Different visual search strategies in stationary and moving radial patterns

E.M. van Loon [a,*], I.Th.C. Hooge [b], A.V. Van den Berg [a]

[a] *Department of Neuroscience, Erasmus University Rotterdam, P.O. Box 1738, 3000 DR Rotterdam, The Netherlands*
[b] *Department of Psychonomics, Utrecht University, Heidelberglaan 2, 3584 CS Utrecht, The Netherlands*

Abstract

This study compared visual search strategies in patterns of radially moving dots (simulating self-motion) to those used in matched stationary displays (radial patterns of lines). To control for differences in target visibility, 75% detection thresholds for deviating motion direction and line orientation, respectively, were determined as a function of eccentricity in Experiment 1. These individual thresholds were used to study saccadic parameters in Experiment 2, when subjects searched for targets in the stationary and moving patterns. Despite similarities in search performance, visual search in moving radial patterns was characterised by fewer saccades, longer initial fixation times, and shorter saccadic amplitudes after the initial saccade than during search in a matched stationary radial pattern. These results suggest that detection performance alone cannot explain saccadic search behaviour, and that different search strategies may be used in moving compared to stable environments.
© 2003 Elsevier Science Ltd. All rights reserved.

Detecting moving objects in sparse environments while moving oneself requires an analysis of whether the target's motion deviates from the global pattern that is continually changing due to one's own motion. The ability to distinguish the direction of object motion from one's own direction of motion is particularly important in sparse environments, for example while driving in fog or at night. When moving forward, the flow on the retina consists of an expanding motion pattern. The centre of this pattern (the focus of expansion) denotes the direction of heading. The trajectory of an object in the environment that moves parallel to the observer will be parallel to the radial flow. However, if an independently moving object has a different direction of motion, i.e. is moving along a path that intersects with that of the observer, its trajectory will deviate from that of the components of the radial pattern. The analysis of these possible deviations of the global pattern must be quick, as typical inter-saccadic fixations during self-motion are 400 ms or shorter (Hooge, Beintema, & Van den Berg, 1999; Lappe, Pekel, & Hoffmann, 1998).

It is not known to what extent saccadic search behaviour in a moving world is similar to saccadic search in a stationary environment, which to date has been studied far more extensively (see for reviews of eye movement in visual search e.g. Liversedge & Findlay, 2000; Rayner, 1998). From the search research in static displays it has been recognised that, during visual search, subjects may adopt different strategies with respect to fixation duration and saccade amplitude. For example, one can search with large saccades and long-lasting fixations as well as with short fixations and small saccades, and both strategies could be equally effective. The aim of this work then, is to compare search strategies (expressed by saccadic parameters) in dynamic displays with search behaviour in static displays with these potential differences in mind.

Orientation and direction selectivity is common in the primary visual cortex (Livingstone & Hubel, 1988), but true motion selectivity is only found later in the cortical hierarchy, most notably in area MT (e.g. Britten & van Wezel, 2002). There is evidence for attentional (for a review see Kastner & Ungerleider, 2000) and contextual modulation in these areas (Lamme & Roelfsema, 2000),

---
* Corresponding author. Address. School of Psychology, University of Nottingham, Nottingham NG7 2RD, UK. Tel.: +44-115-951-5317.
 E-mail address: evl@psychology.nottingham.ac.uk (E.M. van Loon).

indicating feedback from higher brain regions into these more primary sensory areas. We know that some of these higher brain regions contain units that are particularly sensitive to radial flow, which is indicative of self-motion through the environment. For instance such cells are found in area MST (e.g., Duffy & Wurtz, 1991, 1997), VIP (Bremmer, Duhamel, Benhamed, & Graf, 2000), and area 7A (Read & Siegel, 1997). This state of affairs allows one to speculate that the sensitivity to self-motion in these higher order areas might affect motion sensitive units in lower areas.

We know that when targets differ sufficiently in either orientation or motion direction from other elements in a pattern perceptually, they stand out from this pattern. Kastner, Nothdurft, and Pigarev (1999) showed that the responses of a sub-population of neurons in the cat striate cortex were relatively enhanced when stimuli with contrasting orientation or motion were presented compared to when uniform texture fields were shown. This contextual effect led the authors to believe that neurons with preference for feature contrast may be the physiological basis for the perceptual saliency of pop-out targets. Their results also suggest that pop-out of motion and pop-out of orientation are encoded in different pools of neurons at the level of striate cortex. This study did not involve radial patterns, but as a general trend it was found in an earlier study that larger deviation from the local orientation was required when the range of orientations in the stimulus increased (Nothdurft, 1993). This would mean that in a radial stationary pattern the target would require especially large orientation contrast in order to be detectable. Given the special sensitivity to radial patterns of motion in higher brain areas, detection of contrasting motion direction could on the contrary be enhanced!

There is also some evidence for a common attentional mechanism across features to select these targets. An event-related potential (ERP) study by Girelli and Luck (1997) showed that the N2pc component, which has previously been shown to be a neurophysiological correlate of selective attention for a target (Luck & Hillyard, 1994), was present when subjects searched for targets defined by motion as well as orientation.

