



Visual search in depth

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Abstract

The accuracy of saccade localisation during visual search was examined for a search target defined by the single features of orientation or depth or by a conjunction of the two features. Subjects were required to move their eyes to the target which appeared in one of eight possible locations, arranged circularly around fixation, with non-targets filling the remaining seven positions. Search for a target defined by a single feature resulted in approximately 70% correct first saccades in both cases, while search for the conjunction target resulted in only 40% correct first saccades. Furthermore, averaged latency for conjunction search was longer than for simple search. Nevertheless, some subjects showed a remarkably good ability to locate a conjunction target with a single saccade of short latency. An analysis of first saccades in terms of their speed and accuracy indicates that the target selection is not preceded by a covert scanning of the display but rather is a result of parallel processing of the visual information provided. We also relate our study to the study of conjunction search reported by Nakayama and Siverman [Nakayama, K., & Silverman, G.H. (1986). Serial and parallel processing of visual feature conjunctions. *Nature*, 320, 264–265.]. © 2001 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Searching for an item in the world is one of the most common tasks we perform. Trying to spot a friend in a crowd or discover where you put down the keys you had just a minute ago are common phenomena. Search involves isolating the target from the surrounding distracting visual information. Work using visual search tasks has increasingly been employed in an attempt to uncover the nature of early visual processing (Wolfe, 1994; Palmer, Verghese, & Pavel, 2000). This typically involves employing controlled stimuli which are simplified in comparison to everyday visual search problems, e.g. find a red disk in an array of green disks.

1.1. Visual search: efficient conjunction search

Searching for items which differ from surrounding distractors on the basis of a single feature is very efficient. Regardless of the number of distractors present, the item

becomes available almost immediately and appears to ‘pop-out’ of the display. This pop-out of the item is generally taken as evidence that: (a) processing of the visual field takes place via parallel mechanisms; (b) the feature which defines the target is represented preattentively (i.e. the feature is processed automatically without attentional resources); and (c) the representation of such preattentive features of the visual world is an important goal of early visual processing.

In contrast to this many search situations show longer search times which increase with the number of distractors present in the display. This suggests some form of display scanning. The nature of this scanning has been a matter of considerable debate. One well known tradition emphasises covert attentional scanning, the classic example of which is of a ‘mental spotlight’ which randomly moves around the items (Treisman & Gormican, 1988; Wolfe, 1994).

Initially it was reported that a target in an array of distractors which was defined by a conjunction of two features results in a performance which reflects such serial search (Treisman & Gelade, 1980). According to the Feature Integration Theory originally outlined by Treisman and Gelade (1980) this was due to necessity

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of binding the two features together which, Treisman and Gelade argued, required attentional resources that are covertly applied to the display to scan each item sequentially.

However, a number of results have pointed to a more complicated picture of conjunction search. It has been shown that search for a target defined by some conjunctions of two features can result in search performance which is equally fast regardless of the number of distractors which accompanied its presentation. This suggests, given the theoretical constructs of serial and parallel processing signatures, that some conjunctions can be processed in parallel across the visual display (Egeth, Virzi, & Garbart, 1984; Nakayama & Silverman, 1986; McLeod, Driver, & Crisp, 1988; Driver, McLeod, & Dienes, 1992; Driver & McLeod, 1992; Kaptein, Theeuwes, & Van der Heijden, 1995; McElree & Carrasco, 1999; Eckstein, Thomas, Palmer, & Shimozaki, 2000). Of particular interest for the present paper is use of stereo depth as a target in simple feature and conjunction searches. Nakayama and Silverman (1986) examined search efficiency in instances when the target was defined by a single feature or a conjunction of those features. The single feature which defined the target could be colour or motion. In both these cases they found that reaction times did not increase with increasing distractor number. Furthermore, Nakayama and Silverman (1986) examined search behaviour when the target was defined by conjunctions involving colour, motion and stereo depth. In particular the target conjunctions they examined were colour and motion; colour and stereo depth; or motion and stereo depth. They found that when target was defined by colour and motion then reaction time increased with increasing distractor number. However, when the target was defined by a conjunction of either colour or motion with stereo depth then reaction time showed no increase as the number of distractors increased. This suggests that a conjunction of a simple feature with stereo depth is processed very efficiently.

