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Eye scanning of multi-element displays: I. Scanpath planning

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Abstract

We recorded oculomotor scanpaths in a task that required individuals to scan through displays consisting of a small number (between 3 and 12) of near-identical items. The task required each item to be fixated at least once and our objective was to explore the principles governing the generation of scanpaths. In general the observers carried out the task efficiently, although omissions occurred quite frequently (about 25% of trials) in the 12-item case. Backtracking occurred rarely except in the case of immediate rescanning back to the previously fixated item. Such immediate backtracking occurred on about 4% of fixations and, in contrast to more distant backtracking, was not associated with increased errors. Evidence was found for both directional (raster-like) scanning strategies and scanning strategies based on the global external contour.

Keywords: Human; Memory; Oculomotor; Saccade; Scanpath; Search

1. Introduction

Human vision is not normally a passive process. The eyes scan the visual scene, making several saccadic movements in each second of viewing. These saccadic movements are clearly not arbitrary. As aptly described by Mackworth and Morandi (1967), 'the gaze selects informative detail'. However, while this statement captures the statistical regularities that are present in eye scanning, there remains a gap in our understanding of how it bears on the selection of individual saccades, for example in situations where selection must be made between several potentially informative regions. Records of eye scans, such as the well known ones from Yarbus (1967), generally have a random and irregular appearance at the level of detail. Can we develop an account of the choice of where an observer looks next that is predictive at the level of individual saccadic movements?

The task studied in this paper required an observer to fixate each member of a set of near-identical items to complete the task successfully. The task was designed to elicit a scanpath subject to some constraints, but with substantial flexibility. The start item and end item were prespecified but the observer needed to make a choice of which order to scan the intervening items. Thus, the task has some similarity with, for example, the everyday situation of scanning through objects on a table top to find a particular sought item. The results provided a rich data set and are presented in this paper and the accompanying one (Findlay & Brown, accompanying paper; referred to as FB2). This paper is concerned with the choice of scanning route through the items in the display. The accompanying paper is concerned with the more fine-grained detail relating to the generation of the individual saccadic movements.

Findlay and Walker (1999) proposed that eye control is generally the result of automatised routines, and introduced the terms *search selection* and *spatial selection* to describe the types of routines involved. Search selection refers to processes that operate across the whole visual field to enhance activity at locations where

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material similar to a search target is present. The salience map approach, based on the idea of biased competition (Desimone & Duncan, 1995) can generate a good account of search selection, can explain several observed aspects of saccade selection during visual search (Findlay, 1997; Findlay & Gilchrist, 2001, 2005; Motter & Belky, 1998). It is additionally consistent with neurophysiological studies of the search process (Schall, 1995; Schall & Thompson, 1999). The task in this paper, however, sought to minimise any contribution from search selection by the use a set of near identical display elements.

Spatial selection in contrast was envisaged as any process localised within part of the visual field whereby saccades to a particular location or in a particular direction are rendered more probable. In the case of visual search, the term describes processes that distribute fixations so as to sample the whole area of a search display by rendering particular regions of the visual field either more likely or less likely to become selected for the next saccade. One example of spatial selection is when a conscious decision is made to scan a large display systematically, say from left to right. However, spatial selection and other selection strategies may be automated using spatial memory representations that operate below the level of consciousness. The ways in which forms of spatial memory might contribute to search has been a topic of considerable recent interest (McCarley, Wang, Kramer, Irwin, & Peterson, 2003; Shore & Klein, 2000) with both immediate and longer-term forms of memory identified although it has also been argued that spatial memory does not guide attentional deployment in visual search (Horowitz & Wolfe, 1998, 2001).

Shore and Klein (2000) propose that one important use of spatial memory prevents the system being trapped into 'salience loops' and making saccades back and forth between two salient items. They link this to the observation that, following a period of attention to a location, responses to a probe target at this location are slower than those elsewhere in the visual field. This is the phenomenon of *inhibition of return* (IOR). Klein and MacInnes (1999) have proposed that IOR acts as a 'foraging facilitator' to enable efficient searches by rendering unlikely a return attention shift (covert or overt) to a location already scanned. IOR in this respect is a form of spatial memory and has been shown to extend over at least five previously attended items (Snyder & Kingstone, 2000). Other relevant forms of visual memory allowing a subset of display items to be segregated have been postulated in the form of 'visual indices' (Pylyshyn, 2001) and 'visual marking' (Watson & Humphreys, 1997; Watson, Olivers, & Humphreys, 2003). Eye movements during visual search can also be influenced by learned contingencies (Peterson & Kramer, 2001).

We identified several distinct possible ways in which a scanpath might be selected to meet the task requirements of fixating each item in the display. These strategies provide possible ways of selecting which item to fixate next in the scanpath and avoid returning to items that have already been scanned.

1. Direction based strategies. Items could be scanned in some directionally systematic way, for example using a reading-like pattern. As noted by Gilchrist and Harvey (2005), use of a regular and systematic scan could in principle scan each item in an array without need for additional visual memory. Such scans could be raster-like, as in reading, or back and forth snake-like. Such a strategy is an evident possibility for items arranged in a regular array. It might also be employed if the items are not arranged in a regular array provided the observer could somehow impose the items onto an imagined array to guide the search.
2. Perceptual strategies based on local information. A contrasting possibility is that no overall strategy is used but instead scanpaths are the result of a concatenation of a sequence of more immediate heuristic decisions made during each fixation. For example, a possible heuristic would be to move to the nearest item to the current fixation that has not been already scanned. Such a pattern has been found frequently when regular arrays are scanned (Hooge & Erkelens, 1996, 1998). Work on eye scanning in visual search (Findlay & Gilchrist, 2001, 2005) has identified the importance of visual proximity as a factor determining salience and thus the proximity selection part of this strategy could be readily implemented.
3. Perceptual strategies based on global information. The task studied in this paper has similarities with the well-known 'travelling salesman' problem in which a route must be selected through several spatial locations, passing through each location once and minimising the total path length. When presented with a perceptual version of this problem with the locations represented in a visual map-like format, individuals can rapidly generate solutions that are often close to optimal (McGregor, Ormerod, & Chronicle, 2000; Ormerod & Chronicle, 1999). A frequently observed strategy is the *convex hull* approach in which the outside contour of the set of locations is followed systematically (in clockwise or counterclockwise direction) and excursions are made to pick off interior locations that are close to the hull contour. The convex hull strategy involves a selection at the outset of the global overall external contour shape of the locations involved and thus requires a complex, although plausible, stage of preliminary global perceptual processing. Many other known perceptual capacities might also contribute to the task of scanpath planning. For example, the classic Gestalt factors of grouping by proximity or co-linearity could structure the set of items in a way that could then be used in route choice.

This set of strategies is almost certainly not exhaustive. Combinations of the strategies are also possible (although direction-based and some global perceptual strategies appear to be incompatible).

Rather few studies have been specifically concerned with this approach to eye scanning strategies. Zihl and Hebel (1997) presented subjects with a display consisting of an array of small dots and a task to count the number of dots present. Zihl and Hebel found that when the dots were arranged in a random manner, the number of fixations in normal individuals closely matched the number of dots, whereas when the dots were grouped in clusters, a smaller number of fixations occurred, evidently because several dots could be assimilated within a single fixation. The main concern in their study was to compare normal individuals with those having brain damage to parietal and frontal cortex. Zihl and Hebel did not make detailed analyses of the particular scanpaths selected, although commented that some individuals used a regular raster-like scan. Gilchrist and Harvey (2005) have studied the details of how directional strategies are implemented during search through regular arrays.

Our objective in this paper is therefore to investigate the way in which observers choose a sequence of fixations to scan through a set of visual items to determine which strategy or combination of strategies is followed.

2. Method

2.1. Participants

Eye scan records were obtained from six individuals, aged between 23 and 38 years, who had given written consent. Two other subjects were tested and discarded since substantial tracker loss occurred during the course of the recording session.

2.2. Displays

Displays of the type shown in Fig. 1 were constructed to provide a task allowing freedom in the choice of scanning route. Each display was viewed from 60 cm and consisted of a set of 'ring' elements presented within a square display area of 17.2×17.2 deg visual angle. Every ring comprised an inner disk of angular diameter 0.5 deg, surrounded by an annulus of outer diameter 1.2 deg. The inner disk contained an alphanumeric character of height 0.4 deg. The design was chosen so that the rings provided a masking stimulus ensuring that the visual alphanumeric target was only legible with a precise fixation.

The displays were generated by a computer algorithm as follows. Each display had two rings located in fixed positions, a red ring in the top left corner and a blue ring in the bottom right corner. The red ring contained a target letter and the blue ring a numeral. A set of black rings, each containing a letter, were allotted locations chosen at random from within the square display, with the constraint that the separation between all ring centres was at least 2.8 deg. This ensured that a clear space equal to at least one ring diameter separated all rings. The number of black rings in a display could be 3, 6, 9 or 12 and will be referred to as the ring count (N_R). The numeral (comparison number) in the blue ring (N_B) was a single digit number, chosen to be between zero and $N_R - 1$. The number of black rings containing a match letter, i.e., identical to the letter in the red ring, was equal to N_B, $N_B + 1$ or $N_B - 1$.

