Saccade target selection in visual search: the effect of information from the previous fixation

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Abstract

This paper reports an analysis of saccades made during a task of visual search for a colour shape conjunction. The analysis concentrates on the saccade following the first saccade, thus complementing an earlier paper where the first saccades were analysed. The further analysis addresses the issue of what information might be held in trans-saccadic memory. As with the first saccade, incorrect second saccades tend to fall on distractors sharing one feature with the target. The proximity of the target to the fixation location immediately prior to the saccade is a very significant determinant of whether the saccade will reach the target. The results lead to the conclusion that in the majority of cases, choice of saccade destination is made afresh during each fixation with no carry-over from the previous fixation. However, in a small number of cases, second saccades are made after extremely brief fixation intervals. Although these saccades show a similar probability of reaching the target as those following longer fixations, it is argued that this sub-set of saccades are pre-programmed at the time of the preceding saccade. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Human; Saccade; Fixation; Search; Scanning

1. Introduction

Considerable interest has developed recently concerning eye movement control in visual search tasks (Findlay, 1995, 1997; Hooge & Erkelens, 1996, 1998, 1999; Zelinsky, 1996; Zelinsky & Sheinberg, 1997; Motter & Belky, 1998a,b). This has involved a re-evaluation of a tradition (Treisman & Gelade, 1980) in which covert attention was emphasised and led to models of visual search that emphasise search selection using overt eye movements in a way which is concordant with the underlying neurophysiological processes (Schall & Hanes, 1998).

An earlier paper (Findlay, 1997) examined eye movements in search using displays of the type shown in Fig. 1. These displays consisted of 16 items in two concentric rings at eccentricities of 5.7 and 10.2°, respectively. The analyses concerned the first saccade exclusively.

Comparison was made between first saccades in a simple feature search task, in which the target was reached with the first saccade on almost every trial, and those in a colour-shape conjunction task. In the conjunction task, targets in the inner ring were frequently (70–80% of occasions) acquired with the first saccade. The mean latency of these initial saccades was no greater that that for the simple feature search task. The results were used as evidence to support a programming model whereby a number of display locations were monitored in parallel during the latency period of the first eye movement. Such parallel processing is inconsistent with the strictly serial item by item attentional scan proposed originally by Treisman and Gelade (1980). However, similar proposals have received support from a number of different analyses (Pashler, 1987; Eckstein, 1998; Findlay & Gilchrist, 1998, 2000; Motter & Belky, 1998a,b).

The earlier paper considered the programming of only the first saccade. In this note, we consider those occasions on which the target was not acquired immediately and report an analysis of the second saccades made in these cases. This analysis was prompted by two interesting and related questions. First, to what extent

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is the programming of the second saccade in a visual search task similar to that of the first saccade? Second, can information acquired during the first fixation be used to program the second saccade? For such information to be useful, it would need to be held in some form of memory during the execution of the first saccade, and thus, the paper addresses the important issue of trans-saccadic memory. At one extreme, the target might be 'located' during the first fixation at a point too late to cancel an erroneous saccade but with this location information retained in memory to direct the next saccade. At the other extreme no information whatever might be carried over from one fixation to the next with
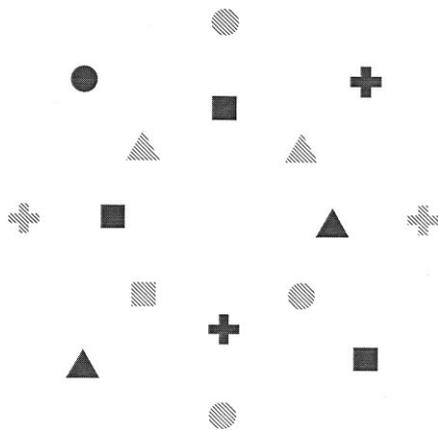

