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Peripheral vision and oculomotor control during visual search

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Abstract

The present study concerns the dynamics of multiple fixation search. We tried to gain insight into: (1) how the peripheral and foveal stimulus affect fixation duration; and (2) how fixation duration affects the peripheral target selection for saccades. We replicated the non-corroborating results of Luria and Strauss (1975) ('Eye movements during search for coded and uncoded targets', *Perception and Psychophysics 17*, 303–308) (saccades were selective), and Zelinsky (1996) (Using eye movements to assess the selectivity of search movements. *Vision research 36*(14), 2177–2187) (saccades were not selective), by manipulating the critical features for peripheral selection and discrimination separately. We found search to be more selective and efficient when the selection task was easy or when fixations were long-lasting. Remarkably, subjects did not increase their fixation durations when the peripheral selection task was more difficult. Only the discrimination task affected the fixation duration. This implies that the time available for peripheral target selection is determined mainly by the discrimination task. The results of the present experiment suggest that, besides the difficulty of the peripheral selection task, fixation duration is an important factor determining the selection of potential targets for eye movements. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Visual search; Guided search; Peripheral vision; Saccades; Control of fixation duration

1. Introduction

If a stimulus exceeds the size of the area that can be inspected during one fixation, a subject generally has to make saccadic eye movements to find a target. During multiple-fixation search, these saccadic eye movements bring parts of the stimulus into the central part (fovea, parafovea) of the retina. If foveated, stimulus elements can be analysed in detail. Specific stimulus elements may be considered for detailed inspection. Peripheral vision plays an important role in the selection of these stimulus elements. Evidence for the role of peripheral vision in multiple-fixation search comes from Green and Anderson (1956) and Smith (1962). They used stimuli containing stimulus elements of different colours. Shorter search times were found if the target colour was specified. In a similar task Williams (1966) measured eye movements. In different conditions, subjects were instructed to find a target that bore a specific number and was specified by colour, size or shape or a combination of colour, size and shape (coded conditions). In one condition subjects were given only the numbers that were printed on the targets (uncoded condition). Williams (1966) reported many fixations on stimulus elements of a specific colour if this colour was specified as the target colour. The time needed to find the target decreased from 22.8 s in the uncoded condition to 7.6 s in the colour coded condition. Colour coding appeared to be an effective method for increasing search performance. Size and shape coding were less effective than colour coding. Luria and Strauss (1975) found similar results in a rather similarly coded search task. If the colour of the target was specified, subjects made many fixations at stimulus elements that shared the target colour. Luria and Strauss (1975) found that size and shape were also less effective for coding targets. Recently, Zelinsky (1996) found different results. Subjects had to look for a green horizontal or a red vertical bar in a stimulus that consisted of five or 17 elements. Zelinsky (1996) reported that non-targets that shared a feature with the target (vertical green and horizontal red bars) were almost as frequently fixated as non-targets that did not share any feature with the target (diagonally oriented blue and yellow bars). Pe-

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ripheral vision did not help the subject to select target-like stimulus elements. Why is coding by shape and size not as effective as coding by colour and what is the explanation for the fact that Zelinsky's results did not corroborate the results of the other studies?

The answer may be related to the control of fixation duration. During fixation information has to be extracted from the foveal and peripheral fields. Depending on the stimulus layout and physical properties of the stimulus elements, these two processes take time. For example, detection of a red target among green distractors (a pop-out task (Wolfe, 1992)) takes less time than detection of a circle among Cs (a serial search task (Treisman & Gormican, 1988)). A nice example of the time dependency of the peripheral analysis is found in the study of Geisler and Chou (1995). In a tachistoscopic experiment (no eye movements) they found that the size of the inspected area increased with presentation time. This means that detection thresholds decrease with presentation time.

Fixation duration increases with decreasing discriminability of the target (Gould, 1967, 1973; Jacobs, 1986; Jacobs & O'Regan, 1987; Hooge & Erkelens, 1996, 1998). But does fixation duration increase with increasing difficulty of the peripheral selection task? There is some evidence that peripheral vision does not play an important role in the control of fixation duration. Henderson and Ferreira (1993), for instance, found in a reading task that the difficulty of parafoveally presented words did not have any effect on fixation duration. If the timing of saccades is mainly determined by the difficulty of the discrimination task, fixation duration may restrict the time available for peripheral inspection. Additional evidence that a peripheral selection task does not determine the duration of a fixation was found by Findley (1995). He used stimuli that consisted of seven green and one red circle placed in a circular arrangement. Subjects were asked to make an eye movement to the red target. In 25% of the trials, the stimulus contained two red targets instead of one. The two red targets were adjacent to each other or separated by one green distracter. In the latter case subjects often made eye movements to intermediate positions after short latencies (185 instead of 300 ms for correctly directed eye movements).

