and shape with few same-shape distractors). Thus, participants were able to change their pattern of visual guidance to take advantage of more informative dimensions.

The present study extended the studies by Williams and Reingold (2001) and Shen et al. (2000) by employing the gaze-contingent window technique to provide convergent evidence for the flexibility of visual guidance. The gaze-contingent window technique, offering a high degree of experimental control, has been used widely in reading, scene perception, and recently in visual search studies (e.g. Bertera & Rayner, 2000; McConkie & Rayner, 1975; Pomplun et al., 2001; Reingold et al., 2001; Saida & Ikeda, 1979; see Rayner, 1998, for a review). Essentially, this technique obscures all objects from view except those within a certain window that is continually centered on the participant's current gaze position. The window steadily follows the gaze position, across fixations. For example, in a study by McConkie and Rayner (1975), participants read text that was masked outside a visual window that included the fixated character and a number of characters to the left and to the right. Only the text within the window was legible. When the participant's gaze position changed, the window followed. By varying the window size across trials and determining the smallest window size that allowed participants to read with normal speed, the perceptual span in reading was assessed.

The major question investigated in the present experiment was whether the type of information made available outside the window would affect saccadic selectivity towards items within the window. Given a feature A that guides visual search by default, what happens when the non-dominant feature B is cued outside the window? If visual guidance can flexibly adapt to changes in the availability of parafoveal and peripheral information, this increase in the informativeness of feature B would bias saccadic selectivity towards B. Since visual guidance is assumed to operate preattentively and in parallel across the display, selectivity should be biased even for saccades aimed at items within the window, which are fully visible. Similarly, masking stimulus features outside the window might decrease guidance even for saccades within the window.

To study these questions, we applied the gaze-contingent window technique to a triple-conjunction visual search task similar to the one employed by Williams and Reingold (2001). The features of search items varied along three dimensions: color (red vs. green), shape (square vs. circle), and orientation (horizontal vs. vertical gratings). There were a SF search condition and a TF search condition, in which the distractor items shared one or two features respectively with the target. The experiment included three basic display conditions: no window, 5° window, and 10° window. We used the gaze-contingent window technique to investigate peripheral and parafoveal cueing and masking effects on visual guidance. To examine cueing effects, in some window trials, only specific stimulus features were visible outside the window-single features (color, shape, or orientation) in the SF condition and pairs of features (color-shape, color-orientation, or shape-orientation) in the TF condition. To examine masking effects, in other gaze-contingent window trials, the stimulus features outside the window were masked. That is, the search items were replaced by gray blobs. Items within the window were fully displayed in an identical manner across all conditions.

2. Method

2.1. Participants

Eight undergraduate students from the University of Toronto were tested individually in five one-hour sessions. All participants had normal or corrected-to-normal visual acuity and had no color vision defects. They were naïve with respect to the purpose of the study and were paid $60 Cdn for their participation.

2.2. Apparatus

Eye movements were recorded with the SR Research Ltd. EyeLink system, which operates at a sampling rate of 250 Hz (4 ms temporal resolution) and measures a participant's gaze position with an average error of less than 0.5 degrees of visual angle. The EyeLink headband has three cameras, allowing simultaneous tracking of both eyes and of head position for head-motion compensation. By default, only the participant's dominant eye (assessed by the sighting test: Miles, 1929) was tracked in our study. The EyeLink system uses an Ethernet link between the eyetracker and display computers for real-time saccade and gaze-position data transfer. The system also performs saccade and blink detection on-line. In the present study the configurable acceleration and velocity thresholds were set to detect saccades of 0.5° or greater. Stimuli were presented on a 19-inch Samsung SyncMaster 900P monitor with a refresh rate of 120 Hz and a screen resolution of 800×600 pixels. A gaze-contingent window was implemented, which followed the participant's eye movements with an average delay of 15 ms (2 ms prior to recording the video frame, 4 ms for image processing, 4 ms for noise filtering, less than 1 ms for data transfer between computers, and 4.17 ms for CRT refreshing). The duration of this delay was verified by inducing a saccade with an artificial eye and measuring the speed of display change with a photocell.

A nine-point calibration was performed at the beginning of each session, followed by a nine-point calibration accuracy test. Calibration was repeated if any point was in error by more than 1° or if the average error for all points was greater than 0.5°. Before each trial, a black fixation target was displayed at the center of the display. The subject fixated this target and the reported gaze position was used to correct any post-calibration drift errors (see Stampe, 1993).

2.3. Materials

The stimulus displays consisted of patches of gratings bounded by a geometrical figure (henceforth 'items'). The features of the items varied along three dimensions—color (red vs. green), shape (circle vs. square), and orientation (vertical vs. horizontal gratings). For each participant, one of these eight item types served as the search target. The identity of the target was counterbalanced across participants. Each participant performed in both the SF and the TF search conditions, in which the target and the distractors shared one feature (color, shape, or orientation) or two features (color-shape, color-orientation, or shape-orientation), respectively. Besides these three 'similar' distractor types, both conditions also included a 'dissimilar' distractor type—a blue, diagonally striped triangle—which shared no feature with the target or the similar distractors. This distractor type was used to derive a baseline for the saccadic selectivity analysis (see Zelinsky, 1996). Target-absent displays consisted of 12 instances of each distractor type (three similar and one dissimilar type), for a total of 48 items per display. In target-present trials, a target-absent display was first generated and then one of the distractors was randomly chosen to be replaced with the target item. There was only one target in any given target-present trial.

All stimuli were presented in a $15.5 \times 15.5°$ field at a viewing distance of 80 cm. The target was never presented within the central $2.7 \times 2.7°$ field of the display. Participants were not informed of this arrangement. Each individual item subtended 1° in diameter, and the minimum distance between the centers of neighboring items was 1.8°. Colors were matched in luminance (20.0 cd/m^2) and saturation. The luminance of the white background was 83.8 cd/m^2. The x, y CIE coordinates for the colors were: red (0.556, 0.342), green (0.298, 0.507), and blue (0.173, 0.115). The square-wave gratings had a spatial frequency of 5 cpd, which is close to the peak of human contrast sensitivity (De Valois & De Valois, 1988).