Given that different mechanisms are involved in the perception of orientation and motion with perhaps different potential for enhancement by feedback from higher centres, it is important that the displays are matched in difficulty when comparing saccadic search strategies in static and dynamic displays. For example, it is known that fixation durations increase when the search task is more difficult (Hooge & Erkelens, 1996, 1998; Zelinsky & Sheinberg, 1995). As Geisler and Chou (1995) state, search performance is to a large extent determined by low-level factors. Geisler and Chou (1995) investigated the role of these low-level factors in multiple fixation visual search by comparing simple-

discrimination performance and complex-task performance for the same stimuli. Results showed that the variance in search time was largely accounted for by the observed discrimination performance. Similarly, Parkhurst, Law, and Niebur (2002) could show in a recent study based on a computational model that the first saccade after stimulus onset is with high probability directed towards stimulus features that were computed to be salient in colour, intensity or orientation. Therefore, before studying oculomotor behaviour in our two displays, we first collected psychophysical data to compare the difficulty of target detection in the self-motion display with that in the matched static display.

1. Experiment 1

The aim of the first experiment was to determine detection thresholds for differences in line orientation and differences in motion direction as a function of eccentricity. It is well documented that most measures of visual sensitivity decline with retinal eccentricity, including the detection of line orientation (e.g. Mäkelä, Whitaker, & Rovamo, 1993) and motion direction (e.g. McKee, 1984; Tynan & Sekuler, 1982). As the rate of this deterioration seems to be task-dependent, and as we are interested in visual search performance throughout the visual field, it is important to know the incline of the detection thresholds with retinal eccentricity for both line orientation and motion direction. Therefore, the first experiment investigated detection thresholds for line orientation and motion direction, within a range of 2–22 deg from the fixation point.

1.1. Method

1.1.1. Subjects

Seven subjects (6 men, 1 woman) with a mean age of 29.8 (S.D. ± 7.4) years participated in this experiment.

1.1.2. Apparatus

Displays were generated by an Apple G3 computer, and consisted of an expanding pattern simulating self-motion (see Fig. 1). Stimuli were back-projected by a Sony VPH 1270 QM projection television on a translucent screen (distance: 2.0 m, 63 deg horizontally × 47 deg vertically; 1024 × 768 pixels) in a completely darkened room. Display rate of the projection television was 47 Hz (with a frame rate of 75 Hz this means that only about 60% of the frames were actually shown; this did not affect the presentation duration however). To prevent head movements, a chin rest was used. Subjects looked binocularly.

To simulate forward self-motion, in the motion direction condition a perspective projection of a moving box filled with dots was presented. The simulated box
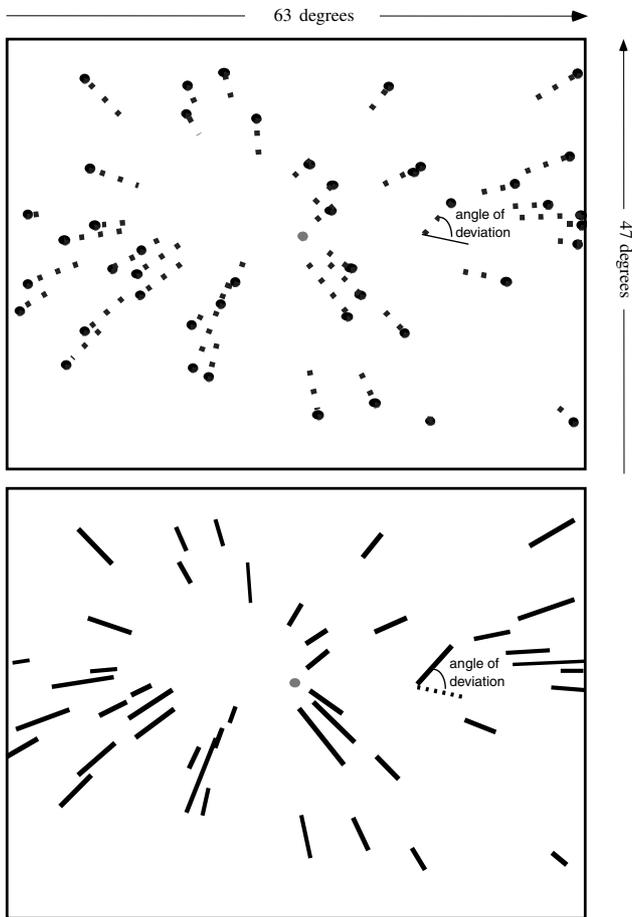
Fig. 1. The displays for the motion direction (top) and line orientation (bottom) search tasks. Stimuli are not drawn to scale.

Fig. 2. Mean (±SE) 75% correct detection thresholds for a deviation in motion direction and line orientation as a function of presentation time, averaged across subjects.

(simulated size $h \times w \times d$: $10.14 \times 13.51 \times 41.50$ m) contained 120 red dots. As the subjects viewed the box through an aperture and never saw the entire box, on average 60 ± 6 dots were visible. Each dot had a diameter of 0.2 deg, and did not scale with distance. The simulated distance between observer and the front of the simulated box was 8 m at stimulus onset. Speed of the dots was 8 m/ s, and heading direction was randomly varied (the centre of flow was at a random position in an imaginary box of 30×30 deg around the fixation point). The elements in the static display were matched with those in the self-motion display in that line length was equal to dot trajectory length for a given presentation time (cf. Matthews, Liu, Geesaman, & Qian, 1999). Target elements and alternative choice points were presented at random locations on six imaginary circles around the fixation point at eccentricities of 2, 6, 10, 14, 18 and 22 deg. Presentation time of the stimuli was 362 ms. This duration was based on a pilot study that indicated that between 300 and 400 ms the steep decline in detection threshold as a function of presentation time for the line stimulus had changed to a more gradual improvement not unlike that for the motion stimulus (see Fig. 2). Thresholds were measured using a two-alternative forced choice procedure.
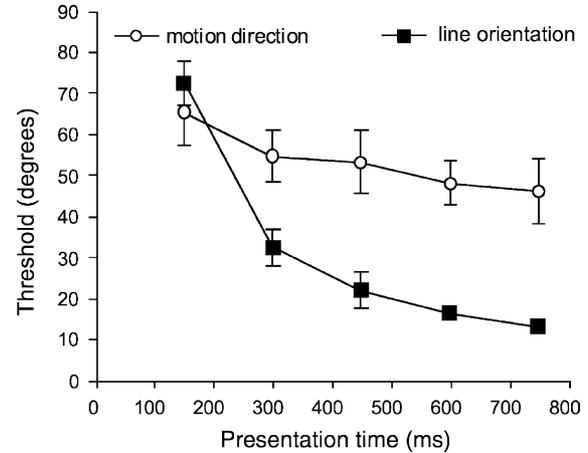
Pilot experiments had indicated that subjects tended to opt for the faster of the two choice points, regardless of their direction of movement. The local speed of the points is determined by $\sin(\theta)/d$, where θ is the angle between the point and the centre of expansion and d is the point's simulated distance from the viewer. To match the local speed (or line length in the orientation condition) for the target and the alternative choice target, the simulated distance of the latter was varied to compensate for its different angular distance to the centre of expansion, ($\theta_{\text{alternate}}$) compared to the target (θ_{target}).