1.2. *Eye movements as a measure*

Visual search is naturally an active process of target localisation. Although in some situations eye movements are not necessary to perform an efficient visual search (Klein & Farrell, 1989) it can be argued that scanning with the eyes provides the most natural strategy to effectively search the stimulus array. Until recently, most studies using visual search tasks used reaction time as a measure (for exceptions see Williams, 1966, 1967; Gould & Dill, 1969; Viviani & Swensson, 1982). However, a number of reports have now appeared which have examined eye movement

patterns during visual search (Binello, Mannan, & Ruddock, 1995; Findlay, 1995, 1997; Motter & Belky, 1998a,b; Williams, Reingold, Moscovitch, & Behrmann, 1997; Zelinsky, 1996; Zelinsky & Sheinberg, 1997; Bertera & Rayner, 2000). Eye movement patterns have been examined for targets defined by single features and conjunctions of two features. It has been found that targets defined by a single feature are frequently indicated by a single saccade (Findlay, 1995, 1997; Gilchrist, Heywood, & Findlay, 1999), but when defined by a conjunction of features the percentage of correct first saccades decreases (Findlay, 1997; Scialfa & Joffe, 1998). However it is remarkable that the number of correct first saccades to a conjunction target is still well above chance. This indicates that the information which defines the target is available to guide the first eye movement after very short periods of time. This complements other analyses (Pashler, 1987; Eckstein, 1998; McElree & Carrasco, 1999; Eckstein et al., 2000) suggesting that more parallel processing of feature conjunction information can occur than postulated by the original version of feature integration theory. Findlay and Gilchrist (1998, 2001) have argued that, when free eye scanning is possible, no additional covert attentional scanning takes place.

1.3. *Current study*

The experiments in this paper use eye movements to indicate search efficiency. The search targets are defined by orientation, known to provide an efficient search feature, or disparity defined depth, also known to result in very efficient search rates, or by their conjunction. Subjects were instructed to indicate the location of a target, present on every trial, by moving the eyes to the target. Search accuracy was assessed by categorising the landing position of the first saccadic movement of the eyes in terms of its angular precision. The latency of response is also reported and refers to the difference between the onset of the visual display and the initiation of the first saccade. If target information can be derived preattentively then subjects should be able to accurately direct their first saccade towards it. Furthermore, the use of eye movements as a measure allows the time course underlying search behaviour to be revealed. (Findlay & Gilchrist, 1997). We were particularly interested in the depth/orientation conjunction situation, since the results of Nakayama and Silverman (1986) suggest that efficient parallel search might occur in that situation. The simpler case of disparity defined target search is also of interest since, to our knowledge, no studies have examined eye movement patterns in a search situation with disparity defined targets.

2. General method

2.1. Subjects

Five subjects, one female and four males with an age range of 27–44 took part in the experiment. All had normal vision and a range of experience in eye movement experiments. Specifically, two of the subjects (VB and BK) had extensive eye tracking experience, i.e. over 7 years. Subjects JH and JP have had limited previous eye tracking experience over the period of one year. Subject AF was completely new to eye tracking. All subjects had good stereo acuity (at least 40 s arc) as measured by the Titmus circle stereo test.

2.2. Displays

All stimuli were generated using purpose written software for a VSG graphics card (Cambridge Research Ltd., UK) and presented on a Vision Research Graphics Inc. 21" monochrome graphics monitor, model B, running at refresh rate of 200Hz with a luminance of 23.4 cd/m². The displays consisted of a thin (0.43° thickness) band of random noise dots arranged around the edge of the screen. Within this a ring of eight equally spaced elements was placed, the ring having a radius of 4.23°. The targets and distractors were rectangles composed of random noise dots.

Ferro-electric shutter goggles (FE-1 Goggles, Cambridge Research Ltd., UK) were employed to generate stereoscopic depth. Use of both the VSG graphics card and the FE-1 goggles automatically allows the frame rate of the monitor to be in synchronisation, thus ensuring that one eye receives the information presented on one frame while the other eye receives the information presented on the next. The shutter goggles employed had the following specifications: the switching time is 100 µs with a 0%–90% switching time of typically 35 µs; the open:close contrast ratio is typically 1000:1; and the luminance of the stimulus through the open shutter glass was 3.3 cd/m². The Vision Research Graphics monitor employed in the experiments had a P46 phosphor, which has an extremely fast decay rate (decay to 10% in 1 µs). It should be noted that the use of the goggles effectively reduced the monitor frame rate to 100 Hz. The specifications of both of these pieces of hardware serve to substantially reduce the amount of any breakthrough information presented to the unintended eye. The experiments were carried out in a dimly lit room and a check for 'ghost' images revealed none visible.