The main question of the present study concerned the relationship between peripheral analysis and fixation duration during multiple fixation search. To investigate this relationship we engaged three subjects in a search task. We tried to gain insight into: (1) how the peripheral stimulus affected fixation duration; and (2) how fixation duration affected peripheral analysis. Our hypothesis was that fixation duration mainly depends on the critical feature for the discrimination. This critical feature may cause short fixation durations and therefore restrict the available time for peripheral analysis. On the one hand, this hypothetical eye movement strategy can be an explanation for the contradictory results of Zelinsky (1996) and Luria and Strauss (1975). On the other hand it can explain why colour coding was much more effective than shape and size coding.

2. Methods

2.1. Subjects

Three male subjects (IH was the first author, CE was the second author) participated in the experiments (age 29–45 years). None of them showed any visual or oculomotor pathologies other than refraction anomalies. The subjects had normal or corrected to normal vision. The three subjects were experienced in wearing scleral coils for eye movement recording. Two of the subjects had no experience in doing this task. Subject IH had some experience because he participated in the pilot experiments. Subject CG was naive concerning the goals of this experiment.

2.2. Apparatus

Subjects sat in front of a large screen at a distance of 1.50 m in a completely darkened room. To prevent head movements, the subject's head was kept steady by a chin and a forehead rest. Stimuli were generated by an Apple Macintosh llci personal computer (refresh rate 66.7 Hz, resolution 640 × 480 pixels) and rear-projected on a translucent screen by a Barco Data 800 projection television. Only the green tube was used. The screen measured 1.9 × 2.4 m. Eye movements of the right eye were measured with an induction coil mounted in a scleral annulus in an a.c. magnetic field. This method was first described by Robinson (1963) and refined by Collewijn, van der Mark and Jansen (1975). The horizontal and vertical eye positions of the right eye were measured at a sampling rate of 500 Hz with a National Instruments 12 bits NB-MIO16h analogue to digital converter. Data were stored on disk for off-line analysis.

2.3. Procedure

Subjects viewed a large stimulus (35° × 27.5°) containing 36 elements placed in a hexagonal arrangement (Fig. 1(A)). The distance between the centres of adjacent stimulus elements was 6.2°. All stimulus elements had diameters of 2.1°. The stimulus contained three types of elements: the target (a circle), thin Cs that only differed from the target by a small gap and fat Cs that had the same gap as the thin Cs, but differed by their larger line-width (Fig. 1(A)). In separate sessions, thin and fat Cs had gaps that measured 0.30 or 0.15°.

Line-width of the circle and the 17 thin Cs was 0.30° in all sessions. In separate sessions line-width of the 18 fat Cs was 0.45, 0.60 or 0.75°. Orientation of each C was chosen randomly from the directions up, down, left and right. Each trial contained the target (the circle).

Trials started with the presentation of a circle on a black screen. Subjects were asked to fixate this circle. The circle remained visible for 1 s. After 1 s, another circle was randomly presented at one of the 36 stimulus element positions. Subjects were asked to make a saccade towards this circle. The saccade towards the second circle was detected on-line. Immediately after the detection of the saccade the circle was replaced by the complete stimulus of 36 stimulus elements, which remained visible for 7.5 s. Subjects were asked to find a circle and to respond, if they found it, by maintaining fixation of the circle until the end of the trial. Because stimulus presentation started during saccades stimulus analysis could start immediately after the first saccades had ended.

Stimuli were presented in six blocks of 50 trials (Fig. 1(B)). Measurements were done on two successive days. Three blocks were presented in one session of 30 min. Gap-size and line-width were kept constant during one block. Thus in one block, we did not vary the discriminability of the circle and the thin Cs. By varying the gap-size, we were able to alter the difficulty of the discrimination between the circle and the thin Cs. By varying the line-width of the fat Cs we were able to alter the difficulty of the peripheral selection task.