Gaze-contingent windows with diameters of 5° and 10° were employed, plus a no-window condition. The gaze-contingent window remained centered on the participant's gaze-position throughout the trial. Inside the window, all item features were shown, whereas outside the window, only selective features (cues) were visible. Table 1 shows the appearance of items inside and outside the window for different cue types: all features (all stimulus features were visible inside the window in all conditions and throughout the display in the no-window condition) and three feature cue types (single features in the SF condition and pairs of features in the TF condition). There was also a masking condition in which all items outside the window were replaced with gray blobs. Items which fell on the boundary were only cued or masked in the part falling outside the window. Fig. 1 shows a sample display with masking outside a 5° window.

The design of the experiment included 36 cells, consisting of the combinations of target status (present vs. absent), search condition (SF vs. TF), and nine different window conditions. These nine window conditions resulted from four types of peripheral cues, each of them combined with two different window sizes, plus a no-window condition. Each participant performed 60 trials for each cell of the design, for a total of 2160 trials. Eight blocks of 54 trials were employed in each of the five sessions. SF and TF conditions were tested in alternating blocks with the order of conditions counterbalanced across participants. The first block of each condition was preceded by 18 practice trials. Within each block, the order of stimulus displays was completely randomized except that no more than four displays of a given target status appeared in a row.

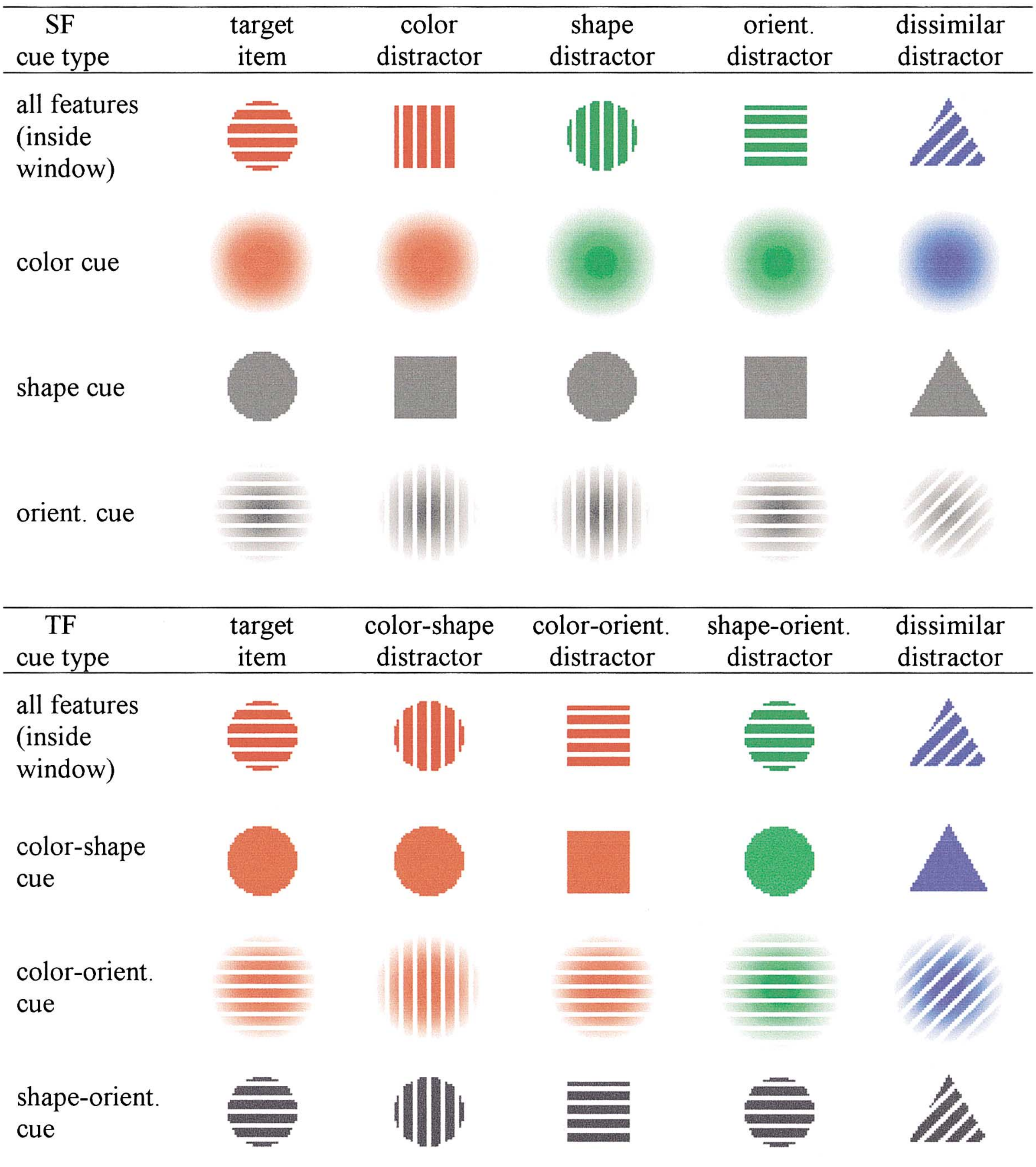
2.4. Procedure

The experiment was run in a lighted room and the luminance of the walls was approximately 30 cd/m^2. Before the experiment started, participants were in formed of the identities of the target and distractors in both the SF and TF conditions. They were asked to search for the target item and indicate whether it was present or absent by pressing an appropriate button as quickly and as accurately as possible. Before each trial, participants fixated on a dot shown in the center of the screen and then pressed a start button to initiate the trial. The trial was terminated if they pressed one of the response buttons or if no response was made within 30 s. The particular buttons used to indicate target presence or absence were counterbalanced across participants.