Fig. 1. Example of a display shown in the search task. Elements were alternating red and green shapes. The task was to move the eyes to a pre-defined colour–shape conjunction target. One target was present on each trial, occurring with equal probability in each of the 16 display locations.
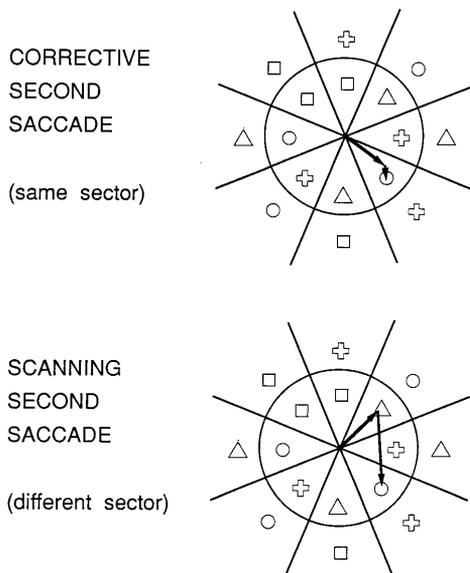

Fig. 2. Analysis of second saccades. The display was divided into 16 sectors as shown. Corrective saccades kept the gaze within the original sector while scanning saccades moved the gaze to a different target sector.

a new selection process occurring on every fixation. In other areas, it has been demonstrated that information acquired from the visual periphery in one fixation (peripheral preview) can influence the subsequent pattern of eye movements. Research on eye-movement control in reading (e.g. Rayner, 1998) has demonstrated the phenomenon of 'preview advantage'. During reading, the eyes move in a series of saccades across the text and reading is slowed if the text is not available in peripheral vision during each fixation. This demonstrates some carry-over of information from one saccade to the next. A similar preview advantage has also been found in situations involving pictorial material (Pollatsek, Rayner, & Collins, 1984).

During the course of the analyses, a further intriguing phenomenon was observed. On a number of occasions, the second saccade was made after an extremely brief fixation (< 100 ms). The properties of these remarkable short-duration fixations give considerable insight into the programming process.

A preliminary account of the findings was given by Findlay, Gilchrist, and Brown (1998).

2. Methods

Analysis was made of the second saccades occurring as four subjects carried out the feature conjunction task shown in Fig. 1. Full details of subjects, task and data-recording procedures can be found in Findlay (1997). For some purposes in the second saccade analysis, the location of first and second saccade end-point was coded according to the sectors of the radial grid shown in Fig. 2. Note, however, that in the analysis of first saccades presented in Findlay slightly broader definition of on-target saccades was allowed in which saccades were included whose direction was appropriate for the target but whose amplitude fell approximately 1° on the 'wrong side' of the midline between near and far display elements.

3. Results

3.1. Number of multiple saccade trials

The displays were presented for 1 s and, with very rare exceptions, the eyes reached the target within this time. Table 1 shows the number of scanning saccades made before the target was reached. This analysis excludes small corrective saccades (see Section 3.2). As explained in Findlay (1997), some recording problems occurred with Subject TH and on a few trials, the number of saccades to target could not be established. The subsequent analyses presented concentrate on the second saccades and the number of data points in-

Table 1
Number of scanning saccades required to reach the target[a]

Subject	1	2	3	4	5	6	Not reached
BK	112	83	46	12	–	–	2
JF	149	78	27	1	1	–	–
RW	30	102	73	31	7	1	12
TH	107	111	24	7	1	–	–

[a] The columns show for each subject the number of occasions that the target was reached after a single saccade (1) or multiple saccades (2–6), or was not reached at all within the 1-s display period. Corrective saccades are not included in this analysis.

Table 2
Percentage of same-sector corrective saccades related to whether the first saccade landed on a target or on a distractor

Subject	First saccade on target (%)	First saccade on distractor (%)
BK	69	3
JF	42	2
RW	53	3
TH	30	3

volved was 143 for BK, 107 for JF, 226 for RW and 159 for TH.

3.2. Scanning saccades and corrective saccades

A well-known feature of the saccadic system is that small corrective saccades are often made following the first saccade. As shown in Fig. 2, corrective saccades were defined as those that remained within a grid sector whereas scanning saccades moved the gaze to a new sector. Corrective saccades included a small number of cases where the first saccade was 'on-target' using the broader window described definition given above, even though the corrective saccades in these cases crossed the sector boundary towards the target. Table 2 shows the proportion (as a percentage) of initial saccades that were followed by corrective saccades when the first saccade landed on a target and that when the first saccade landed on a distractor.