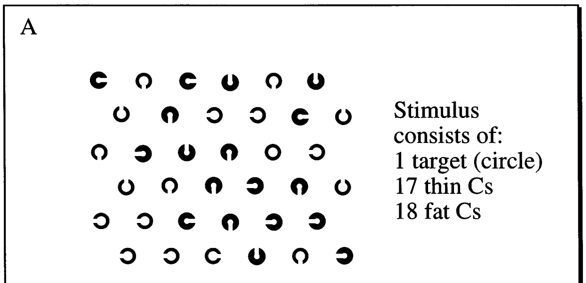

Fig. 1. Panel A shows an example of the stimulus. Panel B depicts the six combinations of stimuli used in the experiment.

Data were analysed off line by a computer program that ran on an Apple Macintosh computer. In the analysis, saccades were detected by a velocity threshold of 100°/s. After detection of a saccade the program searched for the onset and offset of that particular saccade on the basis of a velocity threshold of 25°/s. Onsets and offsets were marked. From these markers the program computed fixation durations and fixation positions. We used an amplitude threshold of 2.1° to remove small correction saccades. A database of marked saccades was compiled which contained the following information about each saccade: number in the sequence, eye position and time at onset, eye position and time at offset, type of stimulus element fixated at onset and offset. From the data base we computed: search times, fixation durations, type of fixated stimulus elements and number of fixations per trial. We define search time as the period between stimulus onset and beginning of target fixation. Search times measured according to this definition will slightly underestimate real search times, defined by the time needed to find the target, because at the beginning of target fixation the target has usually not yet been found. As an illustration, if the first element fixated is the target and no saccades are made, search time is 0 ms according to our definition.

3. Results

3.1. Number of fixations

We checked whether the subject used peripherally presented information to select potential targets for eye movements. For that purpose we counted the number of fixations at the different types of stimulus elements. Fig. 2 shows the average number of fixations per trial on the different types of elements in the stimulus for each of the three subjects. The average number of fixations per trial (black bars) decreases with increasing line-width of the fat Cs. For line-width 0.45° the number of fixations at fat Cs is of the same level as the number of fixations at thin Cs. This effect was clearly observed in the three subjects for both gap-sizes. The decreases in the number of fixations were caused mainly by decreases in the number of fixations on fat elements (horizontally dashed bars). In other words, subjects were able to avoid the fat Cs more effectively when these had a large line-width.

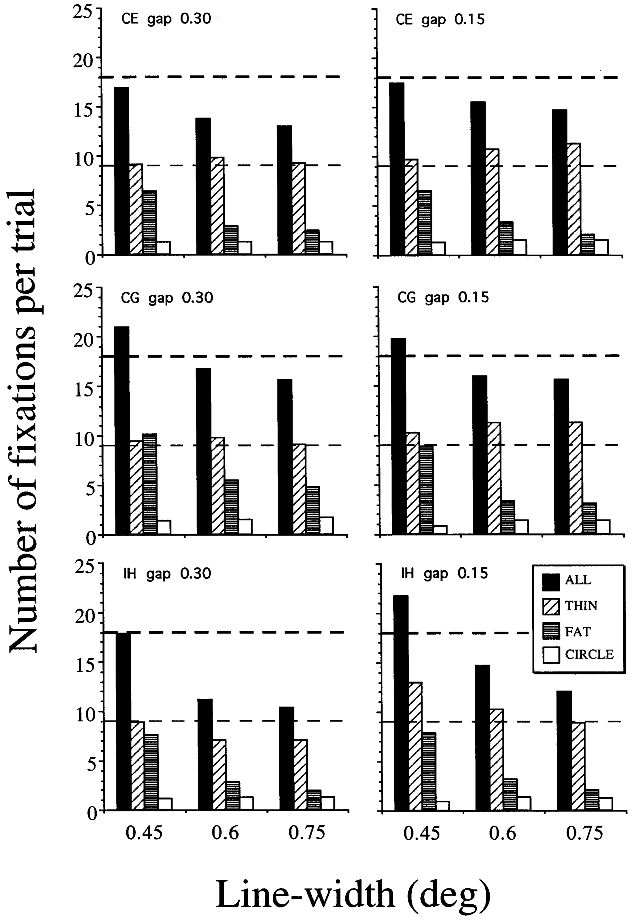

Fig. 2. Mean number of fixations per trial. Black bars denote the numbers of fixations on all elements; diagonally dashed bars denote numbers of fixations on thin elements; horizontally dashed bars denote numbers of fixations on fat elements; white bars denote numbers of fixations on the circle (the target).

