

Eye Guidance and Visual Search

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Introduction

In our chapter for the first edition of this compendium (Findlay and Gilchrist 1998), we argued that active eye scanning is ubiquitous in visual search and so understanding eye scanning must be integral to any theory of search. We proposed an account, based around the concept of a salience map, of how the eyes might be guided during this process. We contrasted that active account with a more passive one in which covert attention ‘scanned’ some mental image and eye movements were incidental. The passive tradition was, at the time, the dominant one in studies of visual search and so we felt our proposal was quite radical. Since then there has been increasing support for an active model of visual search, in part reflecting an increasing realisation of the limitations of accounts based solely on covert attention. There has indeed been widening interest more generally in eye scanning and we have even been prepared to suggest that a fundamental theoretical shift is in the process of occurring (Findlay and Gilchrist 2003). We commence the present chapter with a brief recapitulation of our earlier arguments. This is followed by sections describing more recent experimental work that supports and elaborates the basic account.

Salience maps

A salience map is simply a means of representing information spatially. In its most abstract form, it consists of a set of values of a scalar parameter (i.e. a single-valued one) defined at each point in a two-dimensional space. It can be conveniently envisaged as a contoured landscape of hills and troughs where the scalar parameter corresponds to the height at each location. Peaks represent locations of high salience and troughs the converse. In the case of visual salience maps, the two-dimensional space corresponds to space in the visual field and the salience parameter that is represented by the values at locations in the map corresponds to the significance of the visual information at that location. In this chapter, we shall use salience in this general sense that only partially corresponds with the everyday meaning of the term. In particular, it is important to recognise that salience can be modulated by the current task. The approach entails no commitment to the idea that salience is an intrinsic aspect of the visual environment. It seems plausible to suppose this might be the case, as recognised by the inclusion of an ‘Intrinsic Salience’ route in the framework for saccade generation postulated by Findlay and Walker (1999). However, whether particular visual properties are intrinsically eye-catching should be regarded as an open question, amenable to empirical investigation (see discussion in chapter by Crundall).

The concept of a salience map has its roots in the physiological properties of the visual brain. It is well known that visual processing in the brain occurs in a large number of anatomically distinct visual areas, in each of which the visual field (or

strictly hemifield) is represented in a retinotopic mapping. Different visual properties are processed differentially in these different areas. Moreover these areas connect, also in a retinotopically mapped way, to oculomotor areas such as the frontal eye fields and superior colliculus. There are multiple cross-connections, both forward and backward, but spatiotopic organisation is maintained (Felleman and Van Essen 1991; Stuphorn and Schall 2002). This architecture enables visual information to be transmitted between brain areas in the form of two-dimensional maps.

We propose that at some key stage, probably the superior colliculus, there is an *oculomotor salience map* that is the location at which a unique saccade destination is selected (Findlay and Walker 1999; Trappenberg *et al.* 2001). At this stage, the current point of maximum salience in the oculomotor salience map is selected as the destination for the saccade target. Note that, on this account, selection of a particular spatial location occurs late in the process. This emphasis on late selection differentiates the salience map account from accounts that involve earlier spatial selection, for example by a covert attentional spotlight. In the remainder of the paper we shall first argue the case for late selection and subsequently consider ways in which some forms of earlier selection might also contribute.

Early work on the visual system emphasised that its architecture and organisation showed evidence of hard wiring, but more recent thinking has developed the idea that neural networks possess immense potential for flexible information processing. A neural architecture consisting of a set of interconnected map representations offers the potential for a process that may be termed *search selection*. This can be seen as a manifestation of the *biased competition* postulated by Desimone and Duncan (1995). In their account of biased competition, a short-term description of the relevant search target controls the competitive biases between maps in the visual system, such that inputs matching the description are assigned greater weight. In this way, at least in principle, salience maps may be created in which *similarity* to the search target in part determines the level of neural activity. Detailed computational accounts have substantiated the idea (Itti and Koch 2000; Hamker 2004). The first neurophysiological demonstrations that such maps actually occurred in the visual system during search were made in the early 1990s (Chelazzi *et al.* 1993; Schall and Hanes 1993). Both studies reported measurement of single-cell activity in visual areas of the primate brain (respectively inferotemporal cortex, IT and the frontal eye fields, FEF) and showed that the activity possessed the properties expected if the visual areas coded a representation of salience.

The formation of salience maps implies that visual information from all locations in the visual field is processed in parallel. Parallel processing of simple features, such as colour, formed one facet of the well-known Feature Integration Theory (FIT) of visual search (Treisman and Gelade 1980). However a second facet of FIT proposed that for more complex search tasks, such as feature conjunction searches, an alternative, serial, process came into play. For complex tasks, the *search function*, which describes the relationship between response time and display size, increases linearly. FIT proposed that this linear increase came about because of a serial item-by-item scan. The slope of the search function allowed an estimate of the speed of this scanning and values of around 50 ms/item were typically obtained. Such a rate is clearly too fast to reflect overt eye scanning and so scanning by a covert attentional pointer was invoked as an alternative.

Several difficulties subsequently emerged for this account. As studies measuring visual search speeds accumulated (Wolfe 1998), it became evident that different search tasks generated a wide range of search functions with no obvious discontinuity between those showing parallel properties and those showing serial ones. Duncan and Humphreys (1989) had already pointed to findings in visual search that implicated parallel processing of the search array. Indeed, Wolfe *et al.* (1989) had developed a 'guided search' proposal in which the attentional pointer was itself guided by something resembling a salience map. Nevertheless the idea of a rapidly moving pointer was retained in this account (Wolfe *et al.* 2000) even though more direct measurements of the scanning rate of covert attention gave much slower estimates than those derived from feature integration theory (Egeth and Yantis 1997; Ward *et al.* 1996).