1.1.3. Procedure

The subject was instructed to fixate a yellow fixation point, subtending a visual angle of 0.3 deg, in the centre of the screen. Target elements and alternative choice points were presented at random locations concentric with the fixation point at eccentricities of 2, 6, 10, 14, 18 or 22 deg. After 362 ms, the two choice targets were replaced by blue dots, subtending a visual angle of 0.3 deg, indicating the two response alternatives. The subject's task was to indicate which of the two choice targets had a different direction of motion (heading condition) or line orientation (line condition) in relation to the rest of the display. Responses were made by moving a cursor to one of the dots, followed by a mouse click.

Interleaved staircases were used to determine the 75% correct point for each presentation time in each condition, which was done by taking the average of the last six turning points.

1.2. Results and discussion

1.2.1. Detection thresholds

Thresholds for line orientation were lower than those for motion direction, $F(1, 6) = 102.47$, $p < 0.001$, indicating that the detection of differences in line orientation
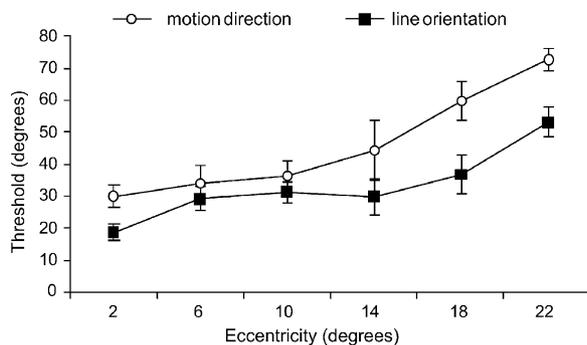
Fig. 3. Mean (±SE) 75% correct detection thresholds for a deviation in motion direction and line orientation as a function of target eccentricity, averaged across subjects.

relative to a radial pattern was superior to that of differences in motion direction (Fig. 3). Thresholds increased with increasing eccentricity, $F(5, 30) = 32.59$, $p < 0.001$. Post-hoc tests showed that thresholds were similar within a range of 6–14 deg eccentricity, lower for 2 deg and increasingly higher for 18 and 22 deg. A significant Task × Eccentricity interaction showed that thresholds for the two tasks were different at all eccentricities apart from 6 and 10 deg ($F(5, 30) = 3.74$, $p = 0.01$), as shown by Newman–Keuls post-hoc tests.

The detection of differences in motion direction relative to a radial pattern was shown to be poorer than that of differences in line orientation. These differences might be due to differences in stimulus energy between the two displays, as suggested by Matthews et al. (1999) in a similar study. The single dots in the motion direction task contain less energy than the entire lines shown in the line orientation task. Matthews et al. (1999) investigated perceptual learning of orientation and direction discrimination. They also found that, when the trajectory length of the direction task was matched to the line length of the orientation task, initial absolute thresholds for orientation discrimination were lower than those for direction discrimination. Furthermore, in their study it was found that orientation discrimination improved more rapidly than direction discrimination, despite the fact that the initial difficulties of the tasks were matched. They argued that these performance differences could be due to differences in stimulus energy; in each frame the target stimulus was an entire line in the orientation task, as opposed to a single dot in the motion direction task.

1.2.2. Eccentricity scaling

Visual performance in many tasks can be made equally good across the visual field by varying the size of the stimulus with eccentricity (e.g. Carrasco & Frieder, 1997; Mäkelä et al., 1993; Van de Grind, Van Doorn, & Koenderink, 1983).

Carrasco and Frieder (1997) showed in a visual search task that equal search performance as a function

of eccentricity can be obtained by cortically magnifying the stimuli. This neutralised earlier findings that target detection is increasingly less efficient as the orientation target appears at more distant field eccentricities (Carrasco, Evert, Chang, & Katz, 1995). The nature of our radial pattern display is such that a certain extent of eccentricity scaling is present: elements in the periphery have a higher velocity/longer line length than elements closer to the centre of expansion; mean line length varied from 2.7 deg at eccentricities of 2 deg to 5.2 deg at eccentricities of 22 deg. This 'magnifying factor', however, does not seem to be sufficient to prevent deterioration of detection performance with increasing eccentricity.

2. Experiment 2

In the first experiment, psychophysical data were presented that describe detection performance of difference in line orientation and motion direction as a function of eccentricity. The goal of the second experiment was to explore possible differences in search strategies, expressed by saccadic parameters (number of saccades, saccadic amplitude and fixation duration), in the stationary and moving radial pattern, when detection of the target is equally difficult.