2.3. Procedure

In an attempt to reduce anticipatory saccades each trial commenced with a central fixation box presented

for a random period of time between 250 ms and 750 ms. A display of eight elements was then shown for 2000 ms. Subjects were told the exact nature of the experiment and were then shown examples of trials until they were comfortable. This was followed by the experiment proper in which 80 trials were carried out in each condition. This generated ten trials per location. The subject was required to make appropriate eye movements to the target as quickly and as accurately as possible.

2.4. Eye movement recording and analysis

Two dimensional recordings of both the right and left eye were made using two Fourward Technologies Dual Purkinje Image Eyetrackers (Crane & Steele, 1985). Head movements were minimised using a bite bar and two forehead rests. Eye position was sampled at 200 Hz via a CIO-DAS802 digital to analogue converter (Adept Scientific Plc., UK) which was housed in a separate computer which recorded the eye position using purpose written software. Each block of trials was preceded by a calibration procedure in which the subject was required to saccade to nine small boxes which were arranged in a centrally presented square lattice at a horizontal and vertical element to element separation of 4.23°.

The eye movement data were analysed off line by a semi-automatic procedure which detected the first incidence of two successive samples exceeding a velocity of 25°/s. The record from each trial was inspected visually and, if necessary, a manual override could be applied (this was sometimes necessary for pure vertical saccades as the version of the in-house software available at the time of the experiments only tested for saccades on the horizontal record.). Saccades with a latency of less than 100 ms were discarded (this comprised of: one trial for orientation search; two trials for the depth search; and no trials for the conjunction search) as were those trials in which the subjects initial eye position was > 1° from the central fixation box (25 trials discarded for orientation search; 14 discarded for depth search; and 39 trials discarded for the conjunction search). The saccade landing position was identified as first eye position after the velocity of the eye had dropped to less than 5°/s for five successive samples. This avoids the artefact that results from lens displacement (Deubel & Bridgeman, 1995) and produced three measures for each saccade: saccade direction, saccade latency and saccade amplitude. Saccade direction measured the direction from central fixation to landing position. Saccade latency was the time from display onset to the initiation of the saccadic movement. Saccade amplitude was the distance between central fixation and landing position. The left and right eye signals were also used to obtain a measure of eye vergence. Detailed discussion of ver-

gence changes in these and other experiments will be reported elsewhere.

2.5. Displays

Fig. 1 shows the display configurations and gives further details.

2.6. Experiment 1

The subjects were required to move their eyes to the vertical rectangle. It could appear in one of the eight locations, the remaining seven of which were taken up by horizontal rectangles.

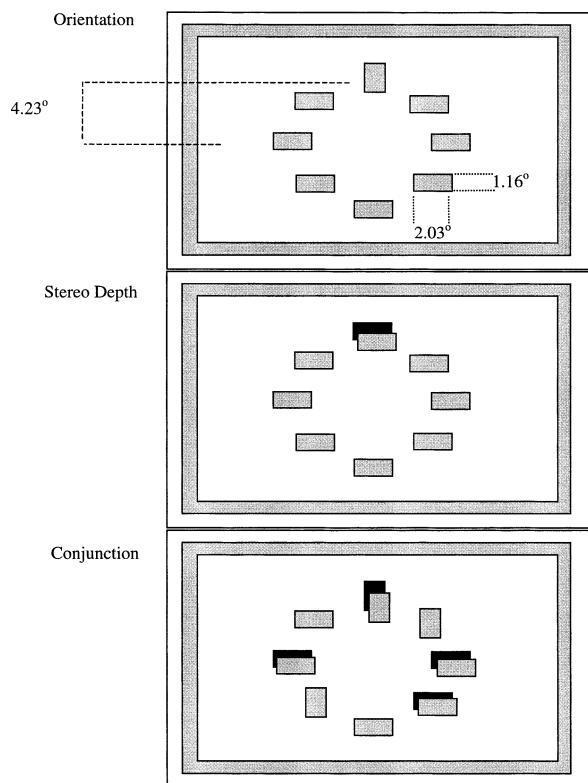


Fig. 1. This shows a schematic representation of the displays employed in each of the three experiments reported here. The top screen shows an example of the search display for a target defined by an orientation difference. The target in all three displays is placed at the 12 o'clock position although in the actual experiment it could appear in any of the eight possible locations. The distance of the centre of each rectangle to the centre of the screen is shown (4.23°) and the size of each rectangle is also included ($2.03^\circ \times 1.16^\circ$). The middle screen shows the target defined by depth. Depth here is represented by an offset rectangle with a black portion above and to the side of those rectangles which appeared in front. The bottom screen shows the target defined by a conjunction of both orientation and depth: a vertical rectangle in front of the display plane.