Corrective saccades occurred very rarely when the gaze was initially directed towards a non-target but were common when the first saccade was directed to the target. A further difference between corrective and scanning saccades emerges in the analysis of latencies presented in Fig. 5.

3.3. Do erroneous second saccades fall on distractors sharing one target feature?

The first saccade analysis (Findlay, 1997) showed that erroneous first saccades did not land at random on non-target elements. They were proportionately more likely to land on distractors sharing one feature with the target and less likely to land on distractors not sharing a common feature with the target. Fig. 3 reproduces this finding for first saccades and also shows the probability of second saccades landing on the different types of target element.

There is a clear tendency for erroneous second saccades to be directed to an item sharing a target feature although the tendency is less marked than with first saccades.

3.4. Does target proximity increase the likelihood of a correct second saccade?

Analyses of the first saccade showed that inner ring targets were much more likely to be acquired with a single fixation. An analysis was carried out to determine the effect of target location on the probability that the second saccade would reach the target. For this analysis, the landing position after the first saccade was coded as the location of the distractor in the sector where the first saccade landed. Although involving
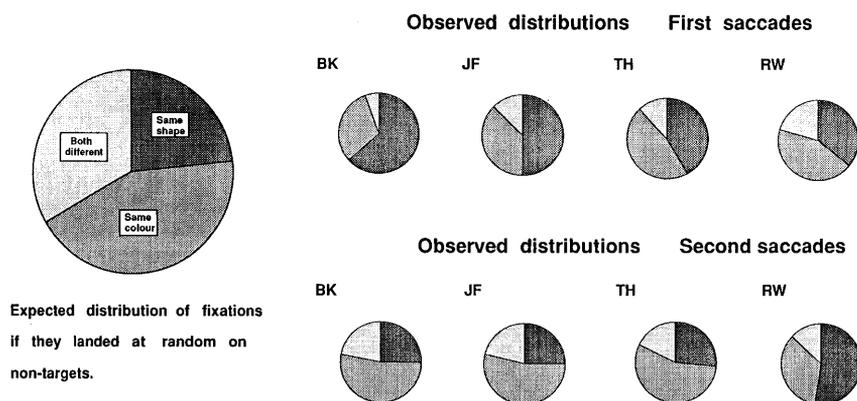

Fig. 3. Saccade destinations of off-target saccades in the search task. Saccades were classified as landing on distractors sharing one or other target feature, or sharing neither target feature. The expected distribution if incorrect saccades landed randomly on non-targets is also shown.
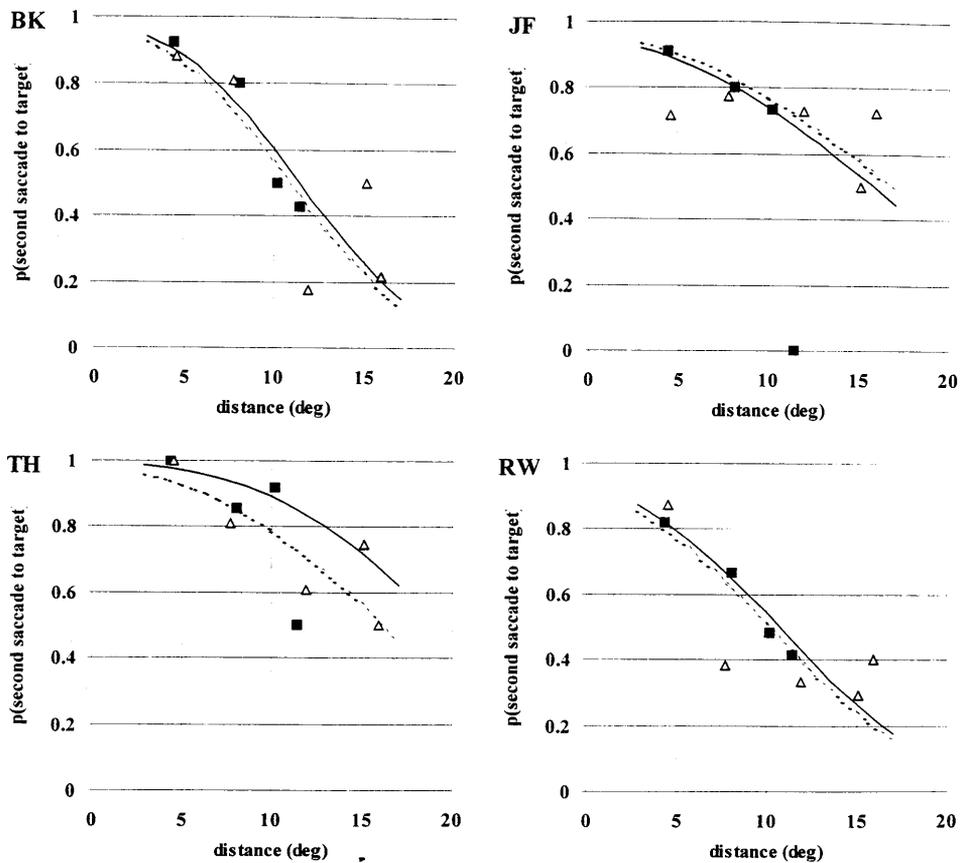
Fig. 4. The proportion of second saccades directed to the target is shown as a function of the distance of the target from the previous fixation location. The data are separated into cases where the target was in the inner ring (filled symbols, continuous lines) and cases where the target was in the outer ring (open symbols, dotted lines). In all but one case (TH 12°, inner circle), each point in the plot is based on five or more saccades. The lines are probit fits to the data points, with weighting given to the number of constituent cases.