2.3. Procedure

The subject's task was to scan the black rings, noting the number of occasions that the enclosed letter matched the test letter provided in the red ring. On 50% of the trials this number matched the comparison numeral N_B thus requiring a YES response to be made on a response keybox. On the remaining trials a NO response was required. The subjects were instructed to look first at the red ring on the top left, then to look through the black rings and finally to look at the blue ring.

Following a brief practice trial set, each subject carried out a block of 80 trials, 20 with each value of N_R. The same set of displays, ordered in a random manner, was used for each subject.

2.4. Eye recording

The subject's head was stabilised with a dental bitebar. Their right eye movements were recorded with a Generation V dual-Purkinje eye tracker (Fourward Technologies), having resolution and accuracy of a few minutes of arc (see accompanying paper FB2 for more detail).

3. Results

3.1. General comments

On each trial, an eye scan record was produced, with the exception of a small number of trials where tracker loss occurred (under 5%). The analysis program allowed the scan record to be subsequently viewed either as a record of the horizontal and vertical components of the eyetracker output plotted against time (example in FB2), or, as shown in the traces of Fig. 2, as a two dimensional scanpath. In this paper, we are concerned with the overall choice of scanning route. Occasionally as seen in Fig. 2B, saccades landed at an intermediate

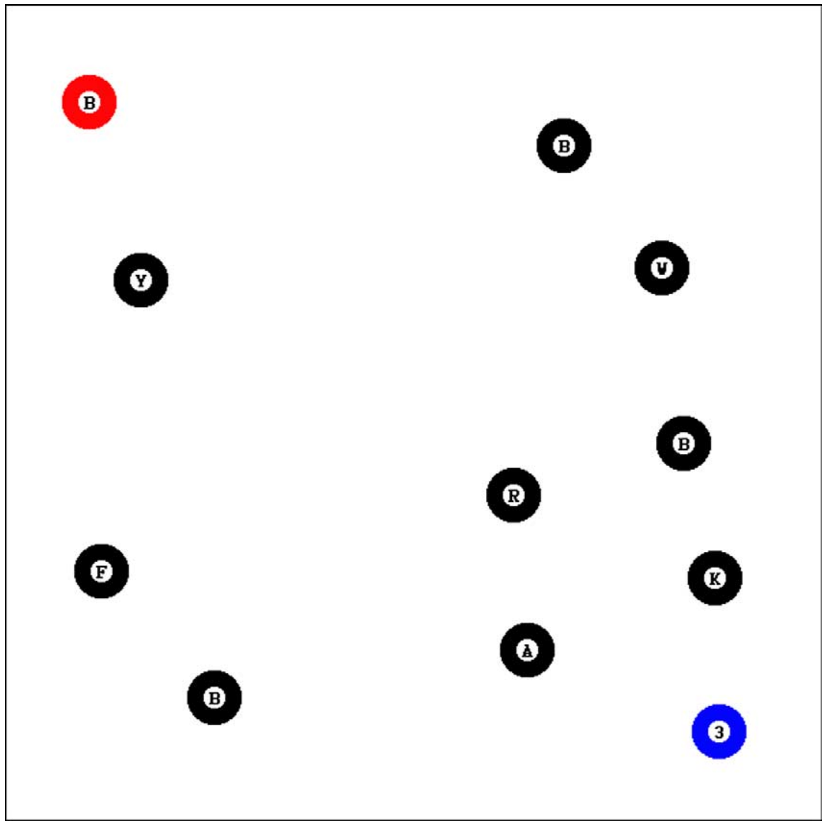


Fig. 1. Example of display used in the experiment. In the actual displays, the top left ring was coloured red and the bottom right ring was coloured blue. Every display had a red and a blue ring positioned in the same location with the positions of the black rings chosen on a random basis. Displays could contain 3, 6, 9 or 12 black rings. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this paper.)

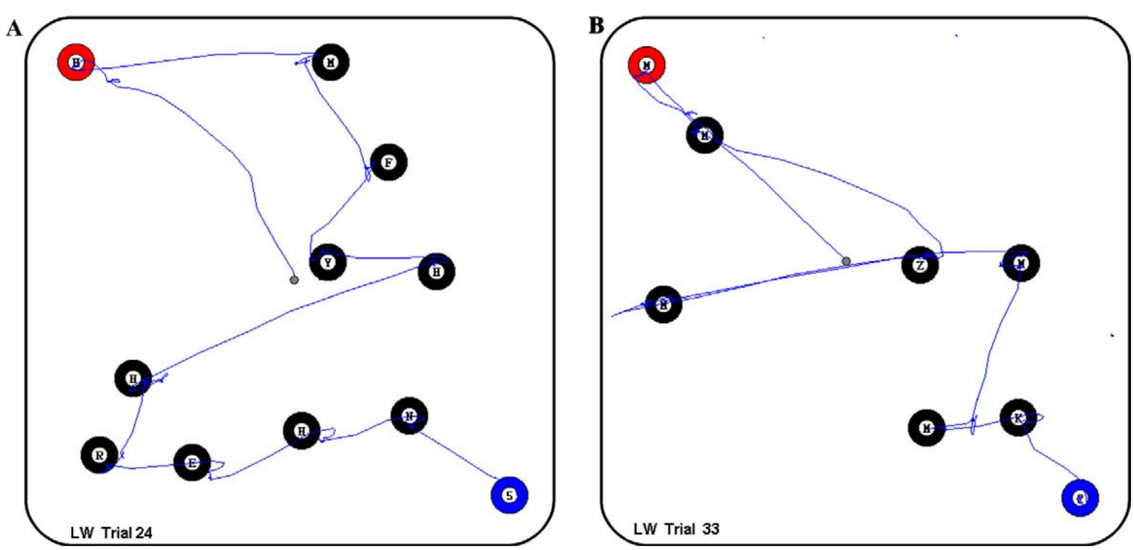


Fig. 2. Two sample scanpaths. The automatic analysis program identified the beginning and end of a saccade and marked these locations with small circles. (A) The subject follows the instructions exactly and makes a saccade first to the red ring (marked saccade), then through each member of the set of black rings before moving to the blue ring. Record (B) shows oculomotor capture by a black ring on the first saccade and the scan then goes to the red ring with the following fixation returning back to the black ring. The scan continues to fixate black rings with a saccade to the central ring of a row of three. This is followed by a saccade to the leftmost item of the row and then a further saccade to the rightmost item, initially following almost precisely the same trajectory but not stopping at the centre item. The sixth saccade (marked) ends at an intermediate location between two black rings. Saccade 7 takes the gaze to one of these and saccade 8 to the other. The final saccade goes to the blue ring. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this paper.)

Table 1
Categories used in classifying scanning saccades

1	First saccade following the fixation on the red ring	457
2	Scanning saccades amongst the black rings (subdivided as below)	3440
3	Saccade to the blue ring	442
2A	Normal scanning saccade to a new item	2102
2B	Inaccurate scanning saccade followed by a corrective saccade	263
2C	Corrective movement following an inaccurate saccade	288
2D	All saccades involved in revisiting a previously scanned location	610

The final column shows the number of saccades falling in each category. Corrective saccades scored in categories 2B and 2C were those greater than 1 deg in magnitude: smaller corrective saccades were eliminated. Category 2D saccades were further subdivided in the coding (first and subsequent saccades of a revisiting sequence; immediate and delayed revisits).

location between two rings but there was no difficulty in deciding the order in which rings had been scanned since such centre-of-gravity fixations were always followed by a corrective movement to fixate a ring more accurately. Centre of gravity fixations are discussed in FB2.

Analysis of the records proceeded in the following stages. The raw records were processed with a saccade detection algorithm supplemented by a visual check procedure.[1] The algorithm (discussed in detail in FB2) used a velocity criterion (approx. 50 deg/s) to detect the saccade start-point and a strict stability criterion (three successive samples with no movement greater than 5 deg/s) for the saccade end-point. For most of the analyses of this paper, all saccades occurring before the red ring was reached were eliminated (these are analysed further in FB2), as were all small corrective saccades (under 1 deg) during the scanning of the black rings, and all saccades made subsequent to the final fixation of the blue ring.[2] The remaining saccades were coded as shown in Table 1, using a routine that allowed a numerical flag to be set interactively with a mouse click. Each subject made saccades in each of the categories of the table.

The program automatically registered the following parameters relating to each saccade and the fixation preceding it: duration of fixation, co-ordinates of fixation, amplitude and direction of saccade, duration of saccade. For the majority of purposes, analyses were carried out on 2A, 2B, and 2D saccades, to obtain details of the scanpath, or on 2A saccades alone, to obtain baseline values of parameters from straightforward scanning sequences.

In addition to the actual subject records, a set of simulation scans was created using the following 'Proximity Heuristic'. For each display, the simulation scan started at the red ring, with the first simulated saccade going to the nearest black ring. This ring formed the launch point for the next simulated saccade, which was again directed to the nearest black ring to the new simulated fixation. The process continued, choosing at each point the nearest item not already included in the scan until all the black rings had been included. Such a simulation scan was generated for each of the 80 displays and measured for some control purposes.