3.2. Search times

In an experiment in which eye movements are needed to find the target, search time is correlated with the number of fixations and the duration of each fixation. The number of fixations on fat stimulus elements decreases with increasing line-width (Fig. 2). What is the effect of varying line-width on overall performance (= search time)? Fig. 3 depicts the relationship between search time and the difficulty of the peripheral selection task. The slope of the cumulative search time curves (which is a measure for search speed) is related directly to the line-width of the fat Cs. We find the steepest slopes for stimuli containing the largest line-width. In general search time decreases with increasing line-width. This result is typical for all subjects.

3.3. Amplitudes

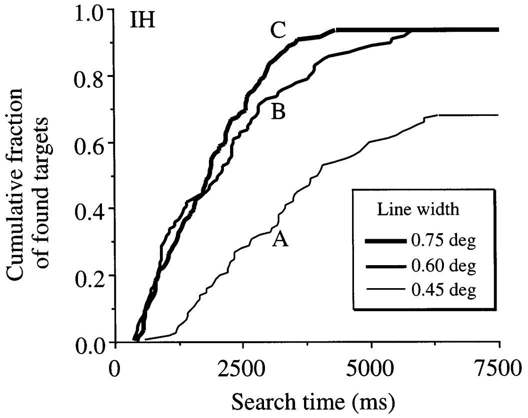

Fig. 3. Cumulative fraction of found targets against search time. Gap-size was 0.3°. Line-width of the fat Cs was (A) 0.45°; (B) 0.6°; and (C) 0.75°. Line width of the thin Cs was 0.3°.

Fig. 4 depicts histograms of saccade amplitudes. The distributions of the amplitudes are slightly bimodal. Peaks of the distribution are found for amplitudes that closely match the distance between the stimulus elements. Small peaks are found for amplitudes of 12°, which is about the distance between two stimulus ele-

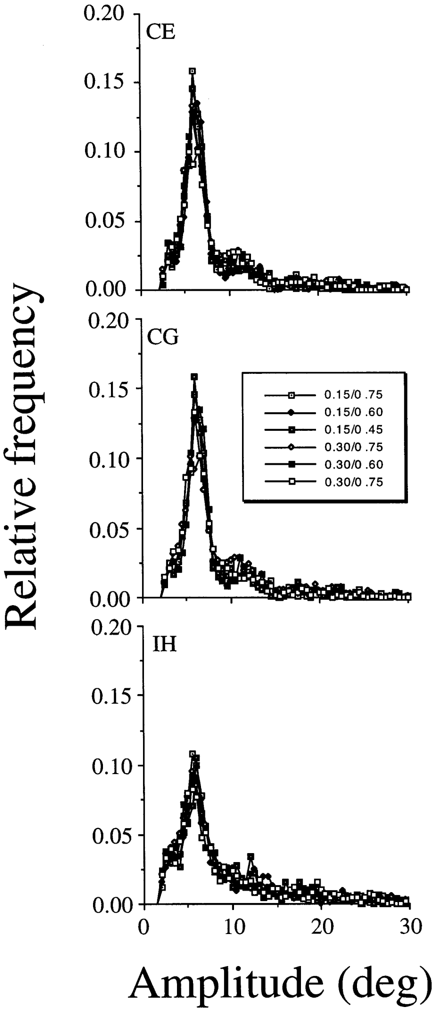

Fig. 4. Relative distributions of saccade amplitudes.

ments. Thus, saccades were mainly made from one stimulus element to another. This indicates that discriminating the circle from the thin Cs is mainly a foveal task. We cannot exclude that subjects sometimes can discriminate a thin C from the circle when it is not fixated. However, when subjects had been able to discriminate the circle while fixating an adjacent stimulus element, we would have expected the median of the distribution of the saccade amplitudes to be longer than 6.2°.

3.4. Fixation durations

How is fixation duration related to the stimulus elements fixated? Fig. 2 shows that a number of fat Cs was fixated in all conditions. If foveated, fat Cs can be discriminated easily from the thin (target-like) stimulus elements. Long-lasting fixation of fat Cs seems to be a waste of time. We checked whether the durations of fixations of thin and fat Cs were distinguishable from each other. Fig. 5 shows the duration of fixation of thin and fat stimulus elements versus line-width for two gap-sizes. In general, fixation duration depended on the type of stimulus element fixated. Durations of fixations of fat elements were shorter than durations of fixations of thin stimulus elements. For subject CE and CG gap-size affected durations of fixations of thin Cs. Fixation durations were longer when gap-size was small (0.15°). In subject IH, fixation durations did not depend on gap-size. Fixation durations of subject IH were shorter than fixation durations of CG and CE in conditions having thin Cs with small gaps (0.15°).