2.1. Method

2.1.1. Subjects

Four of the subjects that took part in Experiment 1 (the three authors EL, IH and AV and one naïve subject MC; 3 men, 1 woman) with a mean age of 32.8 (S.D. ± 7.8) years participated in this experiment. All subjects were experienced in wearing scleral coils for eye movement recording.

2.1.2. Stimuli and task

The same stimuli were used as in Experiment 1. Viewing time was 1.5 s. Once again the displays were matched in that line length was equal to dot trajectory length. In order to prevent the target element from disappearing off the screen before the end of the viewing period (in the motion direction task), the 362 ms display was repeatedly shown during the 1.5 s. In the motion direction task, dots were reset during different instances of the presentation time so that their reappearance was asynchronous. The interval between resets was much larger than the inter-saccadic fixation period, reducing the probability that the target would jump while it being pursued. To match the difficulty of the task in each display for each eccentricity and for each subject, individual threshold angles (as determined in Experiment 1) were taken as the angle of deviation in orientation/motion direction. The subject's task was to find and fixate the target.

2.1.3. Eye movement recording

Horizontal and vertical movements of the left eye were measured with an induction coil mounted in a scleral annulus in an a.c. magnetic field (Robinson, 1994/Skalar eye position meter 3020, Delft, the Netherlands). This method was first described by Robinson (1963) and refined by Collewijn, van der Mark, and Jansen (1975). The dynamic range of the recording system was from d.c. to 100 Hz (3 dB down), with a noise level of less than 10 min arc. Deviation from linearity was less than 1% over a range of +20 deg. Signals were sampled at a rate of 500 Hz with a National Instruments 16 bits PCI-MIO-XE50 analogue to digital converter and fed through a low-pass analogue filter with a cut-off frequency of 62 Hz. Data were recorded in sessions of 360 trials. Data were stored and analysed off-line.

2.1.4. Data analysis

A computer program searched for saccades with a velocity threshold of 20.0 deg/s. The precise moment of saccade onset was determined by computing the mean and SD of the presaccadic velocity in an interval ranging from 100 to 50 ms before the initially detected start of the saccade. The instant at which velocity exceeded the mean presaccadic velocity with 3 SD was taken as saccade onset. Saccade offset was determined by using the postsaccadic velocity in an analogous way (see also Van der Steen & Bruno, 1995). Saccadic latencies shorter than 20 ms were excluded from the analysis. Targets were considered correctly localised when the position of the eye at the end of a trial was within 3 deg from the target line or motion trajectory.

2.2. Results

2.2.1. Search performance

The results showed no significant difference in search performance between the two tasks, $F(1, 3) = 1.48$, $p = 0.31$ (Fig. 4, top) and no main effect of eccentricity, $F(5, 15) = 1.09$, $p = 0.41$. There was no Task × Eccentricity interaction, $(F(5, 15) = 0.92$, $p = 0.49)$. When looking at the search performance after only the first saccade [1] (Fig. 4, bottom), a significant effect of eccentricity is apparent, $F(5, 15) = 10.16$, $p < 0.001$, but once again there is no evidence for any difference in search performance $(F(1, 3) = 0.15$, $p = 0.73)$ or a Task × Eccentricity interaction $(F(5, 15) = 1.21$, $p = 0.35)$. Do note however that, both after the initial saccade and at the end of a trial, performance in the line orientation task is poorer for targets at 2 deg than for targets
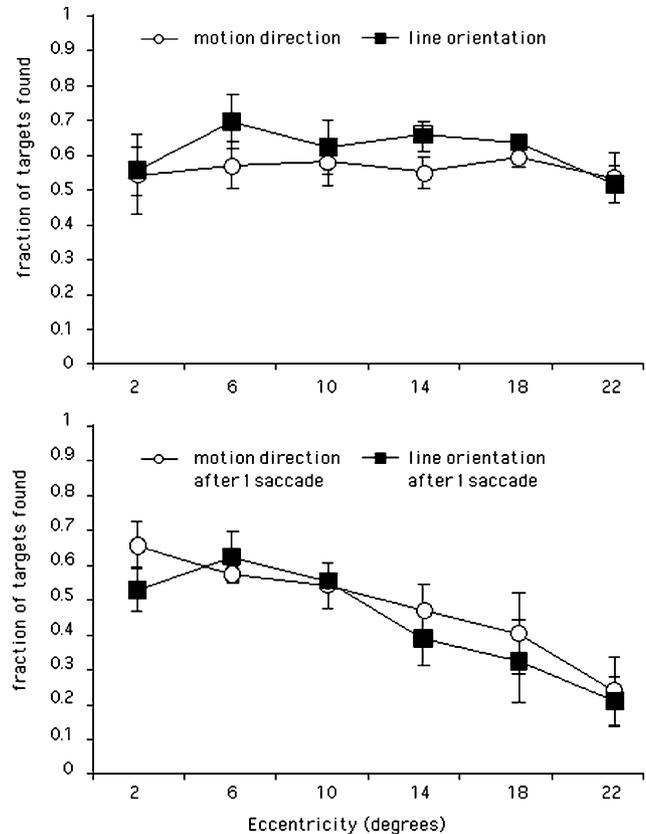
---

[1] The matching of target visibility is less valid after this first saccade, as the position of the eye relative to the target (and therefore the eccentricity) will have changed.