2.7. Experiment 2

The subjects were required to move their eyes to the horizontal rectangle which appeared in front of the fixation plane. Seven distracting horizontal rectangles were also presented which were all shown on the fixation plane. The target could appear in one of the eight locations, the remaining seven of which were taken up by fixation plane rectangles. The target was shown at a stimulus disparity of 35 arc min.

2.8. Experiment 3

The subjects were required to move their eyes to the vertical rectangle which appeared in front of the fixation plane. The target could appear in one of the eight locations, the remaining seven of which were taken up by horizontal and vertical rectangles with the restriction that two vertical and two horizontal distractors appeared on the fixation plane while only horizontal distractors appeared at the same depth plane as the target. The target was shown at a stimulus disparity of 35 arc min, as in Experiment 2.

3. Results

3.1. Saccade direction

Fig. 2 shows the saccade landing distributions for each subject. The results from all eight locations are normalised to the 12 o'clock target location. Subjects indicated that they found the feature search tasks straightforward but Fig. 2 shows that not all first saccades were directed to the target. It can be seen that the accuracy of target localisation for the search for a target defined by orientation is quite high. Slightly more scatter is evident when the target is defined by a depth difference but accuracy is still quite high (it should be noted that fewer data points were collected for subject BK in this experiment due to problems with eye tracking, hence fewer data points are plotted). Finally the search for a target defined by the conjunction of orientation and depth shows a sharp reduction in accuracy and a great deal more scatter. In order to quantify these aspects of the landing distributions, saccades were categorised as *on-target* if the landing position of the saccade showed its direction to be within 15° of the target direction; *inaccurate*, when the saccade direction lay between 15° and 30° of the target centre, i.e. falling in between the target and the distractor; *next* when saccade direction was within 15° of the distractor adjacent to the target; all other saccades were labelled as *other*. This measurement ignores saccade amplitude but as can be seen from Fig. 2 amplitudes were generally accurate. Fig. 3 shows the distribution of first saccade landing positions by sector and subject.

