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SHARED ATTENTIONAL CONTROL OF SMOOTH EYE MOVEMENT AND PERCEPTION

BEENA KHURANA and EILEEN KOWLER*
Department of Psychology, Rutgers University, New Brunswick, NJ 08903, U.S.A.

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Abstract—Subjects performed a concurrent smooth pursuit and perceptual task to determine whether smooth pursuit eye movements and perception share the same attentional mechanism. Subjects pursued a pair of eccentric rows of moving characters while simultaneously attempting to identify and locate the single numeral in these target rows and the single numeral in a pair of untracked background rows, which moved at a different velocity. Average smooth pursuit gain (eye velocity/target velocity) was 0.7 to 1. Visual search was better for target rows (~65% correct) than for background rows (~22% correct). Superior search performance for the target was not due to its lower retinal speed: performance on the target was 2–3 times better than on the background when retinal speeds were the same. Superior performance for the pursuit target suggests that smooth eye movements and perception share the same selective attentional mechanism. A shared attentional mechanism was further supported by findings that subjects could *not*: (1) maintain a stable line of sight on a central stationary point while simultaneously attending to moving rows; and (2) pursue one pair of rows and attend the other, untracked rows. Attempts to attend untracked rows did, however, produce a partial improvement in search performance which was accompanied by only a very slight change in eye velocity. This demonstrates that the effects of decisions about how to apportion attention across the visual field depend on the task. Despite the common selective attentional mechanism, smooth eye movements do not provide accurate external indicators of attention unless the consequences of attentional decisions for performance are determined separately for oculomotor and for perceptual tasks.

Smooth pursuit   Smooth eye movement   Attention   Visual search

INTRODUCTION

Selection from the endless stream of potential visual stimulation is essential to an organism. Given important visual decisions and discriminations to be made, inappropriate selection, or an inability to maintain selection, could have disastrous consequences. Researchers have tried to understand how selection is achieved, and determine the implications of selection for visual processing. The present research deals with a small part of selective functioning, namely, the implications for visual processing of the selection of the target for smooth eye movements. Smooth eye movements are relatively slow, involuntary eye movements used to maintain the line of sight on a stationary stimulus (Steinman *et al.*, 1973) or on a moving stimulus (e.g. Westheimer, 1954).

The role of selectivity in smooth eye movements has been appreciated as far back as Ernst Mach (1906/1959). Mach's appreciation of selectivity was based on introspection. He noted that: "I walk forward by a single act of will . . . My eyes are fixed steadfastly upon my goal without suffering themselves to be drawn aside by the motion of the retinal images consequent upon progression" (p. 147). Mach believed that selection of a voluntary nature ("a single act of will") was responsible for the oculomotor capacity of selecting targets and, consequently, eliminating the influence of backgrounds.

Others since Mach have studied the role of voluntary selective processes in the functioning of the smooth oculomotor subsystem (e.g. Dodge and Fox, 1928; Ter Braak, 1957; Stark, 1971). Consider a relatively recent study with a precise eye movement recording technique. Murphy *et al.* (1975) found that subjects could fixate a stationary point superimposed on a moving, high-contrast, square wave grating. The influence of the moving background on smooth eye velocity was less than 6%. This small influence was further reduced by a factor of 2 or more when the point was replaced by a 26′ diameter annulus. Murphy *et al.* (1975) also

*To whom correspondence or reprint requests should be addressed.

found that subjects could choose between fixating the stationary annulus or tracking the moving grating. They concluded that input to the smooth oculomotor subsystem was dictated by the individual's choice and attention rather than by constraints of the stimulus.

Cheng and Outerbridge (1975) studied selectivity with a different stimulus arrangement. They used a moving pattern of dots on which was superimposed a central, stabilized homogeneous region (diameter up to 30°). They observed that instructions to attend to the moving dots were required in order to observe smooth pursuit, especially when the size of the central, stabilized square region exceeded 20°. Using similar stimuli Dubois and Collewijn (1979) also found that attentional instructions affected pursuit. Uninstructed subjects did not pursue effectively when presented with a stabilized homogeneous region (4 deg diameter) superimposed on a moving grid of black and white bars. But pursuit improved considerably when subjects were instructed to attend the bars. Thus, voluntary selection of the target greatly influenced the pursuit response.