Detailed presentation of the results is set out in six sections. The first considers global task data (errors, response times, mean number of saccades, and mean fixation duration). The second presents analyses arguing for the importance of proximity. The third section involves a statistical analysis of saccade directions, showing evidence that some individuals use a directional scanning strategy. The fourth section presents data relevant to strategies based on global perceptual effects. The fifth section considers cases of backtracking, where rings were revisited during the scanning sequence. The final section examines a repeat record taken from an individual who performed the task again on a second occasion.

3.2. Overall data and fixation durations

The data analysed in this section showed scanpaths usually accorded with the instructions although 12-item trials showed both omissions and increased errors. Mean fixation durations were not affected by the number of items in the scan.

The subjects' responses were generally correct although with occasional errors. The mean number of errors in a block was 7.2 (9%), with individuals (see Table 2) varying from 4 (5%) to 12 (15%). Unsurprisingly,

[1] Modifications at this stage consisted of identification of an occasional very small saccade (less than 1 deg in amplitude) that was below the threshold of the algorithm, and occasional separation of two saccades in cases where a fixation showed high drift and thus the saccade end routine had not triggered. These cases were quite common in the initial scan to the red ring but were very rare in the main scanning sequence. Around 1% of additional saccades were added manually.

[2] Occasionally, subjects made a saccade to the blue ring and then back to one or two final black items before the response was made. These saccades were not included in the categorisation set of Table 1, but the items were not scored as omissions. Also, some subjects did not always follow the instructions and on some trials made an occasional saccade to the blue ring early in the scanning sequence. This saccade and the subsequent one away from the blue ring were discarded, but the remaining scanning saccades were analysed. This pattern occurred on one trial for subjects LS and PB, on ten trials for BR and on 19 trials for JP. A further category was a revisit to the red ring at some point during the scanning. This saccade and the subsequent one were discarded. These revisits were rare and generally occurred immediately after the first saccade in the black ring sequence.

Table 2
Cases where individual rings were not fixated during the course of the scanpath, plotted for each participant and ring count

Ring count	3	6	9	12
BR (12)	0	3	4	8
JP (7)	0	0	1	8
LS (4)	0	0	2	4
LW (8)	0	1	0	4
PB (8)	0	1	1	3
SL (4)	0	0	0	3
Proportion of trials with a skipped ring (%)	0	4.2	6.7	25
Probability of skipping a ring		0.009	0.007	0.027

The number in parentheses after each participant's identifier shows the overall number of erroneous responses in the task (out of 80 trials). The final row takes into account very occasional instances where more than one ring was omitted in the course of a scan.

errors in general increased with the number of rings to be scanned (mean percentage of errors in the 3-, 6-, 9-, and 12-ring trials was 7.5%, 5.5%, 9.0%, and 12.5%, respectively). The deviation from a uniform increase is attributable to one individual (LW) who made four errors on 3-ring trials. Since the eye scan on these records appeared normal, it seems likely that the errors were attributable to response confusion. Also unsurprisingly, trials where rings were not scanned (numbers shown in Table 2) resulted in many error responses. The error probability on trials where a target ring was omitted was 47% as opposed to 8% on trials with no omissions. Error trials were also more likely to show backtracking, discussed further in a subsequent section.

Fig. 3A shows data from individual subjects for the average response time at each value of ring count. Fig. 3B shows the average number of saccades made while scanning the black rings. This count includes all saccades in categories 1 and 2 as defined above, having amplitude greater than 1 deg. The count does not include any scanning after the final fixation on the blue ring, although such scanning occasionally occurred, but does include scanning of black rings following the infrequent cases (footnote 2) where an early fixation on the blue ring occurred. These global data show that the task elicited a scanning pattern which was generally effective. The mean saccade count is increased from the ring count by revisiting saccades. Fig. 3B confirms that saccades in these categories were relatively rare in all the subjects tested.

We present three measures concerning the temporal pattern of scanning in Table 3. The first row shows the average fixation duration[3] when all detectable saccades are included, running from the initial display presentation to the final response. The saccades used in the derivation of this measure include many small corrective movements of less than 1 deg. When these movements are excluded, a measure that is more representative of the duration of gaze on each ring is obtained. Scanning fixations are defined as those separated by category 2 saccades. The second row shows the mean duration of fixations preceding all scanpath saccades other than those resulting in revisits, equivalent to 'first pass fixations' as used in work on eye movements in reading (Liversedge & Findlay, 2000). The third row shows the figure obtained when only accurate saccades during uninterrupted scanning sequences (category 2A) are included.

A test was made whether fixations on a target were shorter if preceded by an earlier inaccurate fixation near the target. Following a corrective saccade of amplitude between 1.0 and 1.5 deg, fixations were shorter by 53 ms (SD 28 ms) than when the target was reached with a single saccade. Fixations following corrective saccades with amplitude between 1.5 and 2.0 deg were shorter by 32 ms (SD 23 ms) and fixations following corrective saccades with amplitude between 2.0 and 2.5 deg were shorter by 16 ms (SD 59 ms). In the first two cases but not in the third, the differences were significant (t values with 5 df 4.58, 3.30, and 1.10, respectively). These figures suggest that some useful visual information could be extracted from an off-target fixation, thus providing 'preview benefit' and allowing shorter subsequent on-target fixation. However the use of such information appears to require fixation no further than 2 deg from the target.

Overall, the temporal characteristics of the scanning pattern were very little affected by ring count (scanning fixation means were 208.9 ms for ring count 3; 210.9 ms for ring count 6; 215.6 ms for ring count 9; and 214.5 ms for ring count 12). The slightly increasing trend is attributable almost entirely to one subject (BR), whose saccade latencies increased systematically from 198.5 ms with ring count 3–240.7 ms with ring count 12.

A final minor point of interest is that the final fixations, generally with the gaze directed at the blue ring, were not included in the top row of Table 3 since these fixations were terminated by the manual button press response rather than by a saccade. However, in contrast to the short durations that might have been expected if these were truncated 'normal' fixations, this final period of fixation was generally much longer. Quite frequently at this point a long stare of up to 1 s occurred with no detectable eye movement. These long fixations are not particularly surprising in view of the multiple cognitive operations required at this point. The average duration of the final fixation was 336.8 ms on correct trials and 382.3 ms on error trials. Although this difference was

[3] The automatic saccade detection algorithm was set to obtain high accuracy in the spatial parameters of the eye scan and the criterion for saccade termination was a continued period of stability following the lens overshoot recorded by the eye tracker (Deubel & Bridgeman, 1995). This procedure increases the measured duration of saccades and decreases that of fixations, by a small amount (estimated at about 30 ms).

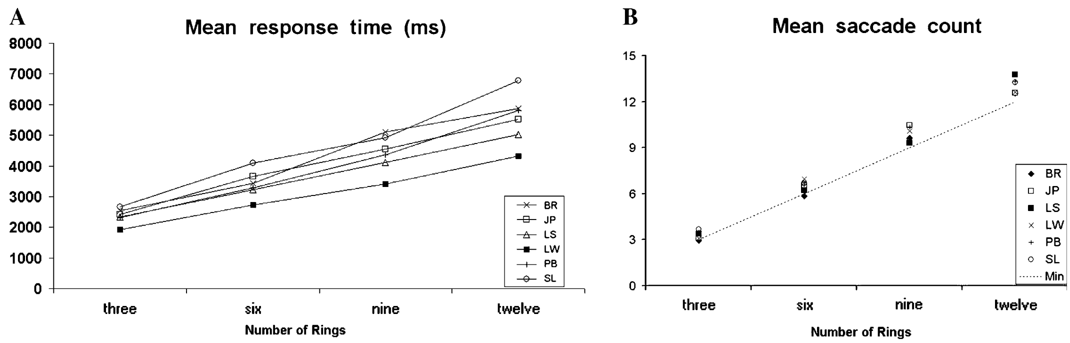


Fig. 3. Global parameters shown for each participant. The saccade count includes all large saccades (above 1 deg) during the scan of the black rings. The dotted line shows the minimum count that would occur if all rings were scanned once only.

Table 3
Value of mean fixation durations (see footnote 3) in ms, with fixations selected as described in the text

	BR	JP	LS	LW	PB	SL	Mean
All	136.3 (1389)	140.4 (1348)	136.2 (1016)	153.4 (1118)	160.9 (1136)	209.9 (1127)	156.2
Scanning (category 2)	220.6 (444)	196.8 (470)	149.9 (472)	209.2 (487)	234.6 (463)	264.9 (465)	212.5
Category 2A	242.6 (298)	207.2 (303)	152.1 (425)	205.9 (385)	240.1 (334)	266.0 (365)	219.3

Number in parentheses show the number of contributing cases.

not statistically significant, five out of the six subjects showed greater final fixation durations on error trials.