some loss of detail information, this approximation both speeded the analysis and grouped the data suitably for data plotting and quantitative curve fitting. Cases were divided into those in which the target was in the inner ring and those where the target was in the outer ring. Note that the numbers in the two groups are different as in many of the former cases the target was acquired with a single saccade.

Fig. 4 plots the probability of the second saccade reaching the target as a function of the distance of the target from the new gaze location at the end of the first saccade. It is evident that target proximity prior to the second saccade, i.e. during fixation 2, strongly determines the likelihood of this saccade reaching the target. Target location during fixation 1 has little effect (for subject JF, targets in the inner ring are actually slightly less likely to be acquired correctly than those in the outer ring).

3.5. Duration of the second fixation

Fig. 5 plots the distributions of fixation durations measured between the end of saccade 1 and the start of

saccade 2. Corrective saccades and scanning saccades are shown separately. It is evident that the two distributions differ. A sub-population of very short-duration fixations occurs for each subject in the case of scanning saccades but such short-duration fixations never precede corrective saccades. These brief fixations appear to be of considerable interest for saccade programming.

3.6. Accuracy of second saccades related to duration of the prior fixation

The second saccades of the scanning type were grouped into four categories based on the previous fixation duration; very short (< 60 ms), short (65–90 ms), regular (95–180 ms) and long (> 180 ms). The proportion of saccades in each time-band that reached the target was evaluated and is plotted in Fig. 6, which also shows the total number of saccades in each band. Since the grouping is post-hoc, the number of cases in each band is variable.

There is no clear relationship between fixation duration and the accuracy of the following saccade. For three subjects, accuracy appears independent of dura-

tion up to durations of 180 ms, while for RW, saccades following brief fixations show a tendency to be less accurate. For BK and TH, saccades following very long fixations also appear less accurate.