3. Results

For each participant, an outlier analysis was performed within each cell of the design to eliminate those

Table 1
Illustration of target and distractor items inside and outside the window across search conditions and cue types. Note that the identity of the target was counterbalanced across participants



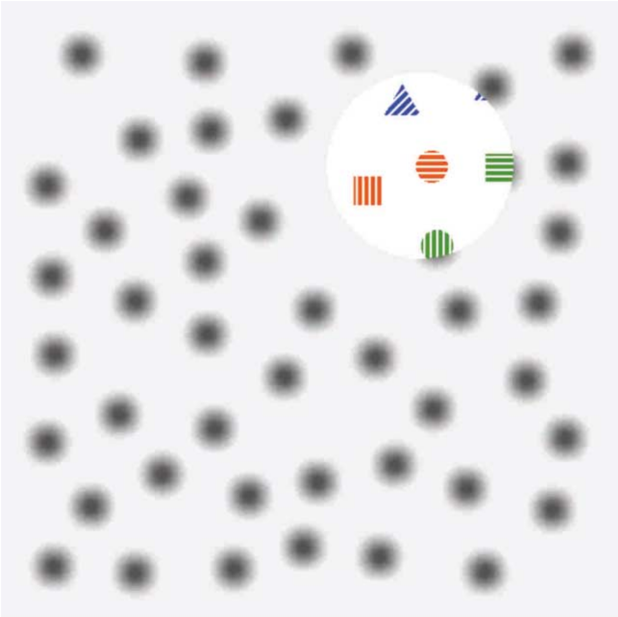


Fig. 1. Sample display with masking outside a 5° gaze-contingent window. The participant is looking at the red, horizontally striped circle in the upper right corner of the display. Note that unlike in the actual displays, the window was highlighted for an illustrative purpose.

response times (RTs) that were more than three standard deviations above or below the mean. This resulted in the removal of 1.5% of all trials (2.1% in the SF search condition and 0.9% in the TF condition). Trials with incorrect responses (0.9% in the SF condition and 2.7% in the TF condition) were also excluded from analysis.[1] In addition, trials with a saccade or a blink overlapping the onset of a display (1.3% in the SF condition and 2.1% in the TF condition) were removed. The remaining 95.0% of trials (95.7% in the SF condition and 94.3% in the TF condition) were analyzed further.

We examined the influences of different peripheral cues and masks on the global performance measures such as RT and number of fixations as well as the distribution of saccadic endpoints. We also examined the effects of peripheral masking on fine-grained eye-movement measures such as saccade amplitude, fixation duration, initial latency, and the spatial distribution of the endpoints of first saccades. All these measures were analyzed with repeated-measure ANOVAs. To simplify the exposition of the present findings, the complete results of these analyses are shown in Tables 1–6. The following discussion highlights the major findings. Throughout the paper, the significance of all statistical tests was evaluated at the $\alpha = 0.05$ level.

[1] Following the convention of visual search literature, we did not report the results from error trials. A separate analysis indicated that results would not change if error trials were included.

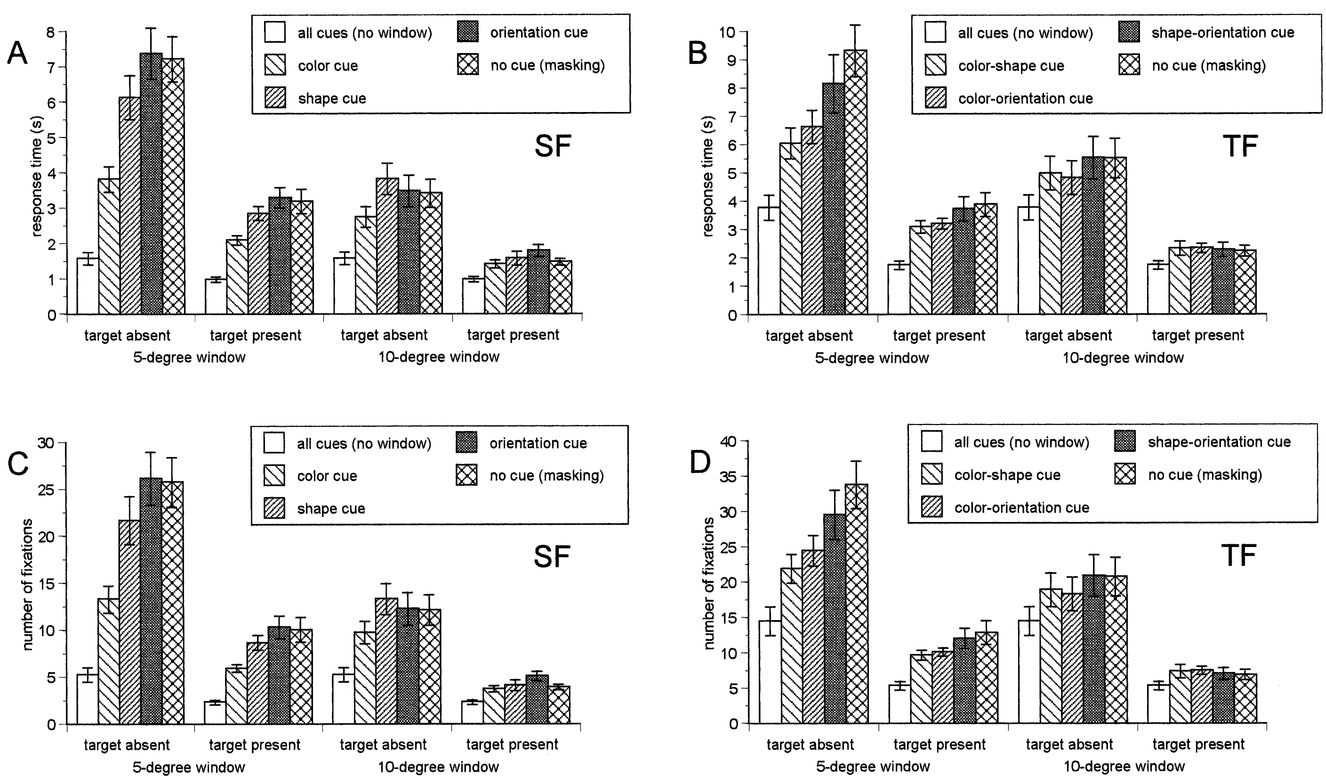


Fig. 2. Response time and number of fixations as a function of cue type, target status, and window size in the single-feature condition (panel A: response time; panel C: number of fixations) and in the two-feature condition (panel B: response time; panel D: number of fixations).