How is fixation duration related to the peripheral selection task? Varying line-width of the fat Cs did not have an effect on fixation duration in the three subjects. This independence was observed for fixations of both thin and fat Cs.

In summary, when the fixated stimulus element was easy to discriminate from the circle (when the C fixated has either a large gap (0.30°) or a large line-width (> 0.30°), we found the shortest fixation durations. Thus, fixation duration mainly depends on features of the foveal stimulus. Features of the peripheral stimulus do not affect fixation duration.

3.5. Fixation duration and peripheral selection

Geisler and Chou (1995) demonstrated that longer presentation times cause better peripheral analysis. In a multiple fixation search experiment, the fixation duration represents the presentation time of the fixated part of the stimulus. Therefore, we expect that longer fixation durations permit better peripheral analysis. To quantify this we need a measure. In the case of successful peripheral analysis we expect the subject to make a saccade to a potential target. Because subjects were

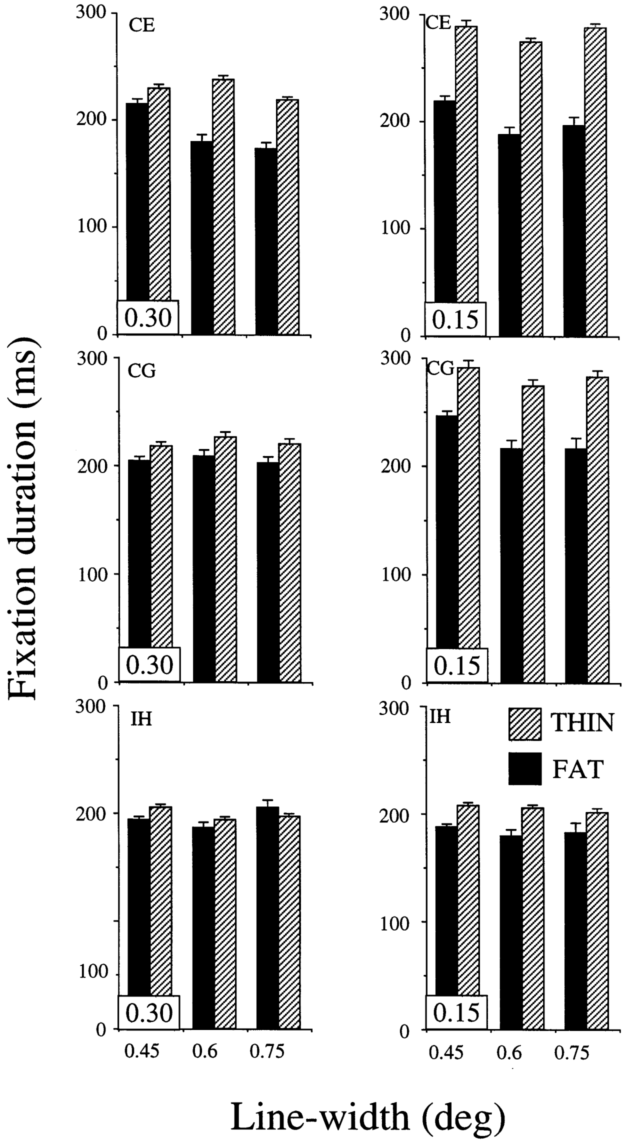

Fig. 5. Fixation durations. Black bars denote durations of fixations on fat Cs. Diagonally dashed bars denote durations of fixations on thin Cs. Error bars denote S.E.s of the mean.

instructed to find the thin circle, thin stimulus elements are potential targets. As a measure for the quality of the peripheral selection we take the fraction of saccades to thin stimulus elements (FST). FST is defined as the number of saccades to thin stimulus elements divided by the total number of saccades to thin and fat stimulus elements. We expect FST to depend on two factors:

1. The difficulty of the peripheral selection task. The difficulty of the peripheral selection task depends on line-width (Figs. 2 and 3). Thus, we expect FST to increase with increasing line-width. Fig. 6(A) shows FST versus line-width. As expected, FST is smallest for difficult peripheral selection tasks (line-width 0.45°) and increases with line-width.