It also proved difficult to integrate the idea of a rapid covert attentional scan with studies of eye movements during search. For large arrays, the number of saccades made before the target is located shows a close parallel to the search time (Binello *et al.* 1995; Motter and Belky 1998b; D E Williams *et al.* 1997; Zelinsky and Sheinberg 1997). Could a rapid attentional scan be operative within each fixation to seek out candidate locations for the next saccade destination? As Findlay and Gilchrist (2001) discuss in detail, the most plausible prediction would then be that saccades directed to the search target would have shorter latency than those directed elsewhere. Two studies (Findlay 1997; Motter and Belky 1998a) both found that saccades to the search target had equal, or longer, latency than those to distractors and both concluded that covert attentional movements were not involved in saccadic selection.

A resolution of these problems requires a hybrid account of visual search that combines parallel processing within each fixation with serial saccadic scanning. The parallel processing through biased competition leads to an oculomotor salience map in which *similarity* to the search target contributes to salience. Items that are similar to the target will tend to have a higher salience level and thus are more likely to be selected as the target for the next saccade. This approach can readily account for an observed property of the saccades made to distractors before the target is located. Such saccades are directed predominantly to distractors having some similarity to the target (e.g. sharing a common feature; Findlay 1997; Motter and Belky 1998b). If it is assumed that the processes creating the salience map possess some intrinsic noise variability, then it is possible for the location with the highest salience to correspond to a distractor, particularly if the distractor is close to the current fixation and so gains additional weighting from the proximity factor discussed below.

The second important factor that has an influence on salience is *proximity* to the fixation location. Studies of saccade selection during visual search show clearly the importance of proximity: items that are closer to the current fixation are more likely to be selected as the target for the next fixation (Findlay 1997; Motter and Belky 1998b). This may be ascribed in part to the anisotropy of the visual pathways. Items presented further into the periphery will be less well represented in cortical brain areas and so more difficult to discriminate

To summarise, the approach proposes that during visual search saccade destinations are determined by selection of the point of highest salience in an oculomotor salience

map formed through the process of biased competition. The two most important determinants of salience are similarity to the search target and proximity to the current fixation location. We propose that this basic account provides the key to understanding saccade generation in visual search but the account requires supplementation in at least three different ways. First, it is too simple to consider salience maps as static. Computational processes of vision are time consuming and so it is more realistic to envisage each salience map as a dynamically changing landscape. Second, there is evidence that forward planning mechanisms allow saccades to be 'pipelined' and supplement the saccade selection process. Finally, other forms of short and longer term storage processes serve to render particular locations or regions either more likely or less likely as the saccade destination. In the following sections we consider each of these points in turn.

Dynamic salience maps: endogenous and exogenous activity combine to shape a complex dynamic landscape

Generation of a saccade requires selection of a unique single location for the saccade destination. The account given so far has emphasized that this selection occurs at a late stage and, prior to this late stage selection, information is carried in two dimensional maps. Thus in the earlier visual stages, information is encoded about multiple potential saccade goals. We first consider experimental studies using the 'oculomotor capture' paradigm, a paradigm in which two competing saccade goals are generated. This work supports the salience map approach and also allows rejection, as inconsistent with the experimental evidence, of the stronger position that independent saccade *programs* are generated concurrently. The studies also show how the representations for the goals develop dynamically. Following this, we consider some of our own studies that show the consequences for visual search of such dynamic representations.

In the 'oculomotor capture' paradigm, introduced by Theeuwes *et al.* (1998), an observer views a display consisting of six grey disks (see Figure 1a). The observer is told that five of these disks will change colour to red and the task is to saccade to the disk that remains grey. This is a simple form of search task that observers can carry out without difficulty. The interest comes when a seventh, new, red disk appears at the time of the colour change. Theeuwes *et al.* found that saccades were frequently directed to the newly appearing disk rather than the search target. Their report was entitled "Our eyes do not always go where we want them to". In this situation there are two potential saccade goals, one provided by the search target and the other provided by the onset stimulus. There are strong grounds for thinking that any newly appearing stimulus activates the mechanisms that produce an orienting response towards it. Whether or not an overt orienting movement is actually made depends on the balance between activity in brain centres controlling fixation and those promoting movement (Findlay and Walker 1999). In the oculomotor capture situation, the system is already predisposed to break fixation and make an eye movement.

Could it be the case that programs for the two saccade goals are processed and stored independently, as indeed suggested by the terminology of 'exogeneous saccades' and 'endogenous saccades' adopted by Theeuwes *et al.* (1998)? We discuss in a subsequent section how multiple saccadic goals can be 'pipelined'. If so, it might then be expected that the saccade whose programming is completed first would be

executed first. On this 'horse-race' account, with two potential saccadic goals saccades would be directed to either one or the other. Most of the time, that outcome was found. However, when the onset target was reasonably close to the search target, a new phenomenon was found. In this situation there were many intermediate saccades that landed at a location in the space between the two target locations (Godijn and Theeuwes 2002). Intermediate saccades would not be expected if each potential saccade goal fully specified a motor program for the movement. Rather the result suggests a shared late stage with both goals represented on a single salience map. The result additionally shows that this representation has low resolution so that the peaks of activity coalesce. This result is similar to the 'global effect' finding of averaging saccades directed to intermediate regions when orienting to a display consisting of two neighbouring elements (Findlay 1982; Walker *et al.* 1997; Chou *et al.* 1999). The result is usually attributed to broad spatial coding as associated with large receptive fields, such as those found in the superior colliculus (McIwain 1975). Averaging saccades are also found in visual search tasks when two identical target elements are present with humans and monkeys showing a remarkably similar pattern (Findlay 1997; Arai *et al.* 2004). It has been argued that this averaging can contribute to search by allowing a strategy of homing in to the target (Zelinsky *et al.* 1997).