Table 2
Analysis of variance on response time and number of fixations with target status, cue type, and window size as within-subject factors in the single-feature and two-feature conditions

Source	Single-feature			Two-feature		
	df	F	P	df	F	P
Response time						
Target status (TS)	1, 7	55.79	<0.001	1, 7	49.24	<0.001
Cue type (CT)	3, 21	34.24	<0.001	3, 21	14.20	<0.001
Window size (WS)	1, 7	176.86	<0.001	1, 7	238.63	<0.001
TS × CT	3, 21	30.05	<0.001	3, 21	14.93	<0.001
TS × WS	1, 7	76.68	<0.001	1, 7	45.07	<0.001
CT × WS	3, 21	33.70	<0.001	3, 21	25.13	<0.001
TS × CT × WS	3, 21	26.68	<0.001	3, 21	12.06	<0.001
Number of fixations						
Target status (TS)	1, 7	51.66	<0.001	1, 7	53.00	<0.001
Cue type (CT)	3, 21	27.01	<0.001	3, 21	15.38	<0.001
Window size (WS)	1, 7	119.50	<0.001	1, 7	248.97	<0.001
TS × CT	3, 21	25.92	<0.001	3, 21	15.82	<0.001
TS × WS	1, 7	82.59	<0.001	1, 7	36.31	<0.01
CT × WS	3, 21	28.59	<0.001	3, 21	26.44	<0.001
TS × CT × WS	3, 21	34.59	<0.001	3, 21	11.17	<0.001

3.1. Cueing and masking effects on global performance measures (RT and number of fixations)

In the current context, cueing effects were defined as an improvement in search performance (shorter RT and fewer fixations) caused by specific feature cues presented outside the window as compared to the masking condition, in which gray blobs eliminated all feature information. Masking effects were defined as a decrease in search performance (longer RT and more fixations) in the masking condition as compared to the no-window condition.

An inspection of Fig. 2 reveals the pattern of cueing and masking effects for both RT (panel A: SF condition; panel B: TF condition) and number of fixations per trial (panel C: SF condition; panel D: TF condition). Because the pattern of results was very similar for the two dependent variables across the search conditions, the results are discussed together. Masking and cueing effects were most pronounced for target-absent 5° window trials, followed by target-present 5° trials, target-absent 10° trials, and smallest in target-present 10° trials. This was reflected in significant cue type by target status by window size interactions (see Table 2) and target status by masking condition interactions (see Table 3).

In the SF condition, among the feature cue types, color had the strongest cueing effect. This effect was significant for target-absent and target-present 5° trials as well as for target-absent 10° trials, all t values $(7) > 4.47$, P values < 0.01. There was also a significant shape cueing effect for 5° and 10° target-absent trials, all t values $(7) > 2.60$, P values < 0.05. There were no significant orientation cueing effects in any of the window size by target status conditions, all t values $(7) < 1.92$, P values > 0.10. Masking effects were significant for 5° and 10° target-absent and target-present trials, all t values $(7) > 5.59$, P values < 0.01.

In the TF condition, color-shape produced a stronger cueing effect than did the other feature pairs. There was a color-shape effect in target-absent and target-present 5° trials as well as in target-absent 10° trials, all t values $(7) > 2.71$, P values < 0.05. Color-orientation had a significant cueing effect for 5° and 10° target-absent trials, all t values $(7) > 3.74$, P values < 0.01. The cueing effect of shape-orientation was only significant in 5° target-absent trials, t $(7) = 4.47$, $P < 0.01$.

Table 3
Analysis of variance on response time and number of fixations with target status and masking condition (no masking, masking outside a 5° window, masking outside a 10° window) as within-subject factors in the single-feature and two-feature conditions

Source	Single-feature		Two-feature	
	F	P	F	P
Response time				
Target status (TS)	59.41	<0.001	51.98	<0.001
Masking condition (MC)	122.16	<0.001	104.54	<0.001
TS × MC	58.89	<0.001	36.83	<0.001
Number of fixations				
Target status (TS)	51.68	<0.001	51.64	<0.001
Masking condition (MC)	90.36	<0.001	107.42	<0.001
TS × MC	59.00	<0.001	37.48	<0.001

Note: all dfs = 1, 7.

Table 4
Saccadic frequency and saccadic bias towards single stimulus features in the single-feature condition and towards pairs of features in the two-feature condition

Condition		5°			10°		
		No window	Masking	Cueing	No window	Masking	Cueing
Single-feature							
Color	Frequency	61.16 (4.33)	39.64 (1.70)	74.31 (3.51)	50.48 (2.05)	42.50 (2.48)	56.65 (2.57)
	Baseline	9.02 (2.24)	19.92 (0.79)	9.37 (1.46)	18.43 (2.36)	18.17 (0.65)	15.24 (1.70)
	Bias	52.13 (5.97)	19.72 (2.46)	64.94 (4.91)	32.05 (3.79)	24.33 (3.04)	41.41 (4.13)
Shape	Frequency	15.74 (3.51)	21.23 (0.64)	44.93 (3.54)	15.63 (1.93)	20.16 (1.05)	29.17 (2.47)
	Baseline	9.02 (2.24)	19.92 (0.79)	13.68 (2.03)	18.43 (2.36)	18.17 (0.65)	16.68 (0.98)
	Bias	6.72 (4.72)	1.31 (1.03)	31.25 (5.21)	−2.80 (3.73)	1.99 (0.68)	12.50 (3.21)
Orientation	Frequency	14.08 (2.78)	19.21 (0.90)	20.55 (0.95)	15.46 (1.39)	19.17 (1.19)	17.47 (0.50)
	Baseline	9.02 (2.24)	19.92 (0.79)	19.00 (1.11)	18.43 (2.36)	18.17 (0.65)	17.63 (1.15)
	Bias	5.06 (2.44)	−0.71 (0.31)	1.55 (1.46)	−2.97 (3.05)	0.99 (1.03)	−0.17 (1.44)
Two-feature							
Color-shape	Frequency	60.24 (2.86)	42.74 (2.47)	62.02 (1.79)	52.23 (2.90)	45.22 (2.02)	50.98 (2.28)
	Baseline	7.21 (1.12)	12.39 (0.65)	6.59 (0.82)	11.06 (0.90)	13.56 (1.04)	9.70 (0.95)
	Bias	53.03 (3.70)	30.35 (2.97)	55.43 (2.53)	41.17 (3.65)	31.66 (2.61)	41.29 (3.18)
Color-orientation	Frequency	23.13 (1.62)	29.68 (1.64)	36.25 (1.60)	25.10 (1.73)	27.55 (1.30)	26.40 (1.45)
	Baseline	7.21 (1.12)	12.39 (0.65)	5.50 (0.96)	11.06 (0.90)	13.56 (1.04)	11.26 (1.20)
	Bias	15.92 (1.58)	17.29 (1.67)	30.74 (1.72)	14.04 (1.58)	13.99 (1.73)	15.15 (1.65)
Shape-orientation	Frequency	9.42 (0.89)	15.19 (1.09)	30.39 (1.84)	11.62 (0.85)	13.67 (0.70)	20.37 (1.86)
	Baseline	7.21 (1.12)	12.39 (0.65)	7.96 (0.87)	11.06 (0.90)	13.56 (1.04)	12.22 (0.92)
	Bias	2.21 (1.28)	2.80 (0.68)	22.43 (1.50)	0.56 (0.57)	0.11 (1.37)	8.15 (1.82)