There was a weak overall positive correlation (0.2–0.4) between fixation duration and amplitude of the subsequent saccade. A similar correlation was noted by Zihl and Hebel (1997). In part this occurred because of the inclusion of short latency corrective movements. When these were removed by inclusion only of saccades with amplitudes greater than 2.8 deg (the minimal inter-ring spacing), the correlations reduced but were still positive and the three subjects who showed a directional scan (see below) had higher correlations (LW 0.32, PB 0.26, and SL 0.16) than those without (BR 0.11, JP 0.09, and LS 0.13). No obvious explanation is forthcoming for this finding since, as shown in the accompanying paper, saccade selection accuracy is no better following longer fixations.

3.3. Saccade amplitudes and the proximity effect

In this section, it is shown that the mean saccade amplitudes were only slightly larger than those expected if fixations were always made to the closest item not already scanned. Other analyses also show the power of the proximity effect.

The most representative statistics for saccade amplitude appeared to be the amplitude of saccades in the scanpath sequence including immediate revisits but excluding corrective movements and more remote revisits. As the ring count increases, the display becomes more tightly packed and the saccade amplitudes decrease. Table 4 shows the mean amplitude for each ring count value and each subject, together with that obtained from the simulation using the Proximity Heuristic. This simulation does not in general generate an optimally short overall scanpath. On a number of occasions, the simulation led to one item being 'left out' as the simulated scan progressed from one side to the other, necessitating a large subsequent saccade (usually at the end of the sequence) to recover the omitted item. If these large saccades were not included the measure from the Proximity Heuristic simulations would be reduced by about 10% for ring counts of 6, 9, and 12.

The proximity effect is the tendency for saccades to be directed to the closest target to the current fixation point. It appears a ubiquitous tendency during scanning and may well reflect the foveocentric organisation of the visual system. One indication of the importance of the proximity effect comes from a comparison of the average saccade size, as shown in Table 4, with the average size in the simulation scan using the Proximity Heuristic. Although the Proximity Heuristic does not guarantee the generation of the shortest route through the items, the saccade sizes produced by this simulation are often closely similar to the shortest routes produced by the

Table 4
Average amplitude in degrees of scanning saccades, together with that obtained from the Proximity Heuristic simulation

	BR	JP	LS	LW	PB	SL	Mean	Proximity Heuristic
3	10.28	9.67	10.81	8.97	8.97	9.39	9.69	8.92
6	7.51	6.21	7.30	6.69	6.69	7.02	6.97	6.41
9	5.88	5.44	6.28	5.47	5.47	6.12	5.83	5.42
12	5.57	4.69	5.45	4.86	4.86	5.33	5.13	4.34

experimental subjects. In many cases, however, the routes generated by humans are longer showing that factors aside from proximity were influential in guiding the saccade target selection.

A further indication of the power of proximity is shown in an analysis of the choice of start point for the scanpath through the black ring set. As discussed in detail in FB2, the first saccade following display onset frequently was not directed to the red ring as instructed but instead showed 'oculomotor capture' (Theeuwes, Kramer, Hahn, & Irwin, 1998) by an intervening black ring. We analysed the destination of the saccade to a black ring immediately following the fixation on the red ring. In cases without capture, 75.5% of scans started at the nearest black ring to the red and a very similar figure (75.3%) was found when the initial saccade showed oculomotor capture by a black ring. When oculomotor capture by a non-proximal black ring occurred, only on 8% of occasions was an immediate refixation made to this ring. The definition of proximity for the analyses above was purely geometrical. In a further proportion of cases in which the first saccade went to a non-proximal ring (about 25%), this was only very slightly more distant from the red ring than the proximal one. However, it is clear that although proximity is a significant factor in the choice of the scan, other factors are also involved.

3.4. Analysis of saccade directions

This section reports that three out of the six subjects show clear evidence of using a directional scanning strategy.

The cumulative distributions of saccade directions during the course of scanning were analysed since these distributions are potentially informative about certain strategies. For example, the cumulative distribution of saccade directions during reading would be expected to show a sharp peak of rightward directed saccades, with a subsidiary peak of saccades to the left generated by regressive saccades and return sweeps, the latter also having a small downward component.

The data analysis program recorded automatically the direction of each saccade made, referenced to the horizontal and vertical display axes. These directions were grouped into bins of 15 deg width for the purposes of computing directional histograms. Since the current task required a scan constrained to start in the upper left position and end in the lower right, the cumulative distribution of directions must reflect this constraint but the data show various ways in which the constraint was met.

The directional histograms are shown in Fig. 4, with separate histograms made for each subject and ring count.

Three subjects show marked peaks in the direction histogram. LW and SL both have a large peak in the rightward direction and a subsidiary peak in the oblique down-left direction. Between these peaks is a marked trough showing that relatively few saccades are made in the down and down-right directions. This is exactly the distribution that would be expected if the subjects were using a reading-like strategy. Subject PB also shows peaks in the histogram, but these are located around the down and up directions, indicating a vertical scanning strategy. For each of these three subjects, casual inspection of scanning records confirms the use of regular directional scanning (for example Fig. 2A was a record from Subject LW).

No such peaks are observable in the direction distributions shown by the other three subjects. The distributions in each case show a broad predominance of saccades in the downward and rightward directions, as would be expected since the overall scan is constrained to go in this direction. These subjects appear to use a scanning strategy that is not based on direction selection in any straightforward way.

A striking feature of the records shown in Fig. 4 is that whenever a directionally selective scanning strategy is used, it is reflected in the records at all values of the ring count. It might plausibly have been anticipated that when presented with a display having a small ring count (e.g., 3 rings), subjects would select targets using a more ad hoc strategy which over-rode any general directional strategy. This does not appear to have occurred.

3.5. Grouping and external contour effects

In this section, we consider how the scans might be affected by global perceptual information extracted early from the display. Perceptual grouping of item pairs or clusters appears to be used, as do strategies based on the external contour.

If the display to be searched contains obvious groups of items, then, as noted by Zihl and Hebel (1997), a possible heuristic strategy would be to scan through the items within a group before moving on. In this section, we first consider evidence for use of such a strategy.

In a number of the displays, the chance positioning of the items led to a reasonably clear grouping of two rings, isolated from the others. Thus, in the left-hand panel of Fig. 5, the two rings at the lower left are somewhat isolated. If this grouping was used in the scanning, then we would expect that the rings would be scanned sequentially. Note that if a strict raster up and down directional strategy was used with this display, the items would not be scanned in sequence.

It was found that such isolated items were almost invariably scanned sequentially. In an effort to provide an objective measure, a *grouping factor* was introduced. This was defined as the ratio of the distance between the items in a pair, divided by the distance from the closest neighbouring item to the closest item of the pair. The