A strict horse-race model would also predict a decrease in latency when two potential target in comparison with that for a single target. In fact Godijn and Theeuwes found that latencies were *increased* when the oculomotor distractor was presented in comparison with control trials where no distractor was presented. (see also Leach and Carpenter 2001). Godijn and Theeuwes (2002) further demonstrated that the saccade destinations varied with saccade latency. They were able to analyse this by taking advantage of the natural variability found in the onset timing for saccades. Figure 1 (a and b) shows the results from the case where the distractor was close to the search target. The fastest saccades (quartile 1: latencies less than 200 ms) were most likely to be directed to the onset distractor or to an intermediate location between onset distractor and search target. The majority of saccades had intermediate values of latency (200-230 ms) and were most likely to be directed to the intermediate location or to the search target. For the slowest quartile of saccades (with latencies greater than about 230 ms), saccades were often directed to the search target and inaccurate saccades were more likely to be directed on the *opposite* side of the search target to the onset distractor than to the intermediate region between target and distractor.

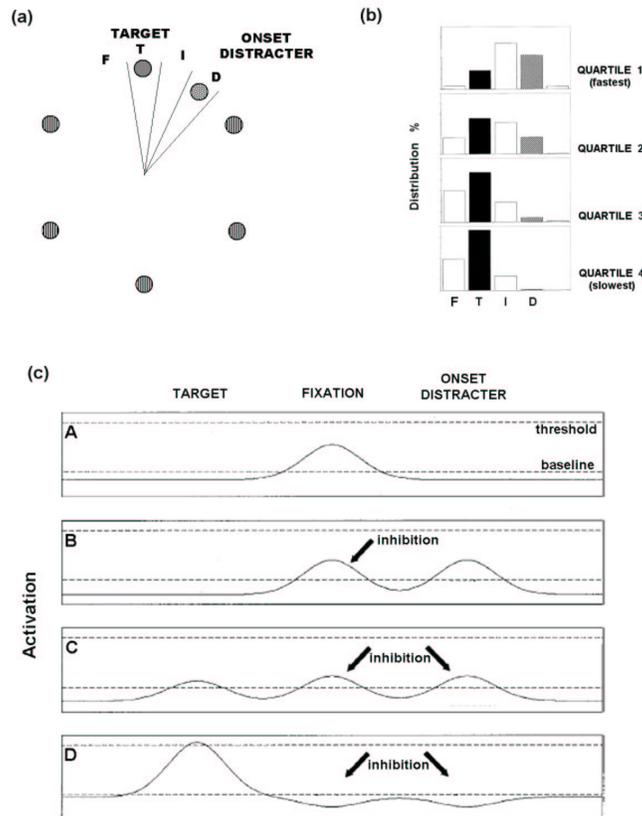


Figure 1. The oculomotor capture paradigm. (a) Display. The search target (T) is the only disk in the stimulus hexagon not to undergo a colour change. The onset distractor (D) may appear at an unpredictable location. The distractor is shown here in the 30 deg location. Saccades were classified as directed to the target (T) sector, distractor (D) sector, to the intermediate sector (I) or the far sector (F). (b) Distribution of saccade directions for the four quartiles of the latency distribution. (c) Schematic representation of the development of the hypothesised salience map landscape in the oculomotor distractor paradigm when target and distractor are in remote locations. Successive rows show the time sequence. Reproduced from Godijn and Theeuwes (2002). Copyright © 2002 by the American Psychological Association. Adapted with permission.

The account given by Godijn and Theeuwes (2002) rejects the horse-race model in favour of a salience map account. However the salience map changes dynamically as illustrated diagrammatically in Figure 1c. Initially (A), there is an activity peak in the fixation region. Following the display change (B), activity develops rapidly at the location of the onset distractor and the fixation activity decreases. The decrease in fixation activity comes about through competitive inhibition with the onset activity (see Findlay and Walker 1999) and would occur more rapidly if the fixation target were removed. At the time shown by (C), activity from the target starts to build up, activity from the abrupt onset now begins to decline and activity at fixation continues to decline. Finally at (D) the activity at the target location has built up to the level necessary to trigger the saccade. This illustrates neatly the processes that can contribute to the dynamics of the salience map. Activity builds up over a finite time, dependent on the speed of the biased competition processes. The activity from the distractor onset is transient and is followed by a reversal in polarity so that excitation

is followed by a phase of inhibition. These themes will recur as we discuss further empirical studies.

Subsequent work by Ludwig and Gilchrist (2002, 2003a) using an adapted capture paradigm demonstrated that if the sudden onset also shared a visual property with the target (in this case colour) then the capture effect was even more pronounced. They used a display in which the search array appeared when four gray placeholders changed colour. One changed to the target colour (e.g. red) and the other three to a different colour (e.g. green). Capture by a distractor having the target colour occurred more often (49% of trials) than for a distractor in the alternative colour (7%). These results show that capture is not simply a stimulus driven phenomenon. Task based effects, for example the characteristics of the target being searched for, influence capture. These results provide further evidence against a simple horse-race model between 'exogenous saccades' and 'endogenous saccades'. Instead the results are consistent with the interactive model in which biased competition leads to preferential processing of display items that share features with the target. This has an influence on the salience map and the selection of the next saccade. While signals that result from onsets may themselves be processed more quickly in such a system, onsets appear not to have a qualitatively different status.