Fig. 4. Mean (±SE) percentage of correctly localised targets in motion direction and line orientation as a function of target eccentricity, averaged across subjects, at the end of the search time (top), and after the initial saccade (bottom).

slightly further out. Furthermore, it can be observed that in the motion direction task mean search performance for this nearest eccentricity level is worse at the end of the trial than after only the first saccade, indicating that in some of the trials subjects moved away from the target after initially having landed on it.

The cumulative fractions of correct trials as a function of search time for each individual subject are shown in Fig. 5(a). From these graphs it appears that search performance was quite similar in the two search tasks for subjects AV, MC and EL, but better in the line orientation task for subject IH. It must be noted that subject IH was the only subject with lower threshold levels in the motion direction condition than in the line orientation condition in Experiment 1, resulting in more difficult targets in Experiment 2, which may explain his poor performance in this condition.

2.2.2. Number of saccades

As can be seen in Fig. 5(b), more saccades were made in the line orientation task ($M = 3.5$, SD $= 0.4$) than in the motion direction task ($M = 2.0$, SD $= 0.1$), $F(1, 3) = 31.52$, $p = 0.01$. The number of saccades made
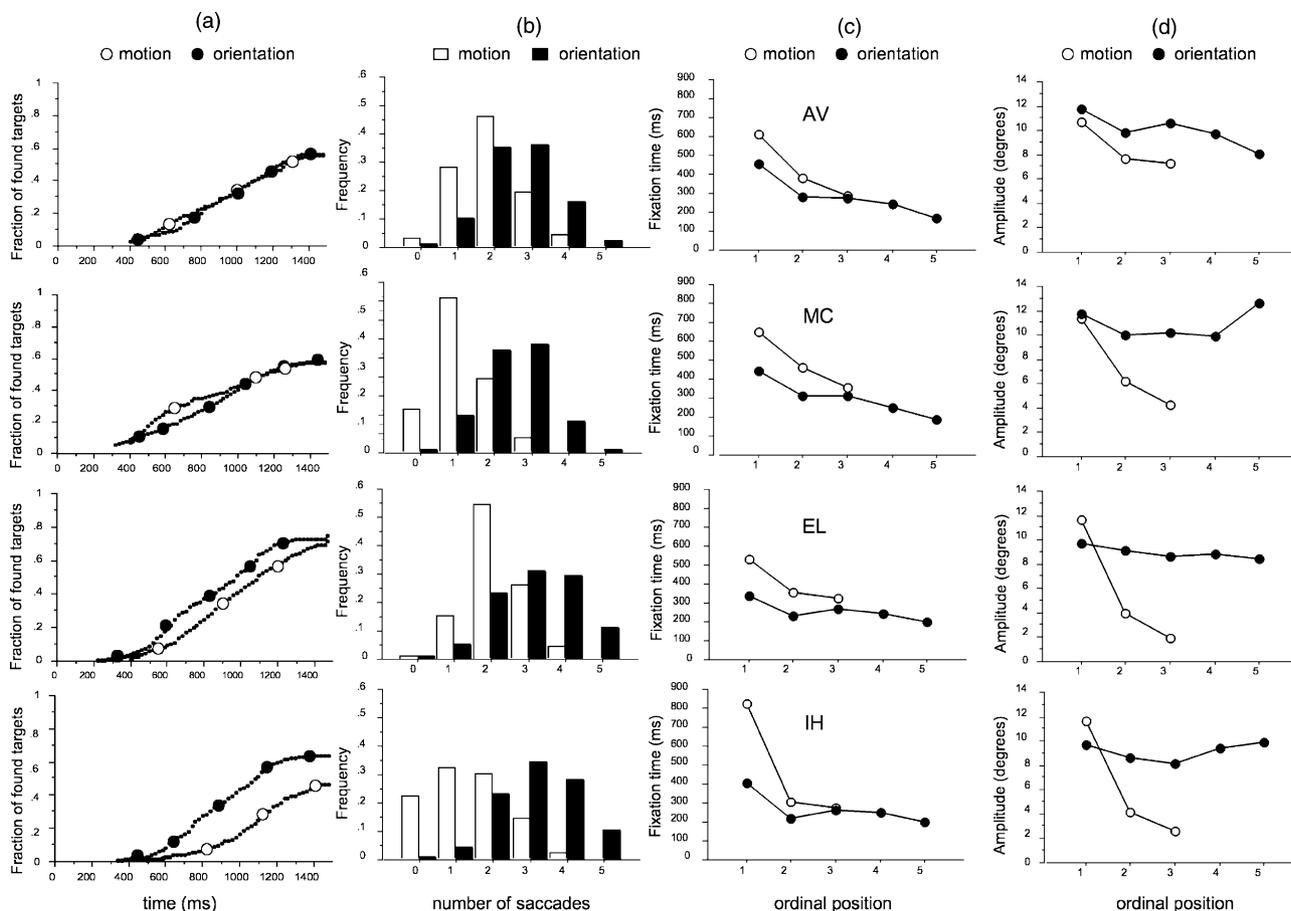
Fig. 5. Overview of search performance and saccadic parameters in both the motion direction and line orientation search task for each subject: (a) the cumulative fraction of correct trials as a function of search time (circles denote the average latency for each saccade in the sequence), (b) the frequency distribution of the total number of saccades, (c) mean fixation time, and (d) mean amplitude as a function of ordinal position in the saccade sequence.

was independent of the eccentricity of the target, $F(5, 15) = 2.33$, $p = 0.09$.

2.2.3. Fixation duration

Fixation durations were shorter in the line orientation task than in the motion direction task $F(1, 3) = 58.92$, $p < 0.01$, and there was a main effect for Ordinal Position, $F(2, 6) = 22.92$, $p < 0.01$ (Fig. 5(c)), showing shorter fixation durations for subsequent saccades in a sequence. A Task × Ordinal Position interaction indicated that the differences in fixation durations between the two tasks decreased with ordinal position in the sequence, $F(2, 6) = 7.65$, $p = 0.02$. The onset of the first saccade was independent of target eccentricity, $F(5, 15) = 2.02$, $p = 0.13$.