Note: frequency, saccadic frequency towards a particular feature in the single-feature condition and towards a pair of features in the two-feature condition; baseline, baseline probability of fixation on a dissimilar distractor; bias, the difference between the saccadic frequency and the baseline; masking, a condition in which feature information was eliminated outside the window; cueing, a condition in which the feature or pair of features that this distractor shared with the target was the only one visible outside the window. See text for more information.

3.2. Cueing and masking effects on visual guidance

The major question of the present study was whether a participant's pattern of saccadic selectivity can be biased by a peripheral cue. The selectivity of participants' eye movements was determined in a manner similar to that used by Zelinsky (1996). Across participants, a total of 61 021 saccades were detected in the SF condition and 84 531 saccades in the TF condition. For every trial, the distance was calculated between each saccadic endpoint and every item in the display. The item closest to the fixation was taken to be the target of that saccade.[2] Once a saccadic endpoint had been assigned to a particular item, that item could be examined to see on what dimension, or pair of dimensions, this item matched the target. For each participant, the number of fixations assigned successfully to distractors was then summed for each dimension in the SF task (color, shape, or orientation) or pair of dimensions in the TF task (color-shape, color-orientation, or shape-orientation). Because a distractor could only match the target on a single dimension in the SF task, whereas it could match the target on a pair of dimensions in the TF task, separate analyses were carried out for the two search tasks.

Following Zelinsky (1996), we used the saccadic frequency towards dissimilar distractors to estimate a baseline probability of landing on a specific item without any feature guidance. For each individual participant, we calculated saccadic bias, a variable quantifying the visual guidance attributable to these features or pairs of features, by subtracting the baseline probability from the saccadic frequency towards each feature or pair of features (see Table 4).

Given that stimulus information within the window was the same regardless of the cue type presented outside the window and was also identical to the no-window condition, cueing and masking effects on visual guidance were investigated by comparing the pattern of saccadic bias across different experimental conditions for saccades aimed at items that were visible within the window. Accordingly, we only analyzed saccades with an amplitude of less than 2.5° in the 5° window condition and saccades smaller than 5° in the 10° window condition and contrasted each window condition with comparable saccade amplitude in the no-window condition. More specifically, to evaluate cueing effects on saccadic bias, for each distractor type, the no-window

[2] On average, the distance between the saccadic endpoint and the center of the saccadic target was 0.78° in the SF condition and 0.72° in the TF condition.

condition was contrasted with a cueing condition in which the feature or pair of features that this distractor shared with the target was the only one visible outside the window. To evaluate the masking effects on saccadic bias, the no-window condition in which all feature information was available throughout the display was contrasted with the masking condition, in which feature information was eliminated outside the window. As pointed out by Zelinsky (1996), the results from target-absent trials can be interpreted more clearly than those from target-present trials, where the presence of the target may influence search behavior. Consequently, only target-absent trials were included in the following analyses.

Fig. 3 shows saccadic bias towards each feature in the single-feature condition (panel A: 5° window; panel B: 10° window) and each feature pair in the two-feature condition (panel C: 5° window; panel D: 10° window). As could be expected from the previous analysis of global performance measures, masking and cueing effects were more pronounced for a 5° window than for a 10° window, and the strength of these effects varied