Even in a very straightforward search task, the transient activity generated by distractors at display onset may occasionally be adequate to promote oculomotor capture and these erroneous saccades can be highly informative. Figure 2 shows an example of the displays used in a study by Gilchrist *et al.* (1999). The task was to saccade to the vertical Gabor patch target, which could be in any of the eight locations, in the presence of horizontal Gabor patch distractors. The right hand plot of Figure 2 shows the distribution of erroneous saccades. Erroneous saccades were directed predominantly to distractor locations, located at 45 deg intervals around the angular axis. This again shows that sudden onsets have a high salience regardless of whether these onsets are task relevant.

An interesting and unpredicted feature revealed by the plot was the gradual decrease shown in both peaks and troughs with increasing angular deviation from the target axis. This effect could be attributed to long-range interaction between aligned Gabor patches, as previously demonstrated psychophysically by Polat and Sagi (1993). We suggested (Gilchrist *et al.* 1999) that the orientation specific long-range interactions operate to enhance the horizontal feature signal at a distractor location when there are other adjacent horizontal distractors. This leads to a gradient in the strength of this signal amongst the set of distractors, with the distractor diametrically opposite to the target showing the maximum enhancement. These enhanced signals feed into the salience map through inhibitory connections and thus result in the presence of an oppositely directed gradient in the salience map. As there is intrinsic noise in the salience map, the point of maximum salience can on some trials be at a distractor location rather than the target. Because of the enhancement of the distractor signal and the resultant reduction in salience, such a distractor directed saccade is less likely to occur for a distractor further removed from the target.

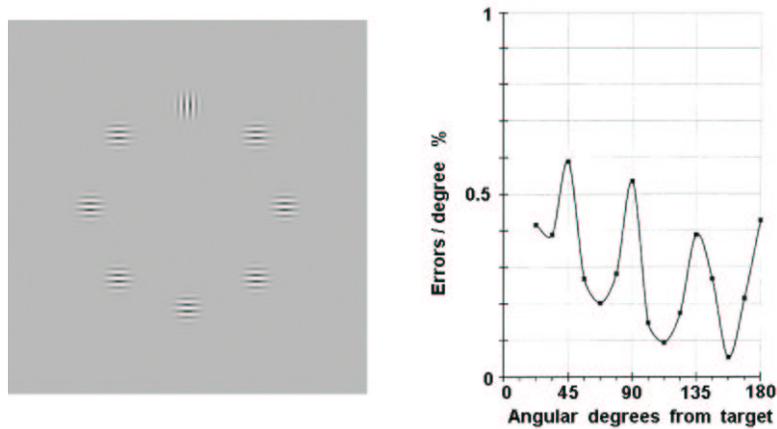


Figure 2. The left hand panel shows the type of display used in the study of Gilchrist *et al.* (1999). The search target was the Gabor patch containing vertical bars, which could occur in any of the eight possible locations. The right hand panel shows the distribution of saccade directions, plotted relative to the axis to the target. The plot shows the distribution on the 317 (37.0%) of trials classified as errors, hence the very large peak of correct saccades at the 0 deg and 11.25 deg points is not shown.

The studies so far have shown that visual onset transients generate a bottom-up signal that peaks more rapidly than the top-down signal generated by search selection. Bottom-up signals may also be generated by an oddball element in a display (sometimes called *intrinsic salience*). However, these signals do not appear to be processed as rapidly. In the studies reported by Findlay (1997), the general design was that a display appeared consisting of eight items, equispaced around a ring and equidistant from the point of fixation. In most cases, one item was the designated target and the others were distractors. The measure of interest was the proportion of first saccades directed to the target. Using the terminology that we have introduced, this measure should be influenced by the speed at which the search selection processes can generate a distinctive peak in the salience map in relation to the activity bursts generated by the onset transients arising from the distractors.

One experiment compared the influence of task factors with stimulus factors in saccade selection by comparing two alternative tasks for the same search displays. The displays contained one unique colour item and seven distractors of a different colour. When the observer had advance knowledge of the target colour, then search was highly efficient (90% of first saccades landed precisely on target with the majority of the remainder only slightly inaccurate). However, when the same displays were used without advance knowledge and the task was to locate the oddball (e.g. a single red item amongst seven green distractors), efficiency was considerably reduced (75% of first saccades were on target). This result shows that the task-based processes (the *bias* in biased competition) can be brought into play rapidly. The relatively poor performance in the oddball condition might seem surprising in the light of ‘pop-out’ accounts of intrinsic salience. However the displays used were quite sparse and, as pointed out by Bravo and Nakayama (1992), oddity pop-out signals increase in effectiveness as displays become more dense.



Figure 3. Stimulus displays used by McSorley and Findlay (2003). The task required subjects to search for a low spatial frequency Gabor target (fat lines) with high spatial frequency Gabors as distractors. With the right hand (16 element) display, many more first saccades were directed to the target than with the left hand (2 element) display.

As a final example in this section, we consider a study by McSorley and Findlay (2003) in which an explanation involving the dynamics of the salience map was invoked to explain a paradoxical result in which search apparently became easier as the number of distractors was increased. The search task involved detection of a target with a particular spatial frequency. This is normally considered to be an easy search task, supporting the notion that spatial frequency channels are involved in early vision (Carrasco *et al.* 1998; Sagi 1990). An example of our displays is shown in Figure 3. The target for these displays was the low spatial frequency Gabor patch, described to observers as ‘fat lines’. The task was to move the eyes as rapidly as possible to look at the target. In the two-element displays (Fig 3a) the elements could appear on the left or the right and the target could appear in the near (3 deg) or the far (6 deg) position. In the 16-element displays, the target could appear in any of the 16 positions. The 16-element display had a slightly smaller size (83.3%) because of screen size limitations but was otherwise identical.