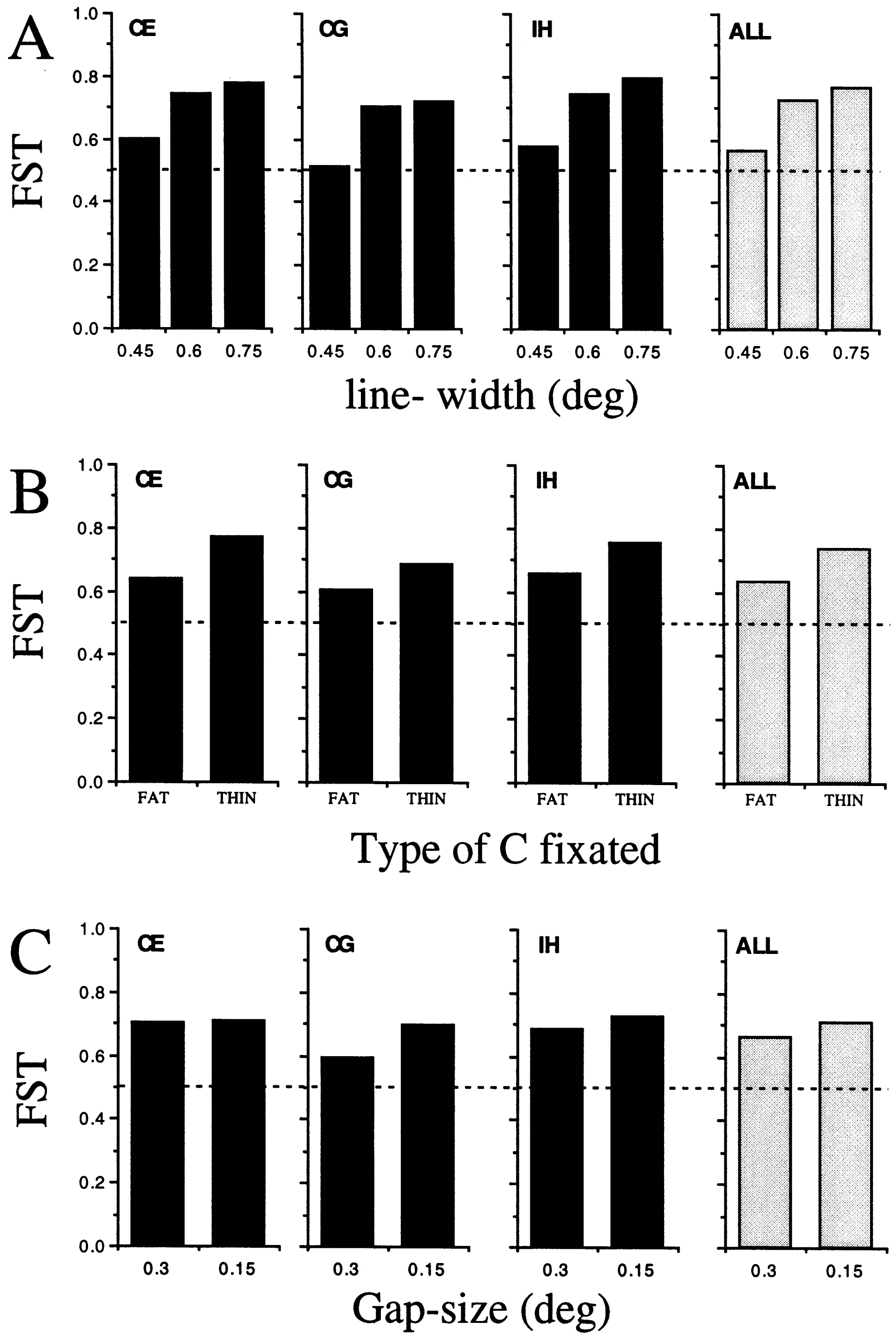

Fig. 6. Fraction of saccades to thin stimulus elements. FST is defined as the number of saccades to thin stimulus elements divided by the total number of saccades to thin and fat stimulus elements. (A) FST vs. line-width; (B) FST vs. type of C fixated; (C) FST vs. gap-size. Black bars show results for individual subjects. Grey bars represent data averaged over subjects.

2. The difficulty of the discrimination task. The difficulty of the discrimination task depends on both the type of C fixated and size of the gap in the C. This enables us to investigate the FSTs both within and between conditions.