3.7. Do short-duration fixations occur when the eye lands off a target element?

Recent work on the physiology of saccade program-ming (e.g. Dorris, Paré, & Munoz, 1997; Everling, Paré, Dorris, & Munoz, 1998) has emphasised the signifi-cance of activity in the rostral colliculus region for the saccade triggering process. It might be expected that if the gaze landed on a distractor, the visual stimulation would result in increased activity in the rostral collicu-lar region whereas if the fixation fell in a blank area away from target elements, the absence of foveal input would reduce the rostral collicular activity. Accord-
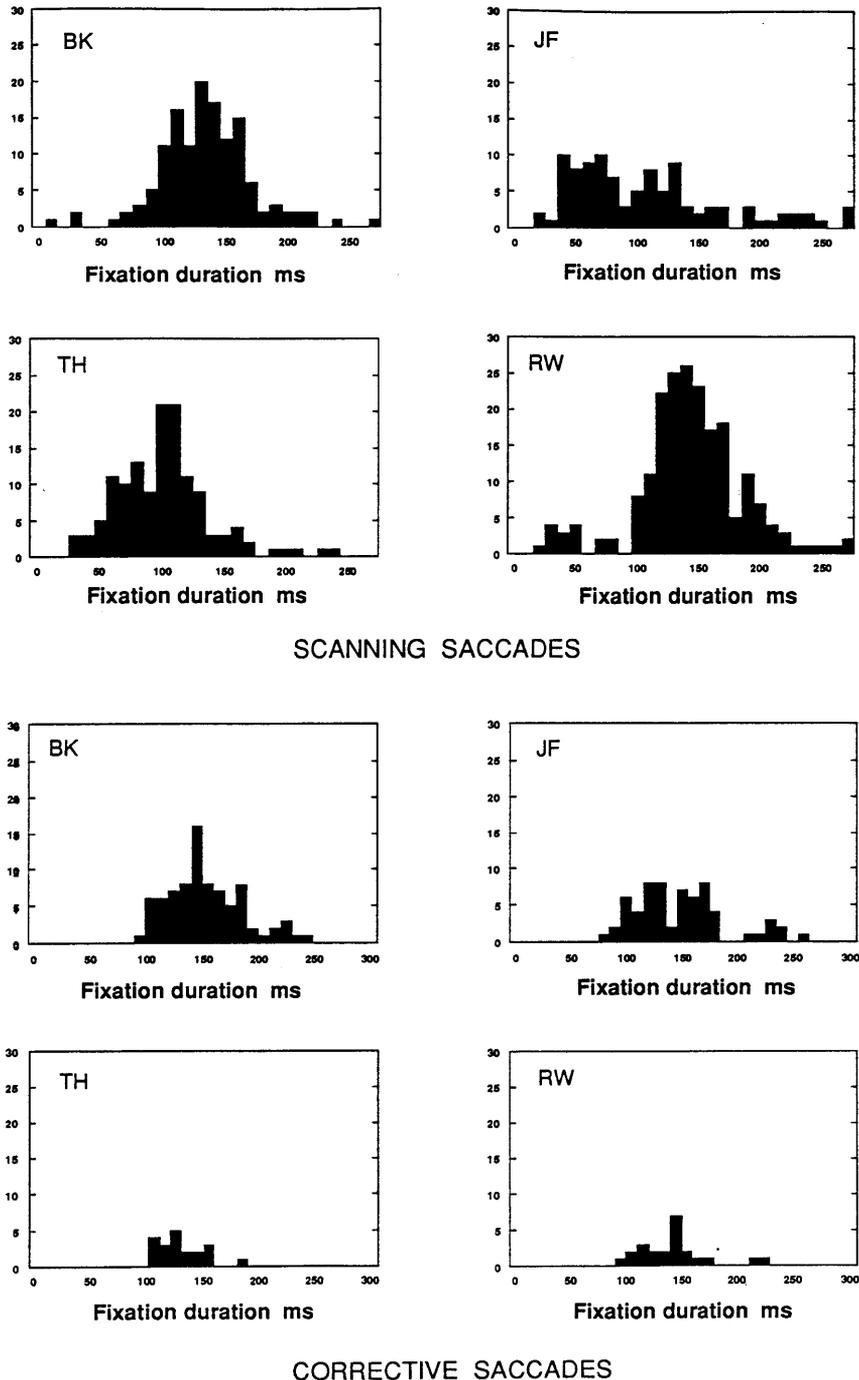