There was a dramatic difference between the ease with which a first saccade could be directed to the target in the two cases. In the 2-element displays with the target in the more distant position (as illustrated) only about 10% of first saccades landed close to the target, even though a generous margin of spatial error was allowed (saccades landing between 4 deg and 7.5 deg were coded as correct). The great majority of saccades landed instead close to the near distractor element although their amplitude was greater than those in control trials with a single target at 3 deg showing that the far target exerted a small ‘pull’ effect on the calculation of amplitude. On the other hand, with the 16-element displays, the task presented little difficulty and around 90% of first saccades were directed to the target. In the displays with the target in the far position on the horizontal axis as illustrated in Fig 3a, the visual stimulation in the region near the target was identical in the two displays. Yet the presence of the additional distractors in the 16-item display resulted in a dramatic performance improvement.

We considered three possible explanations for the result. First, as found in the study by Gilchrist *et al.* (1999) discussed above, the regularity of the distractor elements in Fig 3b might promote perceptual grouping amongst the distractors, in some way

facilitating the task. We carried out further experiments in which the distractor elements were subject to random variations in position, orientation, spatial frequency and contrast. In all cases, the high level of performance was maintained and thus we rejected perceptual grouping as an explanation. The other possibilities we considered arose from the observation that the latencies of the saccades in the 2-element case were around 200 ms whereas those in the 16-element case were 250 ms. This might point to a strategic difference, with observers in the 2-element case deciding in advance to make a rapid inaccurate movement because little time would be lost in fixating the wrong item. We ran an experiment in which 2-item trials were intermixed with 4-item trials where the search displays had two further distractors on the opposite side of the fixation point. Latency and accuracy differences were still found and thus we rejected the strategic explanation, at least as a full explanation of the result. Our final explanation brought in the concept of a dynamic salience map. We attributed the latency difference to the 'remote distractor effect' studied by Walker *et al.* (1997) whereby the onset of a distractor simultaneous with a saccade target results in a slowing of the saccadic orienting response to the target. Thus we proposed that the short latency saccades in the 2-element case were generated from a salience map dominated by the activity from visual transients in which activity from targets and distractors were not well differentiated. The longer latency saccades in the 16-element case on the other hand were generated from a salience map in which the transient activity had dissipated and the predominating activity was from the biased competition of the search selection.

In summary, this section has provided evidence that the salience map involved in the generation of search saccades has a dynamic character. If visual onset transients are present, they appear to generate an automatic wave of activity. This activity is in the form of a time-limited burst and there is evidence that it may dissipate rapidly to be followed by a reverse, inhibitory, effect. A second, more sustained, signal progressively dominates the choice of saccade destination. It should be noted that most of the evidence for a dynamic salience map (and indeed also for the related concept of pipelined saccades discussed in a subsequent section) comes from saccades made in displays with abrupt visual onsets. A challenge for future work is to determine whether these concepts can be usefully applied to the scanning saccades of extended searches.

From the salience map to the saccade

The previous section has emphasized that salience maps must be considered to be in a state of dynamic flux. Why is it that the resultant saccades do not reflect this dynamic activity but instead are ballistic and stereotyped? In fact, some saccades are occasionally found that do seem to 'change their minds' in mid-flight and change direction towards a new goal. This was found regularly for large (40 deg) saccades in a step-tracking task by Van Gisbergen *et al.* (1987) and examples also occurred in the study of McPeck *et al.* (2000) discussed in a subsequent section. Nevertheless these instances are rare and the majority of small amplitude saccades are directed to the goal that was selected before the saccade was initiated. However, although the landing position of smaller saccades appears to be predefined before the movement, the precise trajectory of the movement can, under some circumstances, be influenced by higher-level factors as first demonstrated by Sheliga *et al.* (1994). A number of groups have reported a subtle tendency for saccades to curve away from an irrelevant

distractor (e.g., Doyle and Walker 2001, 2002, Ludwig and Gilchrist 2003b). In these studies, in what is a simplified capture paradigm, participants had to saccade to a target on the vertical meridian, and ignore abrupt distractors presented on the horizontal.

Could this result from on-line dynamic changes in the salience map so that, if the salience of a location rises during the programming of the saccade, the eyes are drawn towards that location? This is very unlikely to be the case. The variability affects saccade trajectory rather than the saccade end-point (as noted in the case of normal saccades by Jürgens *et al.* 1981). Instead saccade curvature almost certainly reflects the activity in the oculomotor salience map *prior* to the generation of the saccade by the burst cell firing. Saccade triggering in the colliculus occurs via a gradual increase in activity in the build-up cells followed by rapid and sudden firing of the burst cells prior and during the saccade. When the burst cell system in the colliculus triggers, it starts a very rapid and rate-limited process (Munoz and Wurtz 1995). This activity is self-sustaining and probably uninfluenced by visual events. The curvature corresponds to the correct programming of the end point position without a full determination of the saccade trajectory. There are two possible sources for the endpoint correction. First, the correction might consist of the continued evolvement of a target related signal within the motor map (Keller and McPeck 2002). Alternatively, an active correction mechanism may be occurring via an alternative system. For example, Quaia *et al.* (1999) suggest that the cerebellum may be involved in the online directional control of saccades.

Ludwig and Gilchrist (2003b) showed how the saccade curvature measure could illustrate the different time courses of signals on the salience map. In their experiments two items were presented one above and one below fixation. Participants had to saccade to the target in this pair that was defined by the colour of the items. Participants also had to ignore abrupt onset distractors presented on the horizontal meridian. The study focused on the curvature of the correctly directed vertical saccades to the target.