2.2.4. Saccade amplitude

When looking at the saccade amplitude as a function of the ordinal position in a sequence, the amplitude of the first saccade is higher than that of the following saccades (Fig. 5(d)), $F(2, 6) = 40.11$, $p < 0.001$. This ordinal effect is more pronounced in the motion direc-

tion task than in the line orientation task, as shown by a significant Task × Ordinal Position effect, $F(2, 6) = 15.18$, $p < 0.01$. Not surprisingly, mean saccade amplitude increased with increasing target eccentricity, $F(5, 15) = 47.12$, $p < 0.001$ (Fig. 6). The mean amplitude in the line orientation task was higher than that in the motion direction task, $F(5, 15) = 39.62$, $p < 0.01$. A Task × Eccentricity interaction, $F(5, 15) = 12.79$, $p < 0.001$, showed that this was particularly true for the nearby targets. Interestingly, the mean saccade amplitude in the line orientation task was higher for targets at 2 deg than at 6 deg. This is probably due to the tendency of subjects to first look away from a suspected nearby target, and return there later once inspection of more peripheral elements confirms that the nearby element is the target. Closer inspection of the fixation duration data revealed that fixation durations were considerably shorter ($M = 318$ ms vs $M = 506$) when subjects initially fixated the nearby target and then moved away compared to when they did not. The shorter fixation times may suggest that the fixation was part of a pre-programmed scanning sequence that could not be inhibited
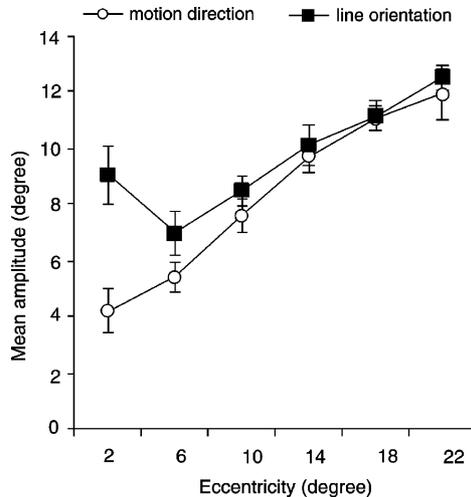
Fig. 6. Mean (±SE) saccade amplitude as a function of target eccentricity in both the motion direction and line orientation search task, averaged across subjects.

and/or that the initial inspection time was too short to decide that the fixated element was the target.

3. General discussion

Saccadic parameters in visual search were shown to differ between stationary and moving radial patterns, although both displays were matched for visibility of the target, and no difference in search performance was found. Saccadic behaviour in the two patterns was remarkably similar across subjects. For each subject, visual search in moving radial patterns was characterised by fewer saccades, longer initial fixation times, and shorter saccadic amplitudes after the initial saccade than during search in a matched stationary radial pattern. That saccadic behaviour was very different in the two tasks, despite similarities in search effectiveness (at least for three of the four subjects) shows that very different strategies could be equally effective.

Based on the differences in psychophysical thresholds (equal or higher for the motion direction condition) and search performance (equal or lower in the motion direction condition) this study does not seem to provide any evidence for enhanced detection of contrasting motion due to radial flow detectors in higher brain areas. Yet, the analysis of saccadic behaviour provides additional and potentially contrary information. When looking at the data of subjects AB and MC it appears that the 'hit rate' (the increase of cumulative fraction of the targets found as a function of time) can be quite similar in the two tasks. This is remarkable, because large differences in the duration of the initial fixation are paired with about equal amplitudes of the first saccade. The amplitude divided by the latency of the initial sac-

cade indicates the extent of the *serially* analysed area around the fixation point. Apparently, that area grows at a lower speed for the motion direction task; yet, the hit rate is the same. It could mean that relatively slower processing of local differences in motion direction (compared to the processing of local orientation differences) is aided by the *parallel* processing of the global radial pattern. As this global information needs time to develop, however, the initial fixation duration is increased. It has previously been shown by Niemann and Hoffmann (1997) that the latencies of saccades to moving targets are increased when they are presented simultaneously with optic flow stimuli (inducing the sensation of self-motion) compared to a static background. This led Niemann and Hoffmann to suggest that the additional processing required for the sensation of self-motion may have an inhibitory effect on the detection of motion of an independent object. This initially inhibitory effect may be compensated for once the global pattern has been established. However, it is not certain that a perception of the global flow pattern was required to perform our motion direction search task. In one of the few studies that have investigated visual search in optic flow fields, Royden, Wolfe, and Klempen (2001) found no evidence for a special status of radial flow fields compared to other structured motion fields when subjects searched for a stationary target. They suggest that, for all flow fields, it is the *local* disruption of the motion field that attracts the attention, and that there is no special treatment of the global properties of the optic flow field. A similar claim has been made by Nothdurft (1993), who argues that pop-out of targets does not occur because of the pre-attentive detection of, for example, a certain direction of motion, but because of local discontinuities in the motion flow pattern, thereby emphasising the importance of local feature contrast of target elements. He showed that lines at a certain orientation and dots with a certain motion direction are detected faster when presented at a locally increased contrast. Given that the subjects in his study did not realise in which direction the target dots had moved, Nothdurft (1993) suggested that analysis of feature variation around a target is obtained from a spatially limited area. Loomis and Nakayama (1973) also found that perceived motion of an object is influenced by the motion of another nearby moving object.