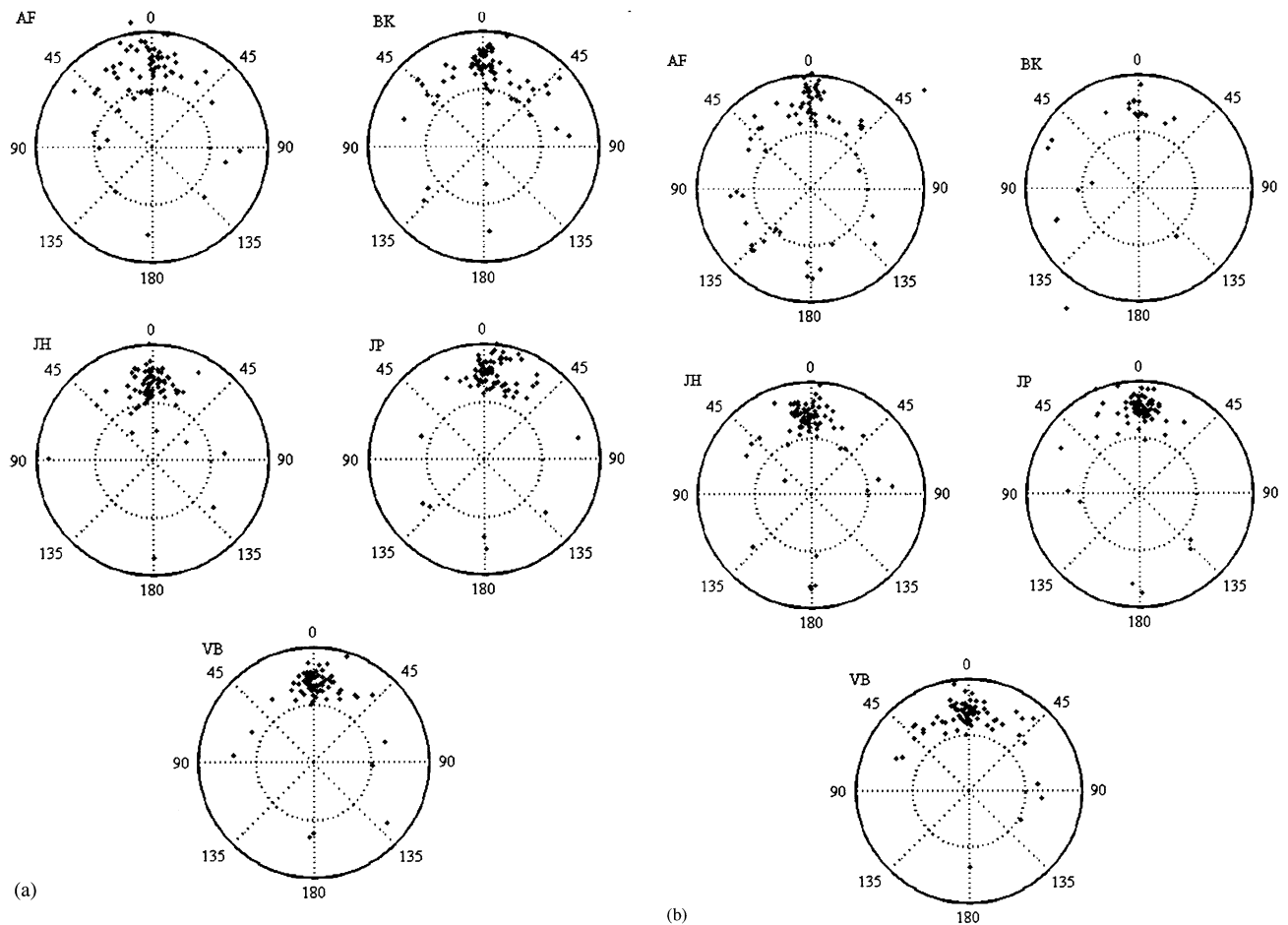


Fig. 2. (a) Shows the saccade landing distributions by subject for a target defined by orientation. (b) Shows the saccade landing distributions by subject for a target defined by stereo depth. (c) Shows the saccade landing distributions by subject for a target defined by the conjunction of orientation and depth.

The saccade landing positions elicited by the orientation target are often accurately directed (69.6%), with a moderate amount of variation among subjects performance (58.1%–78.8%). The saccade landing positions elicited by the depth target show a similar mean accuracy (64.5%) but a slightly greater inter-subject variability (49.3%–79.7%). In the case of search for the conjunction of orientation and depth performance is worse for all subjects (mean 37.7%) and more variable across subjects (22.6%–56.4%).

3.2. Latencies

Fig. 4 shows the latencies of the first saccade elicited by the eight ring displays classified by landing position and identity of search target. In a two-way ANOVA with search target (orientation, depth and orientation and depth) and landing position (15°, 15–30, next and other as levels) a main effect of search target ($F(1,6) = 8.8$; $P < 0.05$) and landing position ($F(1,6) = 10.19$; $P < 0.05$) was found. The interaction between search target and landing position was found to be just not significant ($F(1,6) = 4.51$; $P = 0.078$). The main effect of

search target indicates that latencies were generally longer for the conjunction search, followed by depth and then orientation search. The landing position main effect indicates that latencies were generally longest for correctly directed saccades and quickest for saccades directed to the neighbouring target. Thus there does appear to a general speed accuracy trade off, where correct saccades are longer than those which are incorrect (outside 15° of the target). However, on closer examination this is not the case for all subjects. This can be seen clearly in Fig. 5 showing the saccade position by latency plots for individual subjects for each search task. The subjects with shorter latencies do not show the trade-off.

4. Discussion

The results show that a simple search for a predefined orientation difference or a predefined depth difference elicits about 70% correct first saccades. The relatively low efficiency of search for orientation tallies well with the performance reported by Gilchrist et al.