Fig. 5. Distribution of fixation durations following the first saccade. Distributions are shown separately for fixations followed by scanning saccades and those followed by corrective saccades.
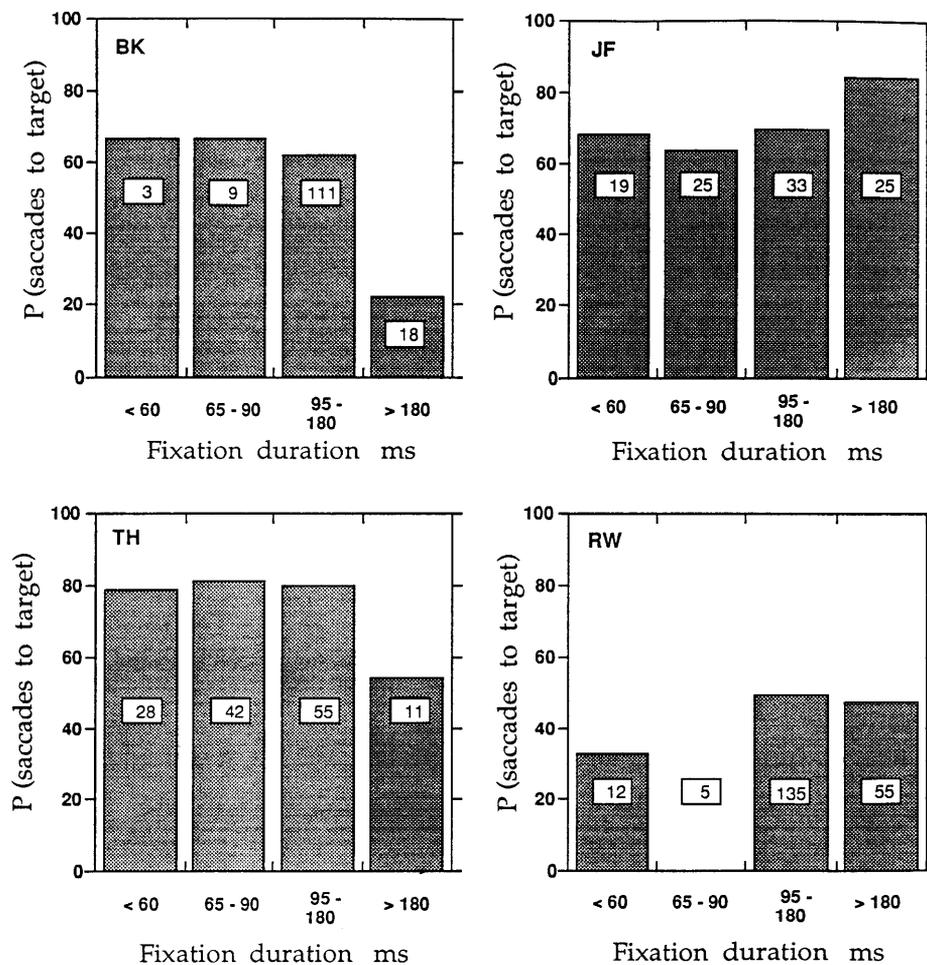
Fig. 6. Plot of second saccade accuracy (percentage of second saccades directed to the target) in relation to the previous fixation duration. The number of cases involved in this post-hoc analysis varies and is shown in the small box accompanying each column.

Table 3
Distribution (proportions and numbers) of saccades, in various bands of intersaccadic interval, as a function of whether the preceding fixation landed on a display element, close to a display element, or in a blank area between elements[a]

Interval band	<90	95–120	125–200	>205
On display element	5.0% (5)	15.0% (15)	61.0% (61)	19.0% (19)
Near display element (within 0.5° of edge)	6.2% (8)	7.8% (10)	56.2% (72)	29.6% (38)
Off display element	12.7% (39)	11.5% (35)	60.9% (186)	14.7% (45)

[a] The numbers are collapsed across subjects.

ingly, an analysis was carried out to establish whether short-duration fixations were more likely if the gaze fell away from a display element (we are grateful to Doug Munoz for suggesting this analysis). The analysis, based on the intersaccadic interval between saccade 1 and saccade 2, is shown in Table 3.

The number of very brief fixations (inter-saccadic interval < 90 ms) which occur when the eye lands on or near a display element is significantly less than the proportion expected on the basis of the overall data ($\chi^2 = 7.66$, $P < 0.01$). Nevertheless, some brief fixations do occur when the eye lands on a distractor.

3.8. What promotes short-duration fixations?

Several other analyses were conducted in an attempt to discover the conditions that elicited short-duration fixations.