In their first experiment they compared onset distractors that were the same colour as the target or the same colour as the distractor (c.f. Ludwig and Gilchrist 2002; 2003a). In both cases the saccades curved away from the onset distractor but there was no evidence of a difference in the amount of curvature in the two conditions. This initial experiment suggested that the colour of the onset distractor did not affect the extent of interference. However, Ludwig and Gilchrist (2003b) reported two further experiments in which there was an increased curvature when the onset distractor was the same colour as the target. In the first experiment, the only change in the paradigm was that the onset distractor was presented slightly (78 ms) before the target. In the second of these experiments the only change to the paradigm was that the fixation point was present throughout the trial: a manipulation that increases the saccade latency to the target. In both cases the curvature metric now showed the influence of the colour of the onset distractor. In these two experiments when the onset distractor was the same colour as the target curvature increased. Both manipulations, in different ways, gave the similarity signal more time to influence the salience map before the generation of the saccade. This additional time was clearly not required for the similarity of the onset distractor to the target to influence curvature. One way to

interpret the finding is that the sudden visual onset results in a rapidly emerging peak in the salience map and that if the onset shares properties of the target then the salience is further enhanced by the similarity processes that emerge slightly later.

Forward planning mechanisms: covert attention and preview

In one respect, our 1998 account requires supplementation. The active vision system contains a component devoted to forward planning. Humans and primates can follow instructions to memorise locations as future saccadic targets. Recent work with ‘triple-step’ sequences (Tian *et al.* 2000) shows that at least two memorised locations can be stored following instructions, although the memorised saccades are never as accurate as those made to a visible target (Gnadt *et al.* 1991; White *et al.* 1994). It seems likely that the process of storing a future saccade goal also occurs on a more automatic basis so that the process of planning the saccadic destination does not necessarily have to start from scratch on every new fixation. Such a process has been clearly demonstrated in studies of the initial saccades made when a new display is first presented, as discussed next.

The terminology of a ‘pipeline’ in which future saccade goals can be stored was used by McPeck *et al.* (2000) who demonstrated its presence with a simple and elegant experimental design. Their subjects were presented with a search display consisting of three items, either two red and one green or two green and one red, arranged in a triangle with all items equidistant from fixation. The subjects’ task was to make a saccade to the oddball item. This is a surprisingly difficult task and generates a large number of errors (e.g. Findlay 1997). Erroneous saccades are followed by a second saccade locating the oddball target. Quite frequently, such saccades occur after an extremely short intermediate fixation, suggesting that their goal had been selected during the initial fixation and stored ‘in the pipeline’. McPeck *et al.* confirmed this with a manipulation whereby on some trials, the display was changed during the execution of the first saccade so that the oddball appeared at a different location. This provided a test of whether the destination of the second saccade was based on a stored goal or on new analysis. If the second saccade goes to the previous target location, it shows it to have been pre-programmed. Such an outcome occurred on the great majority of occasions in McPeck *et al.*’s study. Only when the second saccade followed a fixation of 250ms or more was the second saccade directed to the location at which the search target was actually present during the prior fixation. A recent paper by Caspi *et al.* (2004) further elucidates how visual information is accumulated for the first and second saccades in the pipeline situation.

In our own work (Findlay *et al.* 2001), we also studied initial saccade sequences using a more complex search display consisting of 16 items. We also found that second saccades often occurred with very short latencies following an erroneous first saccade to a distractor, suggesting that their goal had been selected and held in the pipeline. Additionally we were able to show that the likelihood that the second saccade would locate the target depended not on the proximity of the target to the *initial* fixation location but rather on the proximity of the target to the location fixated *after* the first saccade. Moreover this likelihood was independent of the duration of the intermediate fixation following the erroneous first saccade. This points to a remarkable conclusion. Clearly, the second saccade target was selected during the penultimate fixation (the initial fixation) and stored in the pipeline. However, the

selection was made taking into account the outcome of the first saccade in a way that gave increased weighting to locations near the saccade end-point even though the saccade had not been executed.

Direct measurements have shown that visual processing at the saccade goal is enhanced in the period before the saccade is made (Deubel and Schneider 1996; Kowler *et al.* 1995). The concept of preferential analysis for material at or near the saccade goal is one that has long been familiar in studies of eye control during reading. The phenomenon is termed *preview advantage* and it has been shown that preview allows shorter fixation durations when the material is subsequently fixated foveally. As discussed in more detail elsewhere (Rayner 1998, chapter in this volume) reading ability deteriorates if upcoming material in the parafovea ahead of the current fixation position is rendered unavailable, for example using a gaze-contingent display. Preview advantage has also been implicated in saccade planning through the phenomenon of word skipping. During reading, short words are not always fixated and common short words are particularly likely to be skipped (Gautier *et al.* 2000, chapter by Brysbaert *et al.* in this volume).

These findings also provoke a reinterpretation of the role of covert attention. Covert attention describes the well-known finding that it is possible to attend to a location in peripheral vision while fixating elsewhere. Much of the early thinking about covert attention was based on the idea that covert attention could *substitute* for overt attention shifts, i.e. eye movements. The postulation of a rapidly shifting covert attentional spotlight, as discussed above, is one example of this approach. We believe it is more appropriate to regard covert attention as a process that acts to *supplement* the overt eye shifts of active vision through the phenomena of peripheral preview and pipelined saccades described in this section.