One finding in the current study was that performance in the line orientation task was worse near the fixation centre (at an eccentricity of 2 deg) than slightly further out (at 6 deg). The observation that the mean saccadic amplitude for these nearby targets was larger as well, suggests that at least in some trials participants initially moved away from the centre of the display, only to come back to the nearby target later. Whereas the nearby targets in the motion direction task may have sufficiently 'popped out' due to their local properties,

inspection of the relation to the rest of the visual stimulus may have been required in the case of nearby stationary line elements. More research is needed to further explore this phenomenon. It has been argued (Findlay & Gilchrist, 1998; Hooge & Erkelens, 1998; see also Rayner, 1998) that subjects in a visual search task have a tendency to move their eyes even though in some situations it would be a better strategy not to do so. However, in the motion direction search task it may be 'strategic' to limit the number of eye movements. One of the complications of visually scanning the radial motion pattern with saccadic eye movements is that, with each saccade, the new target will move at different speed and in a different direction, which requires a corresponding change of eye pursuit. Thus, the saccades not only shift the pattern on the retina, but also the direction and speed of the visual motion. So, rather than adopting a 'shoot first, think later' strategy (Findlay & Gilchrist, 1998), as in the line orientation task, the subjects may have delayed the release of the initial saccade to subsequently capture the target with only one eye movement on detection.

Apart from clear differences in saccadic parameters between search in stationary and moving radial patterns, similarities have also been observed. Firstly, despite the fact that the initial fixation duration was longer in the motion direction search task than in the line orientation task, the pattern of the timing of *sequences* of saccades was quite similar. The finding that the latency of the initial saccade in a sequence was longer than that of subsequent saccades has previously been observed in visual search tasks by Hooge et al. (1999) and Hooge and Erkelens (1996). The observation that inter-saccadic intervals during visual search can be as short as 10–100 ms (Findlay, Brown, & Gilchrist, 2001; McPeek, Skavenski, & Nakayama, 2000) suggests that some sort of concurrent processing of saccades takes place during the initial fixation. Further evidence for this was provided by Findlay et al., who showed that these short-duration fixations never preceded corrective saccades. Analysis of the distributions of the saccadic latencies reveals that the shorter latencies for later saccades may be due to a lowering of the threshold rise to generate a saccade (Van Loon, Hooge, & Van den Berg, 2002). The fact that mainly the initial saccade is affected by the type of display, supports models which propose additional processing demands only for the initial fixation of a search task (Zelinsky & Sheinberg, 1995).

Secondly, in both tasks, search performance after the initial saccade was dependent on eccentricity, despite having used individual perceptual thresholds as a function of eccentricity for the targets. However, as Wolfe, O'Neill, and Bennet (1998) suggest, the eccentricity effect in visual search (e.g. Carrasco et al., 1995), may be caused by attentional as well as visual factors. When observers start searching from a central fixation point,

items near the centre will receive more (earlier) attention than items in the periphery. Furthermore, the fact that the fraction of localised targets after the initial saccade decreased with eccentricity presumably reflects the declining probability of capturing the target with a single saccade with increasing eccentricity. Although the initial saccade may well have been in the correct direction, the occurrence of multiple or corrective saccades before landing on the target is more frequent with remote targets. The average amplitude of the initial saccade was around 11 deg in both tasks, which is about half way between the nearest and most remote potential targets, consistent with a strategy of generating 'average' saccade amplitudes for the first saccade based on the anticipated spatial distribution of the targets.

In sum, our findings show that detection performance alone cannot explain saccadic search behaviour. Although the difficulty of the tasks was individually adjusted by the experimenter, saccadic parameters differed characteristically for search in stationary and moving radial patterns in all subjects. It appears that in the self-motion display a different strategy is used to find the deviating target element than in the stationary display. When the deviating element is not instantly observed, subjects tend to use a 'scanning' strategy to search the display for local contrasts in the case of a stationary display. In the motion direction search task, however, saccadic behaviour was characterised by a long initial fixation, followed by either a single saccade to the target or a saccade that was followed by one or two smaller corrective saccades. This suggest that, in the self-motion display, subjects adopted a 'sit and wait' strategy; they may have deliberately kept their eyes fixated on the fixation point and waited till they observed the deviating target element in their peripheral vision. This reliance on peripheral vision is possibly related to the need in everyday life to keep one's gaze forward to monitor the way ahead, as for example during driving (Land & Lee, 1994).

References

Bremmer, F., Duhamel, J. R., Benhamed, S., & Graf (2000). Motion sensitive areas in the macaque visual cortical system. In M. Lappe (Ed.), *International review of neurobiology* (pp. 174–191), vol. 44.

Britten, K. H., & van Wezel, R. J. A. (2002). Area MST and heading perception in macaque monkeys. *Cerebral Cortex, 12*, 692–701.

Carrasco, M., Evert, D. L., Chang, I., & Katz, S. M. (1995). The eccentricity effect: target eccentricity affects performance on conjunction searches. *Perception and Psychophysics, 57*, 1241–1261.

Carrasco, M., & Frieder, K. S. (1997). Cortical magnification neutralizes the eccentricity effect in visual search. *Vision Research, 37*, 63–82.

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

Duffy, C. J., & Wurtz, R. H. (1991). Sensitivity of MST neurons to optic flow stimuli. I. A continuum of response selectivity to large-field stimuli. *Journal of Neurophysiology, 66*, 1329–1345.

Duffy, C. J., & Wurtz, R. H. (1997). Multiple temporal components of optic flow responses in MST neurons. *Experimental Brain Research, 114*, 472–482.