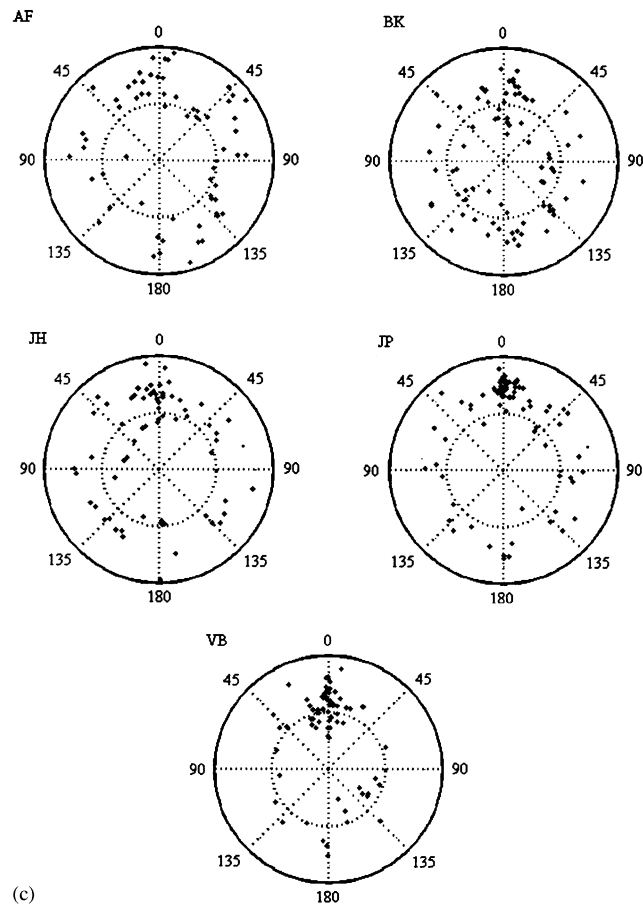


Fig. 2. (Continued)

(1999) who, using Gabor patches, also found approximately 70% correct first saccades to a predefined orientation difference.

The results of a search for a target defined by an orientation and depth conjunction show that first saccades are less likely to be correctly directed toward the target than for either simple search. Only 37.7% first saccades were correctly directed. It has been suggested that the conjunction of two highly discriminable features can be searched for in parallel (Nakayama & Silverman, 1986; Treisman & Sato, 1990). Our data provide only limited support for this suggestion. Rather the results show that subjects find this task more difficult and make more saccades to successfully identify the location of the target than used in the search for the singletons.

Of particular relevance here are the results of Nakayama and Silverman (1986) who reported that search for a conjunction of a single feature (colour or motion) with depth was efficient. Based on the finding that reaction times in the conjunction search conditions did not increase with increasing number of distractors,

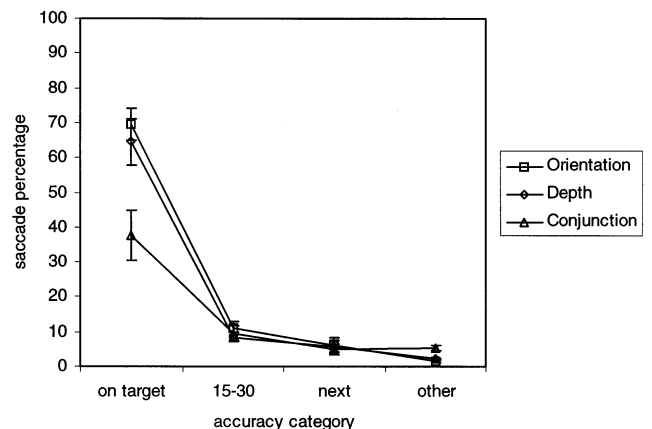


Fig. 3. Percentage of trials on which saccades landed in 30° specified sectors of within 15° of target, 15°–30° of target on each side, and within 15° of the neighbouring patches (averaged over each side). The accuracy sector 'Other' was 270° in angular extent. Therefore, in order to normalise the areas under consideration from all four accuracy categories, the percentage of saccades landing in the 'other' sector has been divided by the number of 30° portions it contains (i.e. 9). Error bars are standard errors.

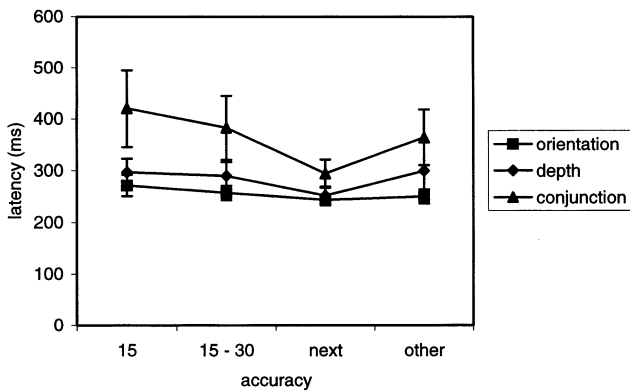


Fig. 4. Mean latencies of first saccades by target type and saccade direction. Error bars are standard errors.