Within one condition (fixed gap-size and fixed line-width, Fig. 1), we found bimodal distributions of fixation duration. Fixation duration depended on the type of stimulus element fixated. Fixations at thin Cs lasted longer than fixations at fat Cs (Fig. 5). This implies that a larger amount of time is available for peripheral analysis during fixation of a thin C. If the extra fixation time were used in this way, we would expect to find a higher proportion of saccades to thin stimulus elements after fixation of a thin C than after fixation of a fat C. Fig. 6(B) depicts the relation between the type of C

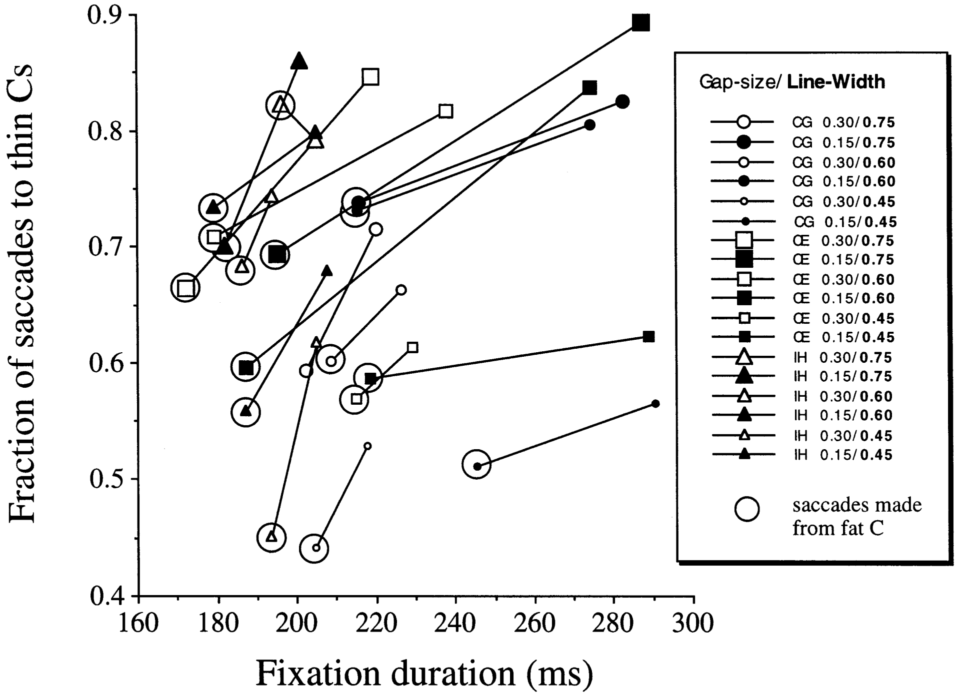

Fig. 7. Fraction of saccades to thin stimulus elements (FST) vs. fixation duration. FST is defined as the number of saccades to thin stimulus elements divided by the total number of saccades to thin and fat stimulus elements. For each combination of gap-size and line-width, we determined FST for fixation at thin and fat Cs separately. FSTs measured in one condition (Fig. 1) are connected with a line. These FSTs can be compared directly because these have the same peripheral selection task. FSTs from fat Cs are marked with a circle. Squares denote results for CE. Circles denote results for CG. Triangles denote results for IH. Large symbols denote line-width 0.75°; intermediate symbols denote line-width 0.60°; small symbols denote line-width 0.45°; open symbols denote gap-size 0.30°; closed symbols denote gap-size 0.15°.

fixated and FST. As expected, we find the highest FSTs for fixations of thin stimulus elements.

In conditions having a gap of 0.15° fixation durations were found to be longer than in conditions having a gap of 0.30° (Fig. 5). Following the same rationale as in the previous paragraph, we expect higher FSTs in stimuli having Cs with small gaps. Fig. 6(C) shows FST versus gap-size. Except for subject CE, higher FSTs were found in conditions having a small gap (0.15°). The effect of gap-size on FST is much smaller than the effect of 'type of C fixated'. We can understand this because 'type of C fixated' has a larger effect on fixation time than varying the gap-size (Fig. 5).