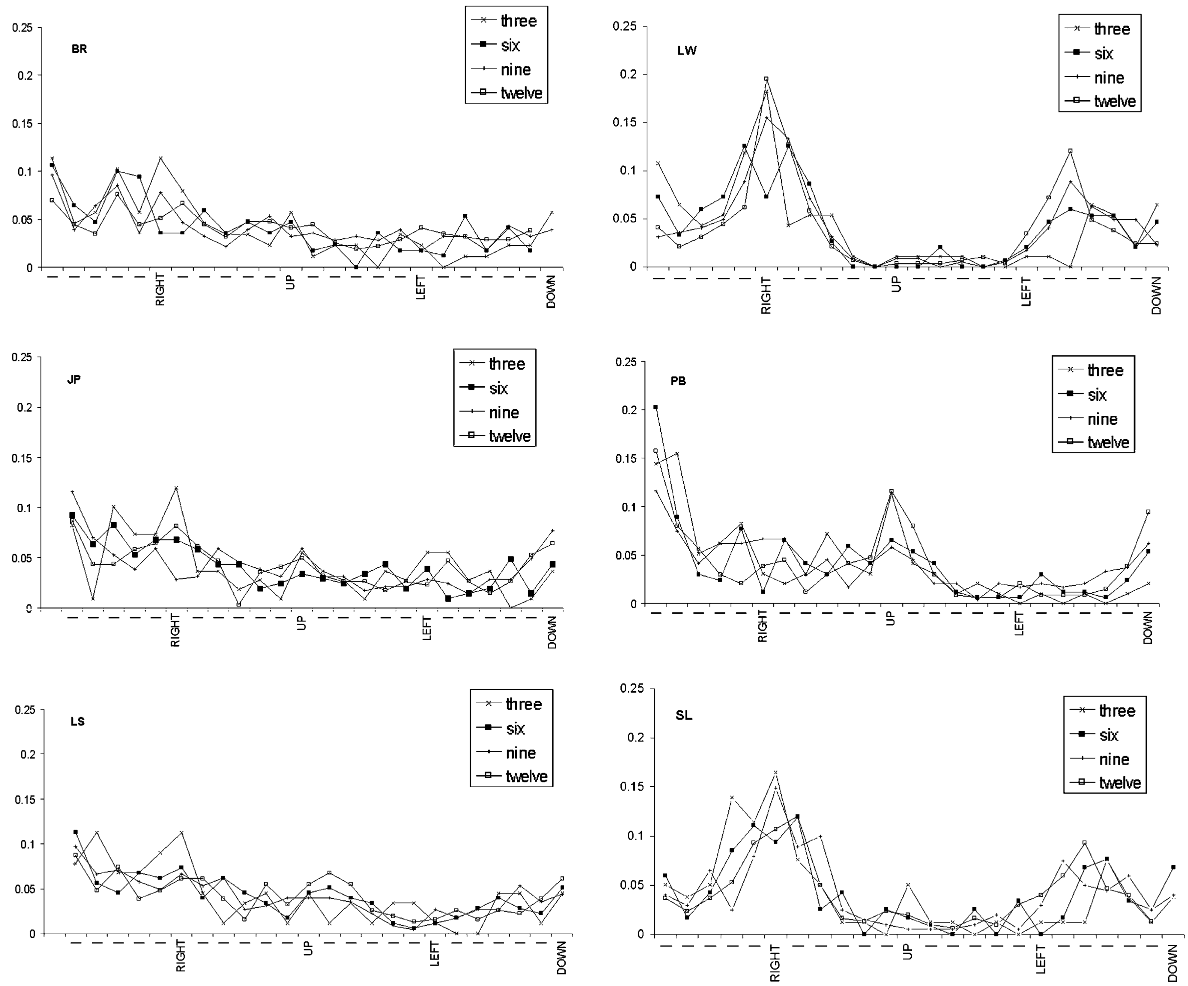


Fig. 4. Directional histograms of all saccades made while scanning through the black rings. Separate histograms are shown for each subject and ring count. The histograms are normalised and show the relative probability of a saccade having each of 24 direction bins.

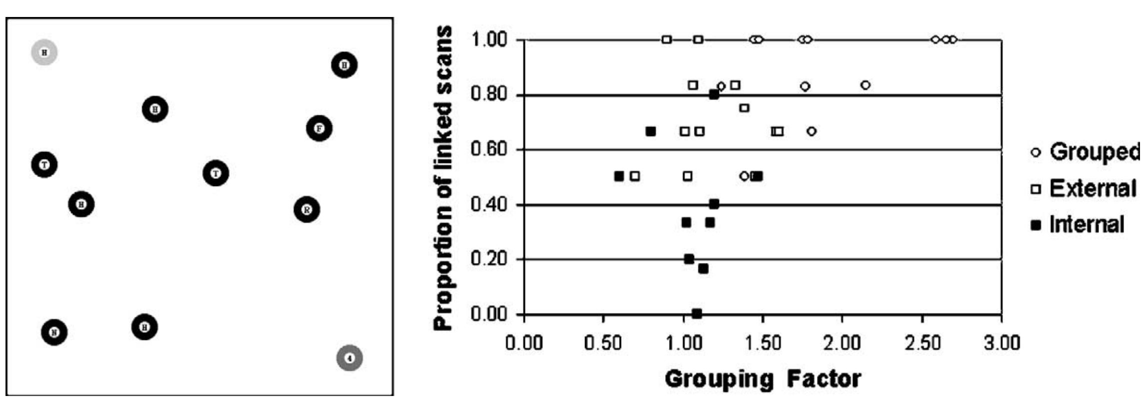


Fig. 5. The left-hand plot shows a display in which grouping could play a role. The two rings on the lower left are somewhat isolated from the remaining ones. The right-hand plot shows that the likelihood of neighbouring rings being scanned in sequence was influenced by the grouping factor, as defined in the text. In the case of the display on the left, the grouping factor for the lower left pair of rings was 1.45 and the proportion of linked scans was 1, i.e., all six subjects made a scan with successive fixations landing on each member of the pair.

higher the grouping factor, the more isolated would be the pair. If the grouping factor is greater than 1, then these items would be linked in the scanpath generated by the nearest-neighbour Proximity Heuristic, since when one item of the pair is fixated, the other item must be the closest.

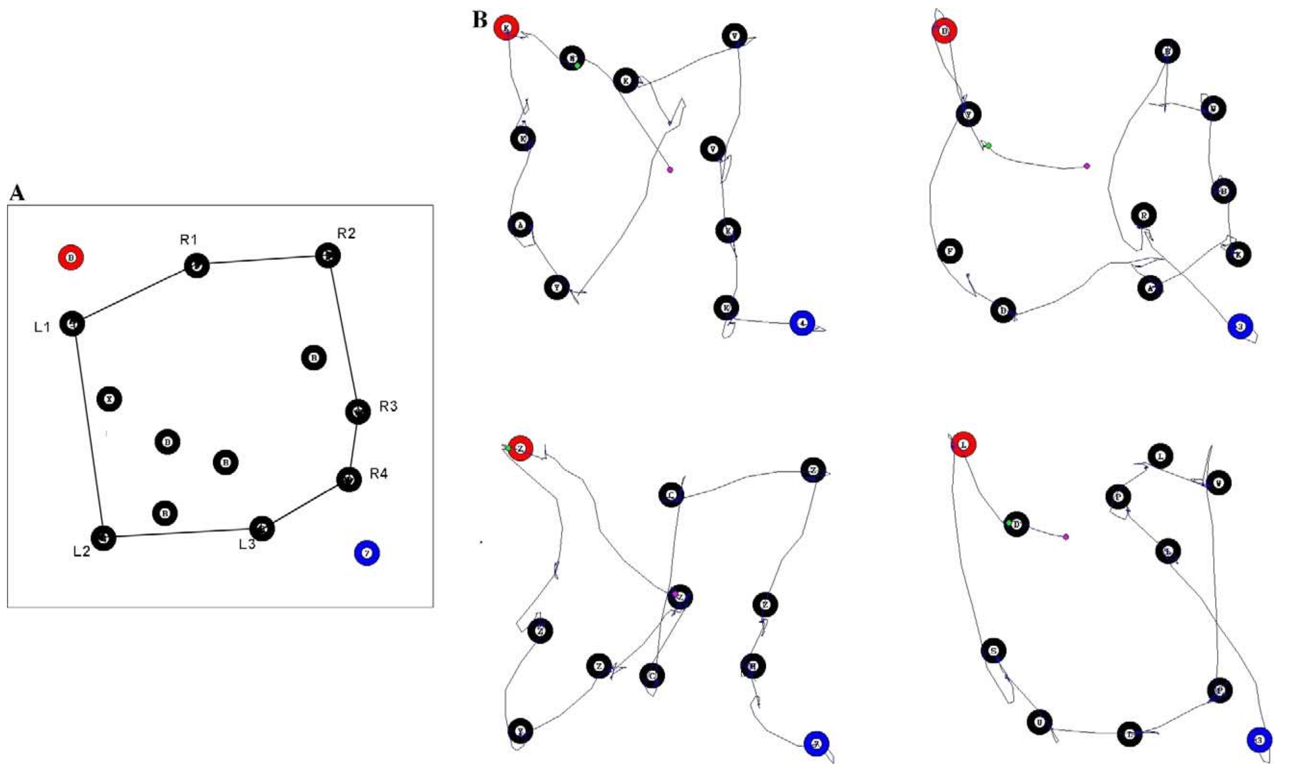


Fig. 6. (A) Illustration of external contour vertex labelling. (B) Four scans from subject JP suggesting that following an external contour may form part of the scanning strategy.

Grouping factors were measured for 15 of the cases considered to be of obvious grouping (items with a ring count of three were excluded). For comparison, a set of 10 further displays were chosen and scans through a specific pair of items on the external contour, which had less clear apparent grouping, were analysed. A further set of 10 displays were used to assess the scanning through specified pairs of items each inside the external contour and not forming part of it. The scans in all these cases were analysed to determine how frequently the specified items were scanned sequentially. The proportion of occasions, plotted against the grouping factor for the display, is shown in the right-hand panel of Fig. 5. Fig. 5 shows that items with high values of the grouping factor were indeed almost always also grouped in the scanning sequence. However, as the grouping factor falls towards the value of 1, then the proportion of sequential scanning falls. Thus, although items group perceptually, it is not possible to know whether the tendency to scan the items sequentially reflects perceptual factors, or simply the use of the Proximity Heuristic.

The analysis above also suggests that points on the external contour are more likely to be scanned sequentially than points having similar grouping that are not part of the external contour. As discussed in Section 1, one strategy that individuals follow when carrying out a pencil and paper version of a similar scanning task is the convex hull strategy, whereby scanning around an external contour is combined with opportunistic deviations to points within the contour. Inspection of the records suggested that some individuals used a scanning strategy based on the external contour. For example on the right-hand side of Fig. 6, four scans from subject JP are shown. In each one the left side of the external contour is followed initially, with the subsequent scan making use of the right side of the contour, but in a less systematic way. Sometimes the items are scanned in a clockwise order and sometimes anticlockwise. Internal items are sometimes incorporated into the contour scan as proposed by the convex hull strategy (two cases occur in the upper left scan).