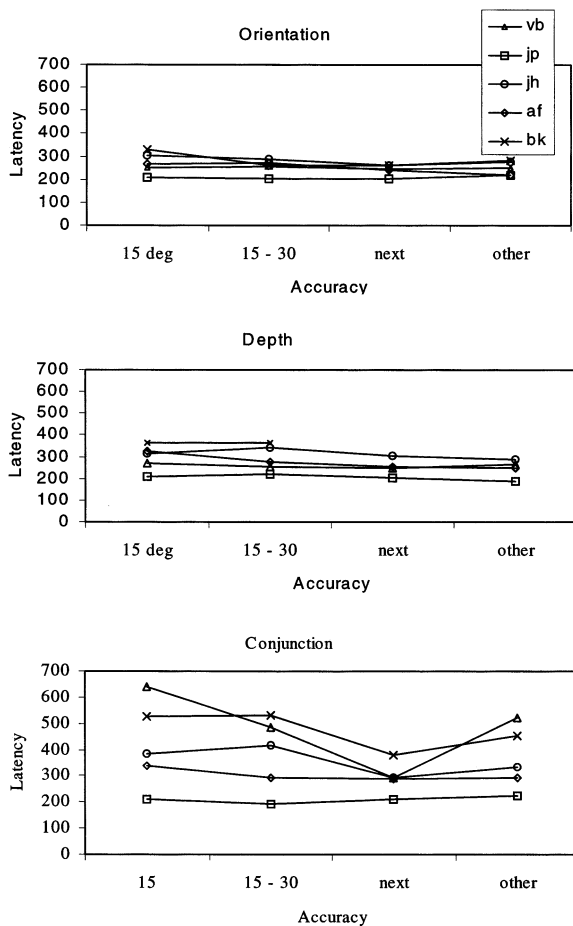


Fig. 5. This shows the individual latency by accuracy plots for each subject. Data from only four subjects are shown in the depth search plot in the accuracy categories of 'next' and 'other', because tracker loss with subject BK did not allow adequately reliable measures.

they proposed that conjunctions of motion or colour with depth were processed in parallel. Nevertheless, the need for caution in interpreting search functions is well known (Eckstein, 1998; Townsend, 1971). The absolute reaction time for stereo depth conjunction searches reported by Nakayama & Silverman (1986) were be-

tween 1 and 2 s, considerably greater than the search time for either dimension alone. This length of time would allow a number of saccades to be made before the presence of the target was identified.¹ When considered in this light it is remarkable how many first saccades were correctly directed toward the conjunction target with a much shorter average latency (420 ms). Nakayama and Silverman (1986) refer to parallel processing of conjunctions involving stereo, and this interpretation has often been made of their data. However, they also note that the segregation of different depth planes contributed to search, which might be seen as a manifestation of a surface-based approach to perception (cf. Nakayama, He, & Shimojo 1995). The long overall times involved in their search task might therefore represent the times for depth plane segregation, facilitated by the use of displays with relatively many elements (15–25). We propose that the sparser displays that we used led to a different, more rapid but less efficient, form of parallel processing.

When the latencies of the correct first saccades are examined it can be seen that orientation and depth are located fairly rapidly between 270 and 300 ms. However, with the exception of subject JP, the conjunction of the two elicit longer latencies suggesting that more processing of the stimuli is required prior to saccade onset and that the observers adopted a strategy of delaying their initial saccades accordingly. Thus the search for a target defined by conjunction of depth and orientation information is less efficient than the search for a target defined by either feature alone. This may provide some support for a covert attentional scanning mechanism operating during the longer fixation before the first saccade.

In order to successfully direct a saccade on to a target two possible explanations can be offered which lie at opposite extremes. A rapid covert scanning may occur which examines a number of items in the display individually, eventually finds the target and selects it for

¹ We set up a depth–orientation conjunction search task using displays as similar as possible to those of the Nakayama and Silverman (1986). Using a single subject, we were able to replicate their findings that search times to make a present/absent decision were long (> 1 s) but independent of distractor number (RTs of 1298, 1150 and 1162 ms for set sizes of 12, 18 and 24, respectively). It should be noted that the subject was given no instructions with regard to eye movements (e.g. the subject was not told to localise the target with an eye movement) but their eye movement records were taken during the experiment. The records showed that there were on average 2–3 saccades per trial with 2 saccades made in response to set sizes of 12 and 18 and 3 saccades made on average for a set size of 24. The average first saccade latency was 271, 281 and 279 ms for set sizes of 12, 18 and 24, respectively. These results back up the suggestion that a number of saccades are made prior to the button response. Thus a target defined by a conjunction of stereo depth and orientation in configurations similar to those of Nakayama and Silverman (1986) does not produce a 'pop-out' phenomenon in terms of the eyes being directed straight to the target.