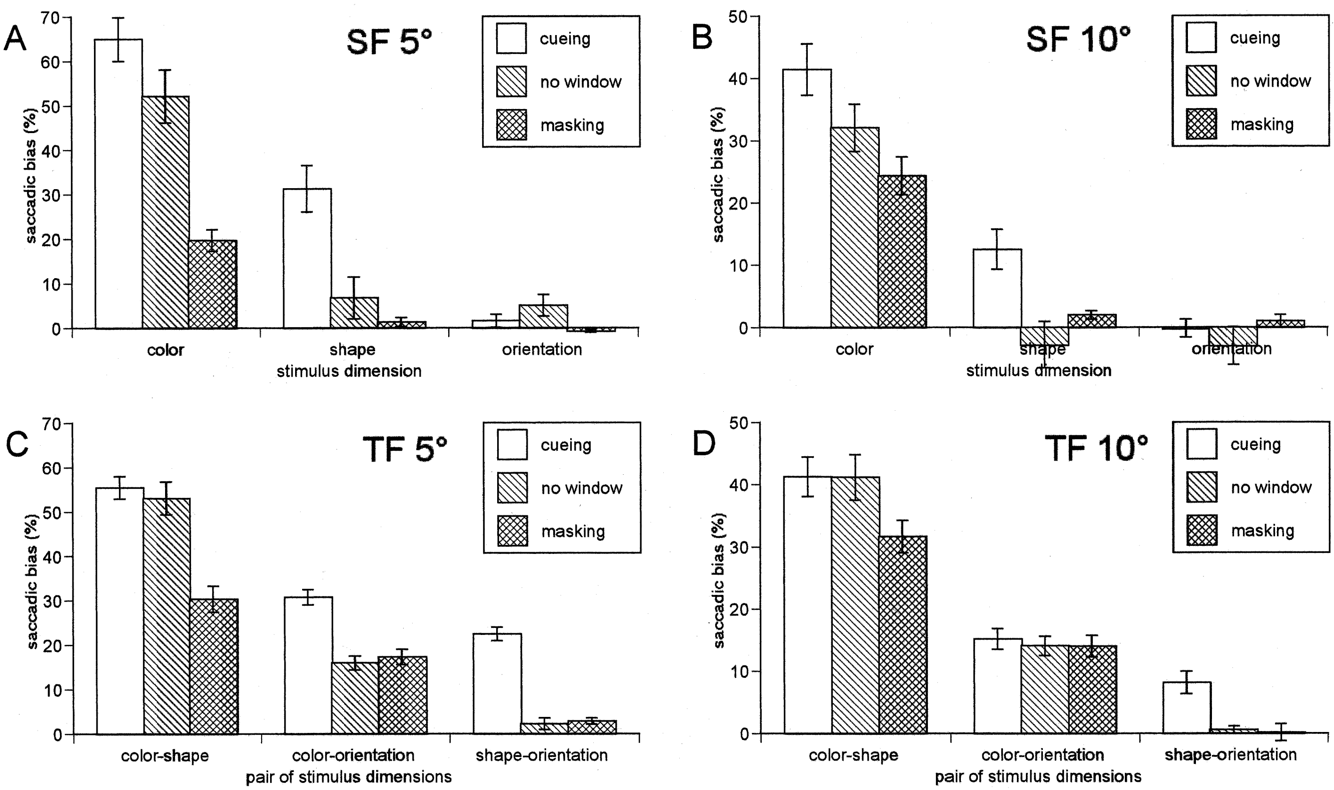


Fig. 3. Cueing and masking effects on saccadic bias towards single stimulus features in the single-feature condition (panel A: 5° window; panel B: 10° window) and towards pairs of features in the two-feature condition (panel C: 5° window; panel D: 10° window). Saccadic bias was calculated by subtracting the baseline probability from the saccadic frequency towards each feature or pair of features (see also Table 4).

Table 5
Analysis of variance on saccadic bias with window size, window condition, and distractor type as within-subject factors in the single-feature and two-feature conditions

Source	Single-feature			Two-feature		
	df	F	P	df	F	P
Window size (WS)	1, 7	23.67	<0.01	1, 7	56.89	<0.001
Window condition (WC)	2, 14	42.05	<0.001	2, 14	57.49	<0.001
Distractor type (DT)	2, 14	184.80	<0.001	2, 14	90.53	<0.001
WS × WC	2, 14	7.98	<0.01	2, 14	38.56	<0.001
WS × DT	2, 14	7.77	<0.01	2, 14	1.31	n.s.
WC × DT	4, 28	14.50	<0.001	4, 28	28.23	<0.001
WS × WC × DT	4, 28	3.64	<0.05	4, 28	12.72	<0.001

n.s., not significant.

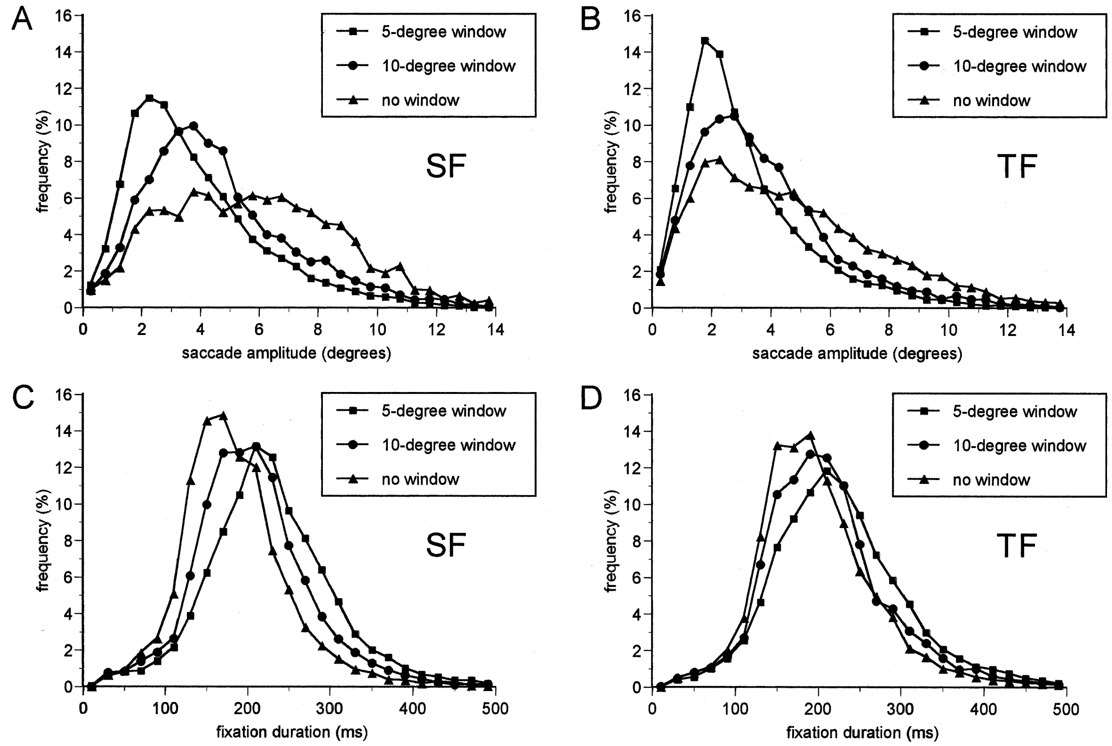


Fig. 4. Distribution of saccade amplitude and fixation duration as a function of window condition in the single-feature condition (panel A: saccade amplitude; panel C: fixation duration) and in the two-feature condition (panel B: saccade amplitude; panel D: fixation duration).

strongly across features or pairs of features. Accordingly, there was a significant distractor type by window condition (cueing, no window, and masking) by window size (5° and 10°) interaction in both the SF and TF conditions (see Table 5).

In the SF condition, color was the only dimension that guided visual search in the no-window condition, that is, had a saccadic bias greater than zero, both t values $(7) > 8.72$, P values < 0.01. There was also a significant cueing effect for color in the 5° window condition, $t\ (7) = 3.03$, $P < 0.05$, and a marginal cueing effect for the 10° window condition, $t\ (7) = 2.36$, $P = 0.05$. Similarly, there was a significant masking effect for color in the 5° window condition, $t\ (7) = 5.30$, $P < 0.01$, and a marginal masking effect for the 10° window, $t\ (7) = 2.09$, $P = 0.075$. Shape did not guide search in the no-window condition, $t\ (7) = 1.93$, $P > 0.10$, but there was a significant cueing effect of shape for both a 5° window and a 10° window, both t values $(7) > 3.04$, P values < 0.05. Since there was no shape guidance in the no-window condition, there were also no masking effects by shape. Orientation neither guided search in the no-window condition nor produced significant cueing or masking effects, all t values $(7) < 2.23$, P values > 0.05.