Saccades that were directed to the target following brief fixations occurred more often when the target was in the inner ring. This was analysed by dividing the number of occurrences of a saccade to target following a short-duration fixation into the number of opportunities for such an event to occur. Results showed the following probabilities for fixation durations ≤ 90 ms

— inner ring targets, BK 9% (4/45), JF 32% (13/40), TH 38% (20/52) and RW 3% (3/101), whereas the proportion for outer ring targets was — BK 2% (2/103), JF 23% (18/76), TH 17% (18/107) and RW 2% (2/125). For very short fixations (≤ 60 ms), the corresponding figures are — inner ring targets, BK 2% (2/45), JF 12% (4/40), TH 13% (7/52) and RW 3% (3/101); outer ring targets and BK 1% (1/103), JF 12% (9/76), TH 6% (6/107) and RW 2%, (2/125). Although none of the comparisons for individual subjects reaches significance on a χ^2-test, in each case a greater proportion of short-duration saccades is found with inner ring targets.

Short-fixation durations were, for two subjects, more likely if the first saccade landed on a distractor of the opposite colour to the target than on one of the same colour. The measure used was once again the proportion of saccades following short (≤ 9 ms)-fixation durations out of the total number of saccades satisfying the condition. These proportions were — for same colour non-targets, BK 9% (4/41), JF 14% (6/42), TH 28% (20/72) and RW 7% (4/54); for same shape non-targets BK 9% (7/69), JF 40% (18/45), TH 42% (21/50) and RW 6% (4/69). A χ^2-test showed that the difference was significant at the 0.05 level for JF and TH.

3.9. Do saccades following brief fixations show the same proximity function?

The proportion of short-latency saccades as a function of target distance was calculated and compared with the overall plots shown in Fig. 4. For the two subjects who had a high number of these saccades, the function appeared identical to that for the whole data set (in the case of JF, the points for distant targets fell midway between the near position and the far position curve). Subject RW made nine short latency saccades when the target distance was greater than 10° and none was correct. Subject BK also made nine short-latency saccades when the target was more distant than 10° and seven of these were on target. There are, thus, no grounds for supposing that the proximity function is systematically different for saccades made after brief fixations.

4. Discussion

Several clear findings emerge from our analysis of second saccades. In the earlier paper analysing the initial saccades of the search task (Findlay, 1997), we found that target proximity was a major determinant of whether the first saccade could be directed accurately to the target. We also noted that when saccades did not reach the target, they tended to fall on distractors

sharing one of the target features. Both these findings characterise the second saccade of the search task.

Fig. 3 shows that second saccades are relatively more likely to fall on a distractor with a shared target feature. The tendency is somewhat less strong than for first saccades and two reasons may be advanced for this. First, since the erroneous first saccade is likely to have been on a shared-feature distractor, the baseline probabilities shown in Fig. 3 will be modified slightly in favour of targets with two different features. A second consideration is that, for the first saccade, eight target elements are present at the same eccentricity whereas for second saccades, this will not be the case. As discussed in the next paragraph, proximity to the fovea is an important determinant of salience (Lévy-Schoen, 1969, 1974; Findlay, 1980, 1983) and, thus, may override target properties. Zelinsky (1996) recorded eye movements during feature conjunction search and failed to find any indication that erroneous saccades were directed preferentially to distractors sharing a target feature. Findlay and Gilchrist (1998) attributed this anomalous result to the influence of proximity and it seems likely that the lower proportion of second saccades to shared-feature distractors can be attributed to a similar influence.

Fig. 4 shows that target proximity is a very important factor in determining whether the second saccade does or does not reach the target. The proximity function is very similar to that shown in the search experiments of Motter and Belky (1998a,b) and target proximity to the fovea is recognised increasingly as a key feature in target search (Carrasco & Frieder, 1997; Carrasco, Evert, Chang, & Katz, 1995). The target proximity effect observed in our data appears to depend solely on the distance of the target on the fi0xation preceding the saccade, that is the position following the first saccadic movement. This suggests that the search process starts afresh at this point. Horowitz and Wolfe (1998) made a somewhat similar suggestion that 'visual search has no memory' although their concern was search without eye movements.

The picture that has emerged so far is that search is guided using a heuristic whereby the information on every fixation is analysed locally with the region closest to the fixation point emphasised. The saccade is then made to the location with highest salience on the salience map resulting from this new analysis. No information is carried over from the previous fixation, although some additional process must be envisaged to prevent the third saccade refixating a location that has already received fixation. We shall not consider further the 'keeping track' factor in this paper although we recognise its interest and importance (Engel, 1977; Klein, 1988; Klein & MacInnes, 1999). The heuristic described accounts well for the bulk of the data. How-

ever, the phenomenon of very short-fixation durations suggests that some modification is needed to this simple picture.