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

Findlay, J. M., & Gilchrist, I. D. (1998). Eye guidance during visual search. In G. Underwood (Ed.), *Eye guidance in reading and scene perception* (pp. 297–314). Amsterdam: Elsevier.

Geisler, W. S., & Chou, K.-L. (1995). Separation of low-level and high-level factors in complex tasks: Visual search. *Psychological Review, 102*, 356–378.

Girelli, M., & Luck, S. J. (1997). Are the same attentional mechanisms used to detect visual search targets defined by color, orientation, and motion? *Journal of Cognitive Neuroscience, 9*, 238–253.

Hooge, I. Th. C., Beintema, J. A., & Van den Berg, A. V. (1999). Visual search of heading direction. *Experimental Brain Research, 129*, 615–628.

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

Hooge, I. Th. C., & Erkelens, C. J. (1998). Adjustment of fixation duration in visual search. *Vision Research, 38*, 1295–1302.

Kastner, S., Nothdurft, H.-C., & Pigarev, I. N. (1999). Neuronal responses to orientation and motion contrast in cat striate cortex. *Visual Neuroscience, 16*, 587–600.

Kastner, S., & Ungerleider, L. G. (2000). Mechanisms of visual attention in the human cortex. *Annual Review of Neuroscience, 23*, 315–341.

Lamme, V. A. F., & Roelfsema, P. R. (2000). The distinct modes of vision offered by feedforward and recurrent processing. *Trends in Neuroscience, 23*, 571–579.

Land, M. F., & Lee, D. N. (1994). Where we look when we steer. *Nature, 369*, 742–744.

Lappe, M., Pekel, M., & Hoffmann, K. P. (1998). Optokinetic eye movements elicited by radial optic flow in the macaque monkey. *Journal of Neurophysiology, 79*, 1461–1480.

Liversedge, S. P., & Findlay, J. M. (2000). Saccadic eye movements and cognition. *Trends in Cognitive Sciences, 4*, 6–14.

Livingstone, M., & Hubel, D. (1988). Segregation of form, color, movement, and depth—anatomy, physiology, and perception. *Science, 240*, 740–749.

Loomis, J., & Nakayama, K. (1973). A velocity analogue of brightness contrast. *Perception, 2*, 425–428.

Luck, S. J., & Hillyard, S. A. (1994). Electrophysiological correlates of feature analysis during visual search. *Psychophysiology, 31*, 291–308.

Mäkelä, P., Whitaker, D., & Rovamo, J. (1993). Modelling of orientation discrimination across the visual field. *Vision Research, 33*, 723–730.

Matthews, N., Liu, Z., Geesaman, B. J., & Qian, N. (1999). Perceptual learning on orientation and direction discrimination. *Vision Research, 39*, 3692–3701.

McKee, S. P. (1984). The detection of motion in the peripheral visual field. *Vision Research, 24*, 25–32.

McPeek, R. M., Skavenski, A. A., & Nakayama, K. (2000). *Vision Research, 40*, 2499–2516.

Niemann, T., & Hoffmann, K.-P. (1997). Motion processing for saccadic eye movements during the visually induced sensation of ego-motion in humans. *Vision Research, 37*, 3163–3170.

Nothdurft, H.-C. (1993). The role of features in preattentive vision: comparison of orientation, motion and color cues. *Vision Research, 33*, 1937–1957.

Parkhurst, D., Law, K., & Niebur, E. (2002). Modelling the role of salience in the allocation of overt visual attention. *Vision Research, 42*, 107–123.

Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin, 124*, 372–422.

Read, H. L., & Siegel, R. M. (1997). Modulation of responses to optic flow in area 7a by retinotopic and oculomotor cues in monkey. *Cerebral Cortex, 7*, 647–661.

Robinson, D. A. (1963). A method of measuring eye movement using a scleral search coil in a magnetic field. *IEEE Transactions in Biomedical Electronics, 10*, 137–145.

Robinson, D. A. (1994). Rites of passage of the magnetic search coil. In J. Ygge, & G. Lennerstrand (Eds.), *Eye movements and reading, Wenner-Gren international series* (pp. 1–7). Oxford: Elsevier.

Royden, C. S., Wolfe, J. M., & Klempen, N. (2001). Visual search asymmetries in motion and optic flow fields. *Perception and Psychophysics, 63*, 436–444.

Tynan, P. D., & Sekuler, R. (1982). Motion processing in peripheral vision: reaction time and perceived velocity. *Vision Research, 22*, 61–68.

Van de Grind, W. A., Van Doorn, A. J., & Koenderink, J. J. (1983). Detection of coherent movement in peripherally viewed random-dot patterns. *Journal of the Optical Society of America, 12*, 1674–1683.

Van der Steen, J., & Bruno, P. (1995). Unequal amplitude saccades produced by aniseikonic patterns—effects of viewing distance. *Vision Research, 35*, 3459–3471.

Van Loon, E. M., Hooge, I. Th. C., & Van den Berg, A. V. (2002). The timing of sequences of saccades in visual search. *Proceedings of the Royal Society: Biological Sciences, 269*, 1571–1579.

Wolfe, J. M., O'Neill, P., & Bennet, S. C. (1998). Why are there eccentricity effects in visual search. Visual and attentional hypotheses. *Perception and Psychophysics, 60*, 140–156.

Zelinsky, G., & Sheinberg, D. (1995). Why some search tasks take longer than others. In J. M. Findlay, R. Walker, & R. W. Kentridge (Eds.), *Eye movement research: Mechanisms, processes and applications* (pp. 325–336). Amsterdam: Elsevier Science.