the saccade destination; alternatively parallel processing of the display may take place and the saccade destination is determined by the 'peak' in a salience map. It would be expected that if covert scanning did occur for the conjunction of two features, this would increase the saccade latencies when compared to search for these features in isolation. This is indeed what was found. Taking a proportion of the latency in the conjunction case (420 ms) to be concerned with retinal and oculomotor processes (estimated to be about 70 ms) then a serial process of covert scanning would estimate about 43 ms spent on each item. This estimate can be compared to estimates of search efficiency derived from standard visual search paradigms where the increase in reaction time with display size is taken to reflect a covert scanning operation, the slope of that function gives an estimate of search rate. A standard example estimate of 28.7 ms is derived from the data of Treisman and Gelade (1980) (experiment 1) in a colour conjunction search. Thus, the 43 ms derived from the present data could easily encompass a serial covert scanning mechanism.

If such covert scanning occurred during the first fixation, an additional explanation is required for why erroneous first saccades are made. It would appear necessary to suggest that some 'deadline' process was operating whereby an eye movement was generated after a certain time if covert attention had not located the target by that deadline. Under that assumption, it would be expected that incorrect saccades would show longer latencies than correct ones (Motter & Belky, 1998b). Fig. 2 shows no evidence for this. Subjects VB and BK show a tendency towards a speed accuracy trade-off with less accurate saccades showing shorter latencies. Data from the other subjects shows little relationship between latency and accuracy. Subject JP behaves very similarly to the subjects in the colour shape conjunction search reported by Findlay (1997), with very comparable latencies in single feature and conjunction conditions.

The consideration of latency and landing position of the first saccade thus suggests that covert scanning does not take place prior to saccade onset. Rather than covert scanning prior to the target selection it can be suggested that eye movements form an integral part of search scanning behaviour (e.g. Findlay, 1997; Findlay & Gilchrist, 1998) and it is via parallel processing of visual information that eye movements are generated. There are a number of models of visual search behaviour which incorporate parallel processing (e.g. Wolfe, 1994). Such models often involve the generation of feature maps via the parallel processing of visual information, from these maps a master activation map is generated, the peak of which codes the location of the target. For example Wolfe

and Gancarz (1996) presented an extension of his Guided Search 2.0 Model (Wolfe, 1994) model to include saccade generation. It involves the generation of feature maps, which are selectively weighted via top down selective processes. This provides the input to a spatiotopic activation map that codes location salience in the form of peaks and troughs. Such a map can be employed to generate targets for eye movements in which the peak of such an activation map is taken as being the eye movement goal. Findlay (1997) has suggested that search for the location of the highest peak in the activation map, which is a search task in itself, can be simplified by use of coarse spatial coding which has been found to be a general feature of saccade generation (see Findlay & Walker, 1999). Neurophysiological evidence consistent with coding in the form of a spatiotopic salience map has been reported at a number of locations in the visual-oculomotor pathways (superior colliculus; Munoz & Wurtz, 1995a,b; Wurtz, 1996; frontal eye fields; Schall & Hanes, 1993, Schall & Thompson, 1999; parietal cortex, Gottlieb, Kusunoki, & Goldberg, 1998)

Cast within this theoretical framework the increase in first saccade latency found in the search for depth and orientation conjunction may be a result of an increase in time taken to generate an activation map via separate feature maps for orientation and depth. This may be a result of the increase in competition which would occur in the network or it may provide some support for using one feature map to constrain the search in the other (Treisman & Sato, 1990).

5. Conclusions

The pattern of eye movements were examined in a search task for target predefined by a specified single orientation or depth or a target defined by the conjunction of both orientation and depth. Search for either single feature target was found to be quite efficient (approximately 70% correct first saccades) whereas search for the conjunction target was found to be less efficient (approximately 40% correct first saccades). Despite the less efficient search performance for the conjunction target the saccade latencies of these first saccades were far less than the reaction times recorded for a similar conjunctions of stereo depth with single features suggesting that conjunction information is available for eye movement generation after a very short period of perceptual processing. It was argued that the data could be accounted for a parallel processing account of search behaviour involving the generation of an activation map for eye movement localisation.

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