Objective support for this observation came by using the labelling procedure shown in Fig. 6A for each of the cases where the ring count was 9 or 12 (40 cases altogether). The convex external contour of the set of black rings was divided into its left and right sides (L and R) and successive vertices labelled. The scanning order through these vertices was then noted. If a scan followed the external contour, then all the vertices on one side would be scanned before all the vertices on the opposite side. On the other hand, if a raster scan was used, the order of scanning would generally intermingle L and R vertices. Table 5 notes the percentage of each of these two types of sequence for each individual, and also the scans generated when

Table 5
Statistics relating to external contour scanning

	BR	JP	LS	LW	PB	SL	Proximity Heuristic
All L before all R or vice versa	51.3	33.3	39.5	5.0	18.4	18.9	27.5
L and R vertices scanned sequentially in intermingled mixed sequence	20.4	20.0	19.0	68.7	58.7	58.7	11.9

The figures show the percentage of trials with the set of external vertices scanned in the designated orders.

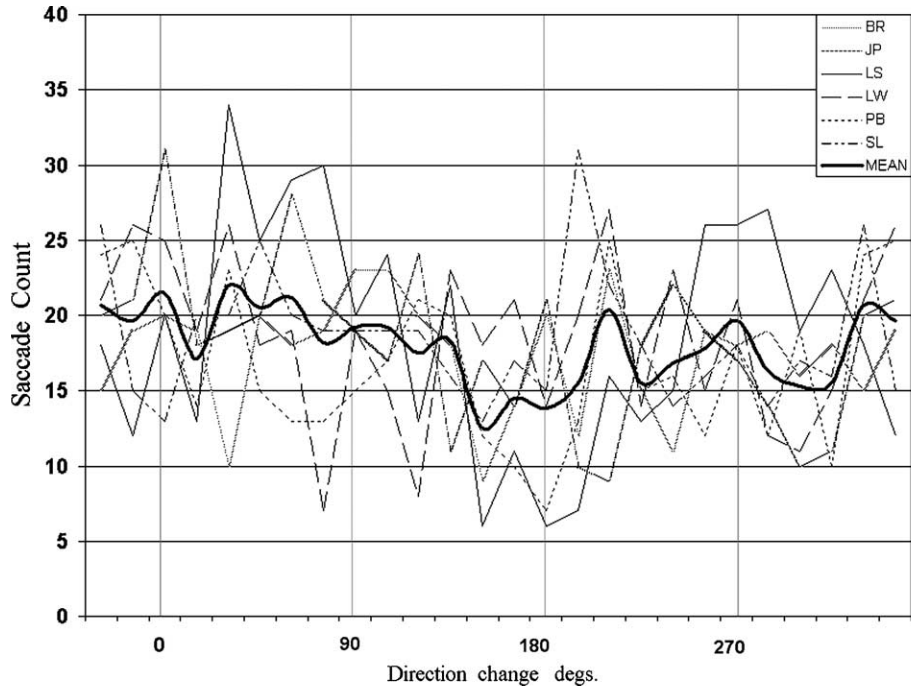


Fig. 7. Direction change histogram plotting the difference between directions of scanning saccades through the black rings. Thus, 0 represents two saccades which are collinear and 180 represents a saccade which backtracks in the same direction of the previous one. The two rightmost data bins have been replotted on the left in wraparound. Data are shown for each individual subject, together with a smoothed curve showing the group mean.

using the Proximity Heuristic simulation. The observers identified as directional scanners, LW, PB, and SL, show many examples of mixed sequences.[4] The other three observers all show a substantially greater proportion of cases where all the vertices on one side of the external contour were scanned before those of the other side, suggesting that they were using a strategy based on the external contour.

A final Gestalt factor which could potentially play a role in saccade target selection is the factor of collinearity. This was tested by the construction of directional histograms, similar to those of Fig. 4, but using the saccade direction *relative* to that of the preceding saccade as the variable. If collinear items were more likely to be scanned sequentially, then a peak around the zero of this plot would be expected. Fig. 7 plots the direction change histogram, including all saccades in categories 2A and 2B (i.e., with saccades involved in revisits excluded). The 0 deg value corresponds to saccades which continue in exactly the same direction as the previous one. There is no tendency for these saccades to show increased prevalence. The graph shows a weak trough around the 180 deg value which may be attributed to the removal of the revisiting saccades.

Table 6
Incidence of revisits during scanning of the black rings

	Backtrack 1	Backtrack 2	Backtrack >2
BR	15	1	15 (+5)
JP	15 (+3)	6	9 (+13)
LS	12 (+1)	3	4 (+3)
LW	29 (+2)	5	4
PB	39 (+8)	5 (+2)	10
SL	13 (+2)	7 (+1)	13 (+7)
Total	123	27	55

Where more than one revisit occurred in a sequence, only the first incidence is included in the main count, and the subsequent cases are totalled in the number in parentheses.

[4] The random positioning of the rings did lead on occasion to a pattern where the left vertices fell in one half of a sequential raster scan and the right vertices in the other. Such instances account for the occasional L before R sequences found with the directional scanners.

Table 7
Gaze durations in milliseconds for immediate revisit ABA sequences

	BR	JP	LS	LW	PB	SL	Mean
Normal scan	242.6	207.2	152.1	205.9	240.1	266.0	219.3
A_1	163.3** (12)	169.6 (15)	105.8** (12)	174.1 (27)	173.4** (32)	218.3 (12)	167.4
B	243.7 (15)	225.4 (15)	167.9 (12)	239.8 (29)	216.7 (39)	272.7 (13)	227.7
A_2	203.4 (15)	192.6 (15)	116.2* (12)	153.9** (29)	170.4** (39)	226.7 (13)	177.2

Figures show mean fixation duration in ms for each member of the sequence, together with a control fixation duration from periods of normal sequential scanning (from Table 3). Numbers in parentheses denote the number of contributing cases. Asterisks denote a significant difference ($^{*}p < 0.05$; $^{**}p < 0.01$) from the individual's normal scan duration in a t test comparison.

3.6. Backtracking

In this section, analysis of trials where backtracking occurred shows evidence that immediate backtracking was often adopted and appeared to form a pre-planned sequence. Backtracking more than one item previously was much less common and was associated with increased errors.

We analyse here cases where a black ring received more than one fixation, separated by an intermediate fixation on a different ring. As well as the revisits after oculomotor capture before fixation on the red ring, discussed in an earlier section of the Results and not analysed further here, all subjects showed trials on which backtracking occurred during the scan of the black rings, so that one or more rings was revisited. Table 6 shows the incidence of three types of revisit. Backtrack 1 refers to an immediate revisit after one fixation on a different ring, backtrack 2 refers to a revisit after fixations on two different intermediate rings, and all other revisits are counted in the remaining column.

The table shows the total number of revisits: on some trials more than one revisit occurred and thus the number of trials containing revisits is lower than the total number. As indicated earlier, there was some association of errors with revisits. Of the 98 trials where only backtrack 1 occurred, 6 were error trials. The probability of an error on such trials, 6.1%, is not significantly different from that on the normal scanning trials with no omissions or backtracking (9 errors in 223 trials—4.0%). The probability of an error trial increases for backtrack 2 trials (14.8%) and again for trials with more distant backtracks (23.3%). Both these proportions are significantly different than that on trials with no backtracking or omissions (backtrack 2: $\chi^2 = 5.59$, $p < 0.05$: backtrack >2: $\chi^2 = 22.98$, $p < 0.001$). This result suggests that some of the distant backtracking may have been a result of a previously scanned item being 'forgotten' and rescanned as a new item. However, backtrack 1 cases were not associated with significantly increased errors and appeared quite frequently.