The effect of fixation duration on FST can also be presented in a more direct way. Fig. 7 shows FST versus fixation duration. For each combination of gap-size and line-width, we determined FST for fixation at thin and fat Cs separately. Only FSTs measured in one condition can be compared directly because then the peripheral stimulus is the same. FSTs measured in one condition are connected with a line. FSTs from fat Cs are marked with a circle. As expected, there is a clear effect of fixation duration on FST. In general, FSTs from fat Cs are found in the bottom left corner of the figure. When the connecting line has a positive slope, fixation duration facilitates peripheral analysis. Except for one condition (IH gap 0.30°; line-width 0.75°), this holds for all lines. For long fixation durations the connecting lines become horizontal, implying that FSTs saturate for long fixation durations.

4. Discussion

4.1. Control of fixation duration and target selection

Physical properties of the stimulus elements, lay-out of the stimulus and instruction play an important role in the selection of potential targets for saccades (Luria & Strauss, 1975). If a feature of the peripheral stimulus is under detection threshold, it cannot be used for target selection. However, the detection threshold is time-dependent (Geisler & Chou, 1995). Both the chance that a target is detected and the size of the area in which it can be detected increase with presentation time. Analogous to presentation time, we asked whether fixation duration determines the quality of the peripheral selection.

In the present study we manipulated both the discrimination and selection task independently from each other. Fixation duration mainly depended on the difficulty of the discrimination task (Fig. 5). The selection task did not affect fixation duration (Fig. 5). This is a remarkable finding because in conditions having a difficult selection task (for example when line-width is 0.45°), FSTs increased with fixation duration (Fig. 7). Thus, longer fixations facilitate FST. But subjects did not adjust their fixation durations to the time needed for peripheral analysis. This result corroborates results of Findley (1995) (see his introduction). In the experiment of Findley individual fixation durations were not always adjusted to the difficulty of the selection task. In the present experiment, the difficulty of the discrimination task, therefore, determines how much time is available for peripheral analysis. This suggests that the dynamics of visual search is mainly determined by the foveal discrimination of the target from the non-targets.

4.2. Speculations on dynamics of multiple fixation search

Search can have either matched or unmatched difficulties of the discrimination and selection tasks. Search time depends on the number of eye movements and the duration of each fixation. We can distinguish three types of stimuli. If the difficulties of the two tasks match (Type 1 stimulus), search time is related to the difficulty of the discrimination task, because this task determines the search time (= average fixation duration × number of fixations). If the difficulty of the two tasks is unmatched, search times are related to the difficulty of the discrimination task if the peripheral selection task is easier than the discrimination task (Type 2 stimulus). Whereas search time is related to the selection task when the selection task is more difficult (Type 3 stimulus).

Search performance is likely to be best when the fixation duration is tuned to both the selection and discrimination task (Type 1 stimulus). Then search time can be minimal. This is often not the case because fixation duration is controlled only by the discrimination task. This may lead to suboptimal search strategies. Let the following examples be an illustration to this. Suppose we have a search task that consists of an easy discrimination task and a more difficult selection task (Type 3 stimulus). Subjects scan fast because it is only the difficulty of the discrimination task which determines fixation duration. A short fixation duration is not optimal for performing a difficult selection task. This causes extra fixations (= long search time). In the opposite case (difficult discrimination task and easy selection task, Type 2 stimulus) peripheral selection is effective. This reduces the number of fixations. But subjects scan slowly (= long search time).

4.3. Conclusion

It is difficult to compare results of different search studies. Aside from stimulus layout, instruction and physical properties of the stimulus elements, we found that fixation duration is also a determinant for the selection of potential targets for eye movements.

In the present experiment we showed that a parameter such as line-width can be as effective as colour for selecting targets. With different stimulus material, we replicated both the contradictory results of Luria and Strauss (1975) and Zelinsky (1996). In the experiment of Luria and Strauss (1975), colour coding was very effective as it was not in the experiment of Zelinsky (1996). By manipulating line-width and gap-size we found FSTs ranging from 0.44 (ineffective coding) to 0.87 (effective coding) (Fig. 7). Coding was less effective when fixation durations were short.

Luria and Strauss (1975) used a search task consisting of a difficult discrimination task (discriminating numbers) and an easy selection task (colour). Our suggestion is that the difficult discrimination task caused fixation times that were long enough for effective peripheral selection (Type 2 stimulus). Zelinsky (1996) used a much easier discrimination task (discriminating color and orientation). Our results suggest that the relatively easy discrimination task caused fixation durations that were too short for effective peripheral selection (Type 3 stimulus). The same rationale holds for the shape and size coding experiments (in which coding was not effective) of Luria and Strauss (1975).

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