The distribution of fixation durations following the first saccade is presented in Fig. 5. An interesting and unexpected feature is the substantial number of saccades that follow the first saccade after a very brief fixation. These saccades occur exclusively when the first saccade lands on a distractor and take the eyes to a new display element. These, generally large, *scanning* saccades were contrasted with small *corrective* saccades, where the gaze remains close to the display element first fixated. Corrective saccades occur frequently when the second saccade lands on or near the target but the fixations preceding these corrective saccades are all of normal duration. Corrective saccades occur very rarely when the eyes first land near a distractor.

Two considerations suggest that short-duration fixations are a distinct population and separate from the main body of fixations. Fig. 5 shows that, for two subjects, there is a separation between the population of short inter-saccadic intervals and the remainder. For all four subjects, short latency saccades occur with a greater likelihood when the target is in the inner, rather than the outer, ring. A number of cases occur with fixation durations of 40 ms or less. This suggests strongly that the 'decision' to move the eye on again rapidly is made prior to the onset of the preceding first saccade. This decision depends on the nature of the item at the first saccade destination (short fixations occur only when the eye falls on a non-target), and is, therefore, influenced by peripheral preview. For two subjects, short latency saccades occur more often when the first saccade lands on a display element of incorrect colour than one of incorrect shape. This suggests that colour analysis might proceed faster than shape analysis.

Recent neurophysiological work on the superior colliculus (Dorris & Munoz, 1995; Dorris et al., 1997) has shown that decrease in activity in the rostral region is a key factor promoting 'disengagement' and the generation of a rapid saccade. In the analysis of Table 3, we showed that brief-fixation duration fixations were more likely if the eye landed in the empty region between display elements rather than on or near an element. Nevertheless, some short-duration fixations occurred even when the eye landed directly on a display element. The arguments advanced in the previous paragraph suggest that peripheral preview is involved in the decision to make a brief fixation. The present results suggest, therefore, that disengagement is additionally promoted by preview of a non-target, or alternatively, that preview of the search target promotes engagement.

Fig. 6 shows that saccades following brief fixations appear to have the same probability of reaching the target as those following longer fixations. This is a remarkable result. The analysis presented in Fig. 4 and discussed above suggested that for each fixation, analysis of the material in the visual periphery commences afresh. It would be expected that a speed–accuracy trade-off would be present in search eye movements as in other actions (such a trade-off was found by Brown, Huey, & Findlay, 1997) with the result that saccades made after brief fixations would be less accurate than when the saccade initiation was delayed. Since many short fixations are followed by saccades on to target, it is also necessary that some form of trans-saccadic memory for the target location occurs. This might take the form of motor memory (cf. Beauvillain, 1999).

We believe that peripheral preview must be invoked to account for the phenomena of short-latency saccades. This peripheral preview must first establish whether the initial saccade is aimed at the target or at a distractor. Although a second saccade occurred frequently after an initial saccade into the target sector, these corrective saccades never had short latencies. Second, since many of the short-latency saccades reached the target after a fixation too brief (< 50 ms) to allow any further visual analysis, we conclude that information about the likely target location in these cases must have also been obtained during the first fixation. This would also account for the fact that short fixations occurred predominantly with targets in the inner ring. In these cases of short fixation durations, we suggest that parallel programming of the first two saccades occurs. Evidence for paired processing of saccades has been presented on several occasions (Becker & Jürgens, 1979; Beauvillain, 1999; McPeek, Keller, & Nakayama, 1999). McPeek et al. studied saccades in a visual search task and also found short fixations, interpreting these as instances of a 'pipelined' saccade pair.

To return to the questions raised in the introduction, we conclude that, in the majority of cases, the destination of the second saccade involves no advance planning using trans-saccadic memory but results from the analysis of information during the preceding fixation. As with the programming of the first saccade, such analysis proceeds in parallel over the area around the newly fixated location, with proximity to the fovea operating as a strong weighting factor. However, on a minority of occasions, a second saccade occurs after an extremely brief fixation. We suggest that, on these occasions, first and second saccades are planned as an entire unit during the initial fixation.

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