Two commonly encountered statements about the relation between covert attention and saccades are “attention selects the goal of the saccadic movement” and “attention shifts to the saccade goal prior to the actual movement”. The latter statement is underpinned by the finding of peripheral preview. However these formulations are problematic in several ways. First, unless we can define precisely the properties of attention, the statements lack explanatory power. Second, they imply that there is an identifiable attentional process, separable from the orienting control system, which exerts tight control over that system. Third, they often carry implicitly the further assumption that the attentional process must have a single localized focus. The spotlight metaphor has been widely used in studies of covert attention but, as Cave and Bichot (1999) noted, its popularity probably derives largely from its similarity to overt orienting. Cave and Bichot show that there is in fact surprisingly little evidence for a sharply localized spotlight-like process of covert attention. Finally, physiological studies are increasingly finding that attentional processes are driven from brain regions such as the frontal eye fields that are generally assumed to be oculomotor (Moore *et al.* 2003). We believe that it is more satisfactory to adopt a position close to the pre-motor view of covert attention (Rizzolatti *et al.*, 1994) that places primary emphasis on an integrated system that is designed to perceive actively through continual eye scanning.

To summarise the findings from this section, it has been shown that, following a display onset, it is possible for two saccadic goals to be pipelined so that a second

saccade can be generated, often after a very brief fixation interval. The second saccade is largely based on information sampled during the penultimate fixation, with some evidence that a preview mechanism weights visual information at and around the goal of the first saccade.

Short term storage mechanisms for distributing fixations

The account given so far assigns control of saccades to properties of the prior visual stimulation sampled either during the immediately preceding fixation or the penultimate one. The factors introduced can account for many properties of saccades during visual search. How are these bottom-up processes combined with more high-level cognitive control mechanisms? One problem immediately shows the need to supplement the bottom-up account. A search driven solely by the bottom-up factors of similarity and proximity would show a strong tendency to be confined to a local restricted region. Suppose two items, A and B, are in close proximity and each have similarity to the target and thus an elevated level of salience. B may be the most salient element when A is fixated and vice versa so that an alternating sequence A-B-A-B . . . is predicted if saccades are driven purely by immediate salience. How should the salience account be supplemented to avoid being trapped into such loops? It would appear necessary for information to be retained in some way about locations that have been visited and/or processed. Retention of information requires some memorial representation. In this section we shall discuss the wide variety of memory mechanisms that have been involved in visual search. As well as the basic studies discussed, this area is providing fertile ground for investigation of neurological conditions (Husain *et al.* 2001; Hodgson *et al.* 2002).

The issue has provoked considerable recent interest following a provocative claim by Horowitz and Wolfe (1998) that 'visual search has no memory'. Their concern was 'passive' visual search without eye movements and it is possible that they would have been ready to concede that when individuals used eye movements, they were able in some way to distribute their fixations over an array. Their claim provoked several rebuttals showing that various forms of memory influence visual search. Our discussion follows the excellent treatment by Shore and Klein (2000), who discuss evidence for at least three separate processes, all of which potentially affect eye control.

According to Shore and Klein, the most rapidly operating form of memory is an inhibitory process discouraging immediate re-inspection. The term 'inhibition of return' (IOR) has become familiar in describing the phenomenon, first noted by Posner and Cohen (1984), of a reversal in the short-lived perceptual advantages found after visual stimulation at a peripheral location. Immediately following stimulation, reaction times to a probe are faster and visual discriminations are improved. However, if, as in the standard covert orienting paradigm, overt eye orienting does not occur, and also if no voluntary covert orienting to the location occurs, then these 'benefit' effects are short-lasting and followed by converse 'cost' effects of slower probe reaction times and poorer discriminations. In early work the reversal was found to occur around 300 ms following stimulation and for a while the effect was held to be automatic, straightforward, having a fixed time course and restricted to one location. However it soon became clear that IOR was complex, with a time course that was

dependent on the cognitive task carried out by the observer and could extend over more than one locus of stimulation (Klein 2000; Snyder and Kingstone 2000).

Klein proposed that IOR assists visual search by acting as a 'foraging facilitator' to avoid refixation of previously attended locations (Klein 1988). Klein and MacInnes (1999) developed this idea further and demonstrated an IOR effect during eye scanning. Subjects were slower to respond to visual probes presented in locations at or near the previous fixation than to those in control locations. However, when eye scans during search are analysed, there is evidence that in fact the eyes do quite frequently make an *immediate* refixation to the location just previously visited whereas refixations with more than one intervening fixation are much rarer. This pattern may be seen in the data of Motter and Belky (1998b, Figure 7) and was demonstrated clearly by Peterson *et al.* (2001). A possible interpretation is that IOR only comes into play after an item is fully processed and immediate refixations occur to complete processing of an item that has not been fully processed (as indeed 'common sense' might suggest). The idea that visual *processing* might itself exert an initial excitatory and subsequent inhibitory influence on the oculomotor salience map was proposed in a perceptive commentary by Crundall and Underwood (1999). It appears worth exploring further.

Leaving aside the issue of immediate refixations, the avoidance of refixations on already scanned items potentially allows an estimate of the size of the memory store for search. The key measure here has been the extent of refixation of distractors. The logic is that when no refixation occurs then the items have been remembered.

A number of groups have modelled search scan data to obtain an estimate of the capacity (Gilchrist and Harvey 2000; Peterson *et al.*, 2001). However the interpretation of refixations as a failure of memory is far from straightforward (Gilchrist and Harvey 2000, *in press*). What is clear from these results is that locations are not simply being selected at random as predicted by a model in which there is no memory. McCauley *et al.* (2003) argue for a memory buffer with a search history comprising 3-4 items.