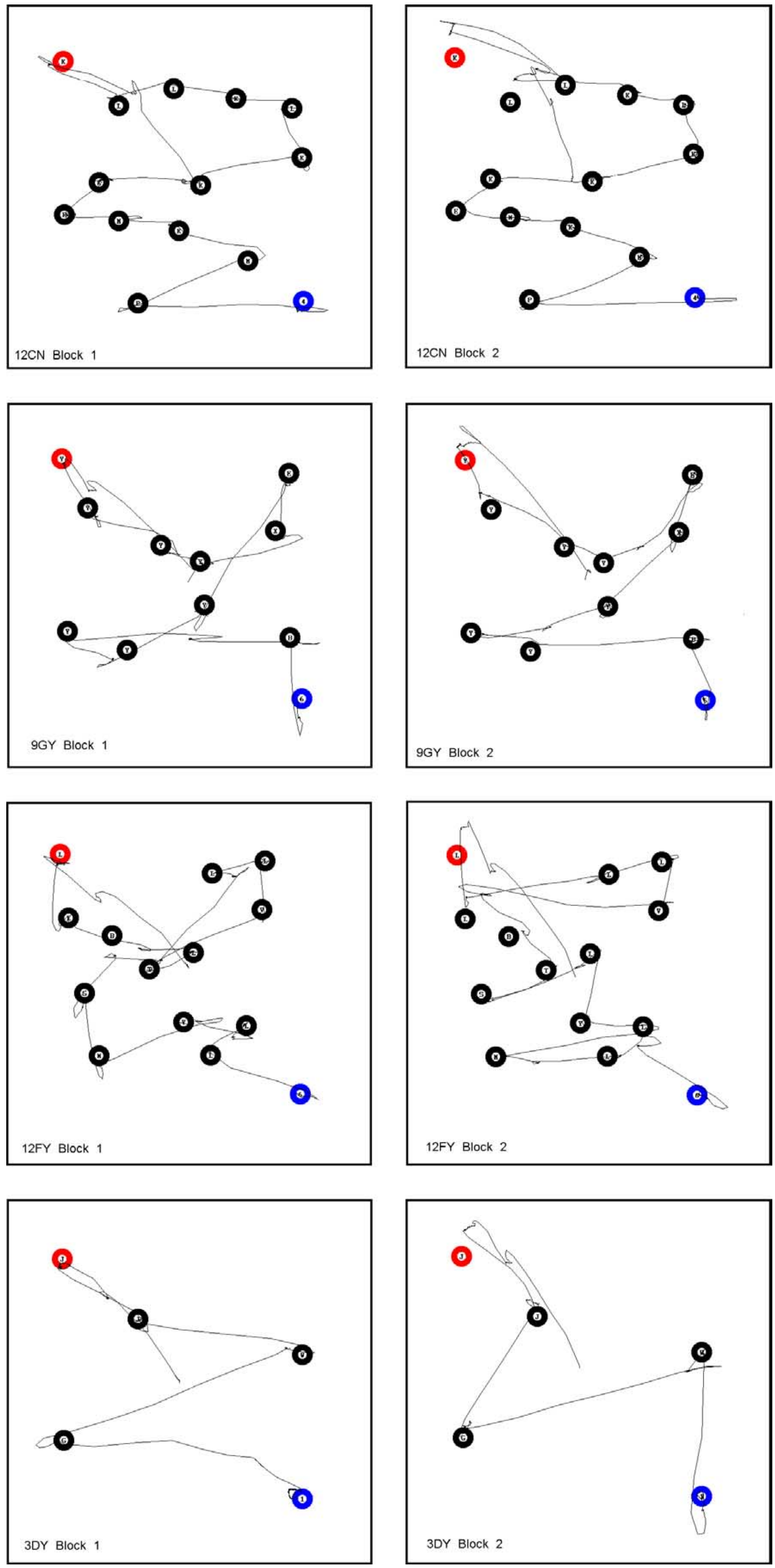
The backtrack 1 sequences were examined carefully. These sequences follow the pattern: Ring A to Ring B to Ring A. The average gaze durations A_1, B, A_2 on successive fixations of the sequence were calculated (in the infrequent multiple ABAB cases, only the first ABA was included). One reason for this interest was to seek any evidence for inhibition of return delaying the return saccade (cf. Gilchrist & Harvey, 2000; Hooge & Frens, 2000; Rayner, Juhasz, Ashby, & Clifton, 2003), which might appear as a prolongation of fixation B. The control fixation duration for this purpose was calculated from all saccades that formed part of a normal scanning sequence (category 2A). This excluded the following cases: backtracking, fixations before and following an inaccurate (e.g., centre of gravity) saccade; and fixations immediately before the final saccade to the blue ring. Table 7 shows the pattern of gaze durations for each subject.

The comparison between gaze duration on item B and that on control scans shows no overall difference. In the data for individuals, two subjects (LW and PB) show differences which are statistically close to the 5% significance level, but in one case the B fixations are longer and in the other case shorter. In contrast, a clear difference emerges with A fixations. Both A_1 and A_2 gaze durations are substantially shorter than that for normal scan gaze durations, by 51 and 41 ms, respectively. The average saccade length for backtrack 1 revisits was slightly, but significantly, shorter than that for the control case (5.14 deg vs 6.04 deg, $t(5) = 3.2$, $p < 0.05$).

In several cases it appeared that the pair of items was 'out on a limb', necessitating a protrusion of the scanpath to take them in. The direction change between

→

Fig. 8. Replicability of scanpaths for subject SL. In the second set of records (right column), tracker inaccuracy was present in the top left quadrant of the display. Each row shows two scanpaths from the first and second block, respectively, in subject SL. In the first pair, the whole scanpath was replicated. In the second row, the second scanpath is substantially similar, but there are two differences in the detail order (reversals at rings 4/5 and at rings 7/8). Also the first scanpath shows a brief extra 'blank space' fixation in the course of the penultimate gaze shift. The third and fourth pairs show scanpaths typical of those scored as 'substantially different'. Both records of the third pair include a revisited ring.


12CN Block 1
12CN Block 2
9GY Block 1
9GY Block 2
12FY Block 1
12FY Block 2
3DY Block 1
3DY Block 2

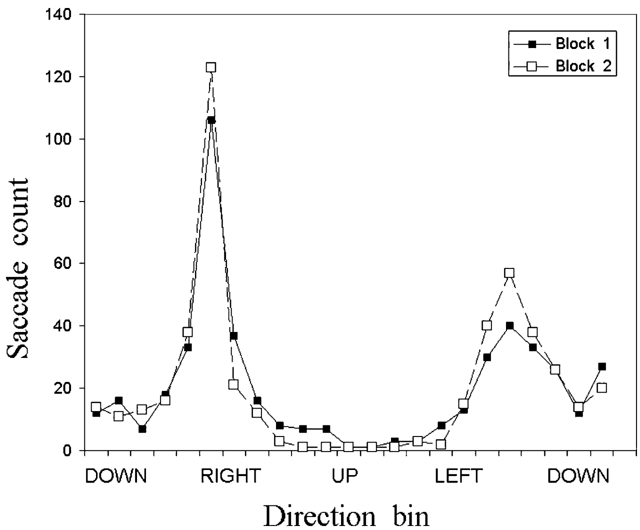


Fig. 9. Distribution of saccade directions for the first and second run of subject SL. Directions were analysed into 15 deg bins as for Fig. 4.

the final, BA_2, saccade and the following saccade in the sequence was measured. In 53 out of 123 cases, this change was less than 45 deg, a significantly greater proportion than that found in a similar analysis of the normal scanning saccades without backtracking (comparison against the direction changes of the 2A + 2B saccades shown in Fig. 7 gave $\chi^2 = 9.7$, $p < 0.01$). This confirms that there is a tendency for the scanpath following a backtrack sequence to depart in a direction away from the pair, roughly following the axis of the pair in the direction of the preceding saccade. Such a tendency would occur if the pair was particularly likely to be treated as a group when they were perceptually isolated from the continuing scanpath.

The proportion of backtrack 1 saccades which were directed to a search target item[5] was as follows: BR 43.8% (7/16); JP 50% (11/22); LS 100% (4/4); LW 76.7% (23/30); PB 52.2% (24/46); and SL 71.4% (10/14). The proportion of items in the displays that were search targets was 49.3% overall, thus some individuals showed a greater likelihood to backtrack to a target. There were also a number of cases of backtracks to nontarget items that resembled the target (e.g., V/Y, 5 instances; T/J, 3 instances). This suggests that immediate perceptual processing can also influence backtracking.

3.7. Replication

One individual (SL) repeated the experiment on a second occasion a few weeks after the first in an attempt to assess how replicable scanpath sequences were within an individual. The same 80 displays were presented in a different random order. Evidence occurred both for some replicability, but also for substantial variability. For trials with a ring count of 3, out of the 19 occasions the scanpath could be compared on the two occasions (one trial had tracker loss), on 13 (68%), there was an exact replication of the scanning sequence on both occasions. Exact replications were rare with higher ring counts (ring count 6, 3 replications from 13 comparisons—23%; ring count 9, no exact replications; and ring count 12, one replication from 18 comparison—5.6%). Fig. 8 shows the example of a complete replication with ring count 12, and also a pair of scans for ring count 9, where a substantially similar scanpath occurred in two cases but the order of two rings was reversed on the second occasion. Scanpaths that repeated apart from a single transformation in sequence order (or an omission) occurred on an additional 4 cases (31%) with ring count 6, 6 cases (37%) with ring count 9 and 2 cases (11%) with ring count 12. The replicability of the first ring visited following fixation on the red ring was also noted. The proportion of occasions the same first black ring was scanned following the fixation on the red ring was 84%, 77%, 62%, and 67% with ring counts 3, 6, 9, and 12, respectively.

Fig. 9 shows the direction histogram, calculated as for that in the earlier section (Fig. 4) except that the calculation was made on only the first scanning saccades (ignoring any corrective saccades or revisit saccades). The saccade counts in the two cases were similar (464 and 471) and so no normalisation has been carried out. It is apparent that a similar directional strategy was operative in both blocks, although the direction tuning in the second block was slightly sharper. The average scan gaze duration decreased from 265.7 ms on the first block to 230.1 ms in the second and the average fixation duration decreased from 209.9 to 167.6 ms.

4. Discussion

In the introduction, it was noted that a systematic scan through a randomly arranged set of items might plausibly be carried out in a number of different ways. Our experimental data show evidence that individuals use several of these strategies.