In the TF condition, there was significant guidance by color-shape in the no-window condition, both t values $(7) > 12.53$, P values < 0.001. Although color-shape produced no cueing effect, both t values $(7) < 1.33$, P values > 0.20, there were significant masking effects for both window sizes, both t values $(7) > 4.35$, P values < 0.01. Color-orientation also guided search in

Table 6
Analysis of variance on saccade amplitude, fixation duration, initial latency, and vertical endpoint with window condition and search condition as within-subject factors

Source	df	*F*	*P*
Saccade amplitude			
Search condition (SC)	1, 7	144.54	<0.001
Window condition (WC)	2, 14	81.87	<0.001
WC × SC	2, 14	5.92	<0.001
Fixation duration			
Search condition (SC)	1, 7	5.54	n.s.
Window condition (WC)	2, 14	63.43	<0.001
WC × SC	2, 14	8.90	<0.01
Vertical endpoint			
Search condition (SC)	1, 7	2.65	n.s.
Window condition (WC)	2, 14	3.30	n.s.
WC × SC	2, 14	16.30	<0.001
Initial latency			
Search condition (SC)	1, 7	2.47	n.s.
Window condition (WC)	2, 14	5.84	<0.05
WC × SC	2, 14	<1	n.s.

n.s., not significant.

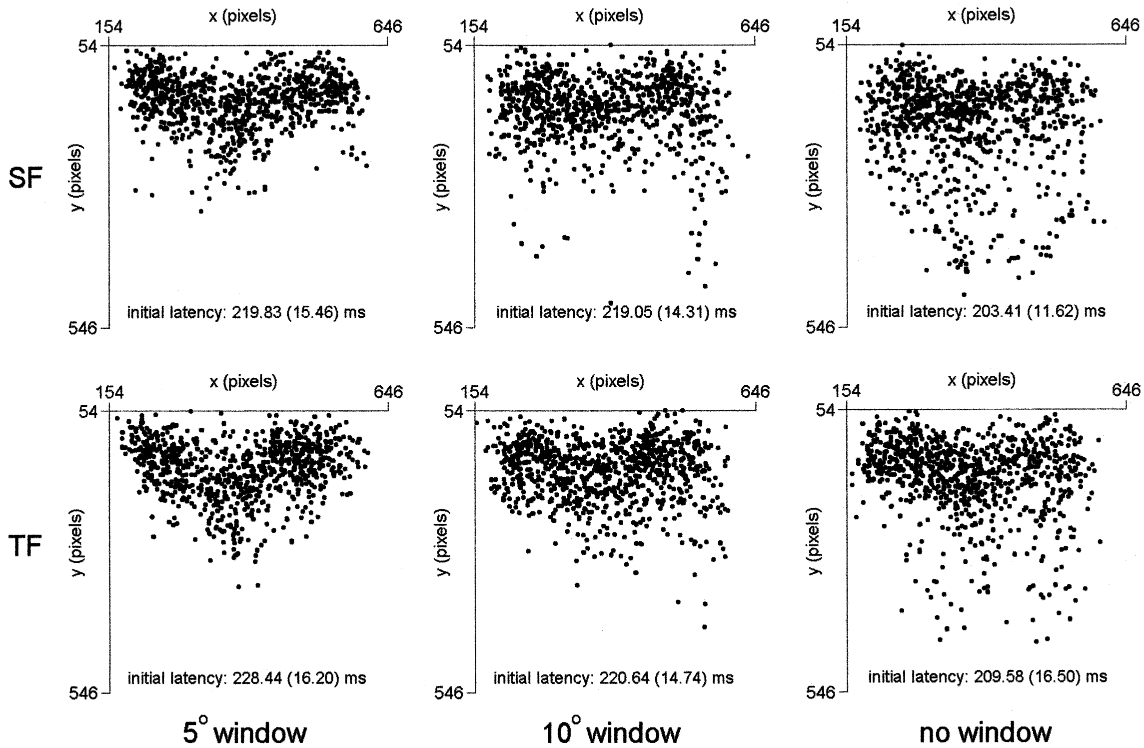


Fig. 5. Scattergram of first saccadic endpoints and initial latency as a function of window condition (from left to right: 5° window without cue, 10° window without cue, and no window) in the single-feature condition (upper row) and in the two-feature condition (lower row). Each panel in the figure corresponds to an area of 492 × 492 pixels, or 15.5 × 15.5°.

the no-window condition, both t values $(7) = 10.10$, P values < 0.001, but to a smaller extent than did color-shape. There was a significant color-orientation cueing effect for a 5° window, $t\ (7) = 8.13$, $P < 0.001$, whereas there was no cueing effect for a 10° window, $t < 1$. No significant color-orientation masking effects were found, both t values < 1. Shape-orientation, which did not guide search in the no-window condition, $t\ (7) = 1.89$, $P > 0.10$, produced significant cueing effects, both t values $(7) > 5.49$, P values < 0.01.

3.3. *The effect of the window on fine-grained eye-movement measures*

To examine the effect of window manipulation on fine-grained eye-movement measures (saccade amplitude, fixation duration, initial latency, and the spatial distribution of the endpoints of first saccades), we compared three different window conditions: 5° window masking, 10° window masking, and no window. For each window condition, Fig. 4 shows histograms of saccade amplitude (panel A: SF condition; panel B: TF condition) and fixation duration (panel C: SF condition; panel D: TF condition). As can be seen clearly, while the increased window size resulted in longer saccades in both the SF condition (means and standard errors across conditions: 5° window condition: $3.80 \pm 0.28°$; 10° window condition: $4.61 \pm 0.24°$; no window condition: $5.80 \pm 0.31°$) and the TF condition (5° window condition: $3.15 \pm 0.20°$; 10° window condition: $3.76 \pm 0.24°$; no window condition: $4.68 \pm 0.32°$), these effects were more pronounced in the SF condition than in the TF condition. Similarly, fixation duration decreased with increased window size in both the SF condition (5° window condition: 227.9 ± 7.0 ms; 10° window condition: 205.7 ± 6.5 ms; no window condition: 183.9 ± 8.7 ms) and the TF condition (5° window condition: 228.0 ± 6.1 ms; 10° window condition: 210.4 ± 6.9 ms; no window condition: 198.8 ± 7.9 ms), with a more pronounced effect in the SF condition. This finding was reflected in a significant window condition by search condition interaction for both saccade amplitude and fixation duration (see Table 6).