A similar conclusion had been reached less directly in earlier work (Engel 1977; Ellis and Stark, 1986). These studies showed in some search tasks that following the first few fixations on a display, subsequent fixations can be modelled by a process of random sampling with replacement. Figure 4, derived from Engel (1977), plots data from a search task for a small circular disk in a field of slightly larger distractor disks. The data points show how the probability of finding the target increases with search time. The thick lines show two models for sampling. The 'no replace' model scans regions until the target is found but never returns to a region previously visited. The 'replace' model chooses new regions on a purely random basis and revisits can occur. For the first second of search, the systematic model fits the data best but following this, search appears to become random.

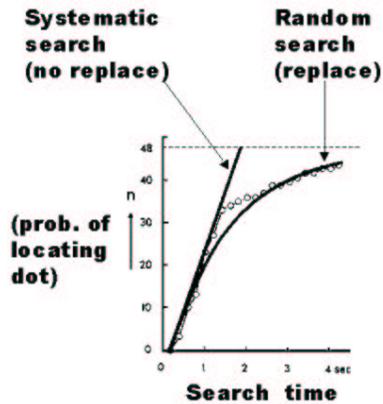


Figure 4. Plot showing data from a search experiment (Engel 1977). The task involved search for a small disk target in a large array of slightly larger, but otherwise identical, distractors. The observer viewed 48 displays, each with a different target location (chosen from an 8x6 grid to distribute the locations evenly across the display area). The displays were each presented for four seconds and the time to locate the target noted. The data points (from one observer) show the number of displays in which the target was located plotted cumulatively against the search time. The solid lines represent two search models as described in the text.

Long term and strategic mechanisms for distributing fixations

Shore and Klein (2000) discuss two more long term forms of memory that might be interpreted as influencing the salience weighting of particular search targets. First, the phenomenon of ‘priming of pop-out’ has been demonstrated (Maljkovic and Nakayama 1994, 1996, 2000). This term describes the finding that the altered salience weightings of the biased competition process are found to show long-term persistence even when the higher level voluntary processes have switched to a new search target. Saccades to targets where popout priming has occurred subsequently have shorter latency and improved accuracy (McPeck *et al.*, 1999). This serves as a timely reminder that the settings of the biased competition network are affected not only by voluntary processes, but also through more automatic implicit mechanisms that are subject to learning.

The final learning mechanism considered by Shore and Klein is more long term perceptual learning of contingencies. Visual search has been widely studied by presenting subjects with multiple trials in which similar displays are presented, with the location of the target and distractors changing from trial to trial. If, under these conditions, the target is more likely to occur in a particular location, this contingency is learned to permit faster search (Miller 1988). A somewhat more complex form of learning has been demonstrated by Chun (Chun and Jiang 1998, Chun 2000). If, during the course of a search experiment, certain specific displays are repeated, faster search times occur for these displays. This speeding can occur whether or not subjects show any awareness of the repetition. The process has been termed *contextual cueing* and has been shown to depend upon the local configuration of distractors around the target element (Olson and Chun 2002). Peterson and Kramer (2001) drew the following conclusions from a study in which eye fixations were recorded in a contextual cueing paradigm. First, cueing occurs sufficiently rapidly so that the very first saccade when the repeated display is viewed is slightly more likely

to reach the search target. Initial saccades were directed to the target more often in repeated displays (11.3%) than in control trials with novel displays (7.1%). An increased probability was also found over the subsequent 4-5 fixations, suggesting that the process detecting the local configuration can occur at any time during the scanning sequence. Second, when the cueing effect was operative, saccades were directed precisely. There was no tendency for neighbouring distractors to receive increased numbers of fixations as would have been expected if the cueing gave low resolution spatial information.

Shore and Klein consider that the processes just discussed reflect implicit memory, describing this as “the countless automatic and uneventful aspects of our everyday lives, which are affected by previous experience without our necessarily linking the present episode to the past learning environment” (Shore and Klein 2000, p 61). Implicit memory processes are generally considered to operate automatically and below the level of conscious awareness, contrasting with the more explicit processes involved in conscious cognition. Shore and Klein note that more explicit memory is involved for such things as memory of the nature of the search target and the response that is required. More explicit strategies can also be used to distribute fixations over the whole of the search display. A number of authors have suggested that there may be a bias in the direction of saccades in search and that these biases reflect a systematic process rather than the action of a random process (L G Williams 1966; Hooge and Erkelens 1996; Gilchrist and Harvey *in press*). This systematic behaviour coincides with the intuition that when search becomes very difficult we tend to start in one place and work systematically through the display. The deployment of such a systematic process may have an additional consequence, namely that it reduces the need to remember each and every location visited. Instead subjects simply have to remember the order in which they searched the display (Gilchrist and Harvey *in press*). When systematic scanning of this type occurs this has serious implication for the use of refixations as a measure for memory capacity as discussed above. Participants may fail to refixate items not because they remember that location as visited but instead because they are following some fixed route through the display (see Gilchrist and Harvey *in press*, for a fuller discussion of these issues).

We have thus identified a number of ways that memory process can provide additional guidance to the saccadic selection process. Some of these, for example the inhibition of return mechanism, appear appropriate for the task of preventing the capture by local loops. Others, particularly those involving directional strategies, may contribute to local loop avoidance but potentially also serve the purpose of distributing fixations across different regions of an extended display. The more high level strategies may require more conscious involvement to implement.

Summary

In this chapter we have presented an account of eye guidance during visual search. We have argued that the eyes are guided from an oculomotor salience map, shaped by the process of biased competition to form a representation in which similarity to the target controls salience. In addition to this basic mechanism, saccades can be planned ahead in a pipelined manner and further mechanisms such as inhibition of return prevent return to items that have been scanned in the very recent past.

(8476 words)

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