In three individuals, clear evidence was found from the saccade direction histograms (Fig. 4) that saccades in certain directions showed high probability whereas those in other directions were much less frequent. These directional preferences were clear even though the task required a scan constrained to move fixation overall from the top-left of the display to the bottom-right. A familiar task in which a directional strategy is employed is that of reading text, achieved by a raster scan involving a sequence of small rightward directed saccades fol-

[5] We are grateful to an anonymous referee for suggesting this analysis.

lowed by a larger saccade to the left and slightly down to commence the next line of the text. Two subjects (LW, SL) showed distribution histograms similar to ones that would be obtained in reading. In contrast, the third subject to show a directional strategy (PB) showed a preponderance of vertically directed saccades. This pattern is consistent with a vertically oriented raster scan and indeed such a pattern was evident in individual scan traces. For the remaining three subjects, no compelling evidence of directional preference appears from the histograms.

Directional strategies are one example of the *spatial selection* type of strategy described by Findlay and Walker (1999) and envisaged as selecting one region of visual space as the potential saccade destination. A second alternative strategy identified in Section 1 was the use of the global contour. It seems plausible to suggest that the global contour of a cluster of objects is readily available to the perceptual system and that it might be employed in the choice of scanpath. Examination of the scanpaths of the three individuals who showed no clear directional strategy provided evidence that they used the global contour. Instances in which successive vertices in the global convex contour were scanned in sequence were much more common in these individuals than in those who used a directional strategy (Table 5).

It has been shown that the external contour is frequently used by subjects in a task which has similarities with the present one. Researchers have asked people to carry out a perceptual version of the 'travelling salesman' problem whereby subjects are shown a cluster of dots and have to generate a path which includes all dots and has the shortest possible path length (McGregor et al., 2000; Ormerod & Chronicle, 1999). A commonly used strategy is based on the 'convex hull, whereby the external contour is followed and forays are made from this contour to include internal points. Despite the similarities, this task differs from ours in important ways. In our task, there is no premium on establishing the shortest scanpath. Probably more important, the pencil and paper version of the task provides subjects with an external memory of which items have been already scanned.

The observations thus extend our understanding of the concept of spatial selection. The direction analyses presented in Figs. 4 and 9 show the directional tuning expected if a reading-like strategy were employed. Although the appropriate analysis was not made, it seems apparent that the direction preference must interact with gaze location within the display, with the likelihood of leftward scanning increasing sharply as the right-hand edge of the screen is reached. The demonstration of contour following in three subjects extends our understanding both of available search strategies and of the ways in which spatial selection routines can be implemented.

Even though we generally have little awareness of the details of how our eyes are moving, familiar experience would suggest that, when a scan is made, some form of memory is available about locations that have been already inspected. Can our data provide information on how this memory operates? The record of backtracking shown in Table 6 is informative in several ways. First, backtracking of any sort is relatively rare, supporting the proposal that previously scanned items are avoided through some specific process. Backtracking occurs about equally often both for individuals using a directional strategy and those using a different strategy. Thus, although a directional strategy in itself constitutes a form of memory that in principle allows avoidance of already scanned items (Gilchrist & Harvey, 2005), other processes must also play a role.

In contrast to more remote backtracking, backtracking to the immediately previous item occurs with a higher frequency. Also in contrast to more remote backtracking, these immediate revisits are not associated with increased response errors. Similarly, immediate revisits occur to black items fixated as a result of oculomotor capture before fixation on the red ring, provided these are also the closest item to the red ring. Immediate backtracking during a visual search task has been noted previously (Hooge & Erkelens, 1996; Peterson, Kramer, Wang, Irwin, & McCarley, 2001). Motter and Belky (1998) note that such backtracking saccades occur on 3–4% of cases in their data on visual search in monkeys, a similar proportion to that of the present study. It thus appears that immediate backtracking is a fairly normal pattern in scanning sequences. There is evidence both that its incidence is affected by immediate perceptual factors, since backtracks were somewhat more likely occur to the search target or items closely resembling the target, and also that it may sometimes be pre-planned, since backtracks were more likely when the subsequent scan maintained the direction of the backtracking saccade.

The finding that immediate backtracking occurs frequently has implications for understanding the form or forms of memory used in scanning. The phenomenon of inhibition of return (IOR) has been extensively studied and is usually described by saying that an attended item is in some way inhibited subsequently. IOR is readily demonstrated in laboratory tasks when attention is captured exogenously with a peripheral flash cue (Posner & Cohen, 1984) and in these cases appears very rapidly (300 ms) following cue onset. Klein, 1998 proposed that the function of IOR is to act as a foraging facilitator and prevent return to immediately fixated items during an active visual scan. Subsequently Klein and MacInnes (1999) subjected this idea to an experimental test in a free scanning situation. During the course of a search task requiring eye scanning, a visual spot probe was used, which could be programmed to occur at the location of a prior fixation, or elsewhere. Subjects were required to make an immediate saccade to the probe. Saccades to the region of previously scanned locations showed longer latencies.

At first sight, our finding of regular backtracking is not easily reconciled with this account of IOR. Nevertheless, it may be premature to reject Klein's attractive idea. Early work on IOR led to a belief that it operated as an automatic process with a fixed and rapid time course. However, more recent studies have shown that the time course of IOR can be affected by the cognitive task in which the subject is engaged (Klein, 2000). Moreover, in a complex task, IOR extends over multiple previously attended items (Snyder & Kingstone, 2000; Tipper, Grison, & Kessler, 2003). Thus, both the time course and extent of IOR appear to depend on cognitive processing factors, rather than being automatically preset. Indeed, Klein and MacInnes (1999) report in their results that targets presented precisely at the previously fixated position were fixated faster than expected. If an account of IOR could be envisaged that was sufficiently flexible, then it might be consistent with both the present results and with other forms of short-term memory in search such as visual marking (Kunar, Humphreys, Smith, & Hulleman, 2003).

The time course of the immediate (ABA) revisits was also of interest. If it had been necessary to 'overcome' IOR to refixate A, a longer duration might have been expected for the fixation on B (Gilchrist & Harvey, 2000; Hooge & Frens, 2000; Rayner et al., 2003). However, the average duration of the fixation on B was the same as that found in normal scanning. In contrast the duration of both the A_1 and A_2 were significantly reduced, suggesting that the A item was processed over both fixations. It is possible that the short fixation on A_1 was a chance occurrence that led to the subsequent refixation. However, an alternative possibility is that the whole ABA sequence was a pre-planned integrated unit. Support for this comes with the observation of a tendency for ABA sequences to occur with items that were 'out on a limb' with the saccade following the A_2 fixation returning to the main body of items.[6] The lack of any 'inhibition of saccade return' contrasts with the findings of Hooge and Frens and of Rayner et al. However, the scanning situation used by Hooge and Frens did not involve any cognitive activity and, as discussed in the previous paragraph, immediate IOR for the previously attended item may occur only in simple situations. Although inhibition of saccade return was the preferred explanation of the findings by Rayner et al. that fixations preceding regressive saccades are longer, the complexity of the reading task renders alternative explanations possible.

In many of the trials in which subjects made an error in their manual response, it was possible to associate this error with an abnormality in the scanning pattern. The most obvious cases were those where when one target ring had been omitted from the scanning sequence. Such omissions occurred for all subjects, although appeared slightly more common in those who did not use a directional strategy. Cases where backtracking occurred were also associated with increased error probability when this backtracking was to a more remote ring than the one immediately preceding the current fixation. Trials showing a normal scan were rarely erroneous and some of these probably occurred as a consequence of response confusion. This is suggested by the observation that some errors occurred with ring count 3, providing a very simple task.

The repeated trial with subject SL produced some interesting findings. Fixation durations were considerably lower on the second occasion (13% reduction in average gaze duration), presumably as a consequence of greater familiarity with the task. Even though the directional strategy that this individual used was reproduced with very little modification, the individual scanpath records showed considerable variability even for the simplest pattern (ring count 3). It is possible that some of this variability could have been reduced by a tighter control of the conditions (for example the use of the same ordering of trials on the two occasions). However the most likely conclusion seems that the variability can be attributed to the combination of a wide number of individual sources. Variability is found at the micro-level in the timing and amplitude of individual saccades, gaze position is never replicated with absolute precision, varied adaptational and learning processes are occurring, and differences in cognitive state at the time of the trial may affect the outcome. Previous investigators (e.g., Mannan, Ruddock, & Wooding, 1997) have reported variability in scanpaths when a complex scene is presented on a second occasion. The variability in the latency of saccades in simple situations has been studied extensively by Carpenter and group (Leach & Carpenter, 2001) and the argument has been made that behavioural variability in simple responses could be biologically advantageous (Carpenter, 1999, 2004). Following this line of argument, variability in scanpaths may be intrinsic and possibly even functional, with limited prospects for deterministic, as opposed to statistical, predictions.

Acknowledgments

We are grateful to Edward Chronicle, Iain Gilchrist, and Simon Liversedge for suggestions about this work, to Bob Metcalf for programming assistance and to Anna Everatt for assistance with data analysis.

[6] As pointed out by a referee, frequent backtracking return saccades were found by Hooge and Erkelens (1996) in a task requiring a scan around a circular display, where an explanation involving preplanning is less plausible. It seems probable that backtracking can result from more than one cause.

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