It is possible that the window had a stronger effect in the easier SF search condition than in the more difficult TF search condition. This is because visual span, the region from which information is processed during a fixation, was larger in the former than in the latter condition. It has been shown that visual span is affected by task difficulty (e.g. Pomplun et al., 2001). To the extent that visual span is larger, it would be expected to be more adversely affected by the field of view restriction imposed by the masking outside the gaze-contingent window. The finding of a decrease in saccade amplitude and an increase in fixation duration replicates previous findings employing a gaze-contingent window technique (Bertera & Rayner, 2000; Rayner & Fisher, 1987).

In a recent study on guidance of eye movements, Zelinsky (1996) argued that oculomotor strategies can be adopted by participants to aid the search process in a multi-element display. Instead of biasing saccadic endpoints towards one specific type of distractors, oculomotor strategies are responsible for programming a series of fixations in an orderly fashion such that every display element has an equal chance of being recognized correctly. In accordance with this argument, he found that the endpoints of the first saccades were biased towards the top-left quadrant of the search display (see also Previc, 1996; Williams & Reingold, 2001). As shown in the analysis in the previous section, in the current study there was a reduction in visual guidance in the gaze-contingent masking conditions. In order to examine whether this decrement in visual guidance was accompanied by an increase in the use of oculomotor strategies, we examined the spatial distribution of the endpoints of first saccades in a manner similar to Zelinsky (1996).

As shown in Fig. 5, in both search conditions, participants seemed to more often start their search in either the upper left or the upper right corner of the display when a 5° window was employed. For the 10° window and no-window conditions, the distinctness of this pattern decreased. We took the vertical pixel coordinates of first saccadic endpoints, increasing from 1 at the top to 600 at the bottom of the display, as quantitative indicators of oculomotor strategies and found lower endpoints for larger windows, with a stronger effect in the SF condition (5° window condition: 135.0; 10° window condition: 153.9; no window condition: 181.8) than in the TF condition (5° window condition: 141.3; 10° window condition: 145.8; no window condition: 159.4). This was also demonstrated by a significant window condition by search condition interaction of this measure (see Table 6). These results support the conclusion that, at least in the SF search condition, smaller windows increase the usage of oculomotor scanning strategies. Finally, as shown in Fig. 5, both window conditions induced longer initial latency (i.e. the time between stimulus onset and the execution of the first saccade) than the no-window condition in both the SF condition (5° window condition: 219.83 ms; 10° window condition: 219.05 ms; no window condition: 203.41 ms) and the TF condition (5° window condition: 228.44 ms; 10° window condition: 220.64 ms; no window condition: 209.58 ms). This was reflected in a significant effect of the window condition on initial latency (see Table 6). Longer initial latency is consistent with the hypothesis of more strategic selection of first fixation targets in the window conditions and with the longer fixation durations in these conditions.

4. Discussion

The gaze-contingent window manipulation in the present study produced strong support for the flexibility of visual guidance (Shen et al., 2000; Williams & Reingold, 2001) by demonstrating parafoveal and peripheral cueing and masking effects on global visual search performance (RT and number of fixations) and on the pattern of saccadic selectivity. Typically, cueing and masking effects were stronger for the 5° window, but there were still significant effects for the 10° window, demonstrating that not only parafoveal, but also peripheral information processing contributes considerably to visual search performance. Furthermore, consistent with previous findings (Bertera & Rayner, 2000; Rayner & Fisher, 1987; Saida & Ikeda, 1979), the restriction of the visual field caused by masking produced shorter saccades, longer initial latencies, longer fixation durations, and greater reliance on oculomotor scanning strategies (i.e. higher proportion of first saccades were directed at the top of the display; see Previc, 1996; Williams & Reingold, 2001; Zelinsky, 1996).

Color cues in the SF condition and color-shape cues in the TF condition produced the strongest cueing effects, while orientation was the only cue type that did not have an effect on search efficiency. Consistent with these results, the analysis of saccadic selectivity revealed that color in the SF condition and color-shape in the TF condition were dominant in guiding visual search in the no-window condition. Cueing non-dominant dimensions (shape) or dimension pairs (color-orientation and shape-orientation) outside the window produced significantly stronger saccadic bias towards their respective distractor type inside the window as compared to the no-window condition. This demonstrates that participants were able to take advantage of the parafoveal and peripheral feature information by flexibly adapting visual guidance to the corresponding feature or pair of features. Similarly, masking parafoveal and peripheral information had a detrimental effect on visual guidance. A further inspection of the individual participant's performance revealed that the cueing and masking effects were robust and the same numerical trends were shown in all eight participants.

It is important to note that in the present study, changes in saccadic selectivity were observed for saccades directed at items within the window, whereas cueing and masking manipulations were carried out on items outside the window. When a particular feature or feature pair was cued outside the window, saccadic selectivity was biased towards this feature or feature pair within the window. Similarly, when items were masked outside the window, the pattern of guidance, that is, the direction towards most informative features or feature pairs, became less distinct even within the window. These results yield strong support for the conceptualization of visual guidance as a preattentive process operating in parallel across the display, as proposed by the Guided Search Model (Cave & Wolfe, 1990; Wolfe, 1994; Wolfe, Cave, & Franzel, 1989). Accordingly, the informativeness of specific dimensions is assessed in parallel for all display items, producing higher activation for cued features or feature pairs and low activation across features or feature pairs in the masking condition. This activation pattern guides the subsequent search process and generates saccadic selectivity patterns reflecting these changes in activation, even for saccades aimed at items within the window. Prior theoretical framework such as the modified Feature Integration Theory (Treisman, 1991a,b, 1993; Treisman & Gormican, 1988) suggested that certain irrelevant dimensions might be inhibited. The present results suggest that it is more likely that there is a continuous weighting function for the informativeness of dimensions, which can be biased in real-time to take advantage of more informative dimensions. This hypothesis is similar to the concept of attentional bias, which has been successfully integrated into a current computational model of attention. In their neural approach, Tsotsos and his colleagues (Tsotsos, Culhane, & Cutzu, 2001; Tsotsos et al., 1995) simulate a visual processing pyramid, which is selectively tuned by 'attentional' processes. Thus, it appears that the flexibility of saccadic selectivity is a fundamental aspect of visual guidance and an important determinant of search efficiency.

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