The studies described above showed that subjects could choose between maintaining the line of sight on a central stationary target or pursuing an eccentric moving background. Other studies have demonstrated comparable selective capacity with a stimulus consisting of a small target moving against a large stationary background. For example, Kowler *et al.* (1978) showed that pursuit of either a single point or a 2-point acuity target was unaffected by the presence of a homogeneous background. Similarly, Collewijn and Tamminga (1984) found virtually no influence of a diffusely illuminated background on voluntary smooth pursuit of a target. However, they found that when the background was structured, smooth pursuit velocity was reduced by about 10–20%.

The previous studies cited above all used target and background stimuli that had different physical properties. Thus, the relative strength of the target and background as stimuli for smooth eye movements could have contributed to the effectiveness of voluntary selection. Kowler *et al.* (1984) investigated voluntary target selection when the target stimulus and the background stimulus were physically identical. They presented two, superimposed, full-field patterns of randomly-positioned dots, with one field stationary and the other moving at a constant velocity. The size, density and luminance of the dots were the same in each field. They found that subjects could either maintain the line of sight on the stationary field or smoothly pursue the moving field. The influence of the background field on smooth eye movements was less than 4%. They concluded that the ability to screen out background stimuli by means of voluntary selection was virtually perfect.

These prior demonstrations showed that voluntary selection could determine the stimulus for smooth pursuit eye movements. It is now reasonable to ask whether the decision to select a certain stimulus also results in improved perceptual processing of the same stimulus. This would be a plausible outcome because instructions to attend some part of the visual field has been found to improve performance on perceptual tasks such as visual search (Sperling and Melchner, 1978; Shaw, 1980, 1982). The question posed in this paper is whether the decision to pursue a certain stimulus has the same consequences for perceptual processing as the decision to attend a stimulus. If this proves to be the case, then only a single selective mechanism is available to achieve both the smooth pursuit and the perceptual performance. On the other hand, if the decision to pursue a certain stimulus does not affect perceptual processing, then there may be two selective mechanisms available, one engaged in selecting the target for the smooth oculomotor subsystem, and the other in selecting the target for the perceptual system.

Kowler and Zingale (1985) previously attempted to determine whether there is a single selective mechanism. They used smaller fields of random dots (5.2° × 5.2°) than those used by Kowler *et al.* (1984). One field was stationary and the other moved to the right at 1 deg/sec. The perceptual task was to detect the disappearance of a subset of dots from either the stationary or moving field and to state from which field the dots disappeared. Kowler and Zingale (1985) found a higher proportion of correct responses when dots disappeared from the target field than from the background field.

Kowler and Zingale (1985) concluded that the improved performance for the target most likely indicates that there is a single selective mechanism for smooth eye movements and perception. However, they also pointed out that their results could be attributed to two other factors. First, the retinal image speed of the background field, although slow (about 1 deg/sec), was faster than the retinal image speed of the target field. So, the lower retinal speed could have contributed to the better perceptual performance with the target. Second, the greater success at detecting the disappearance of dots from the target field could have represented a reduction in the subject's criterion for detecting events in the target field. Consistent with this possibility is Shaw's (1983) finding that the effects of attentional instructions on the detection of luminance increments, such as those reported by Posner *et al.* (1978), could be attributed to changes in decision criteria rather than to reduction of visual thresholds. By contrast, attention affects a search task (locating a target letter) by changing visual coding processes rather than decision processes (Shaw, 1983).

The goal of the present study is to find out whether there is a single selective mechanism shared by both smooth eye movements and perception. The experiments were designed so that effects of selection could be determined independently of either effects of shifts in criteria for detection, or effects of retinal speed. In the present experiments subjects used smooth eye movements to pursue a target stimulus while making concurrent perceptual judgments about both the target stimulus and a background stimulus. The target for smooth eye movements was a pair of rows of horizontally moving alphanumeric characters, one row located above and the other below the line of sight. Another pair of rows of characters, moving at a different velocity, served as the background. The subject had to identify and locate the single numeral contained in the target rows and the single numeral contained in the background rows, while at the same time matching horizontal eye velocity with the target rows. Effects of selection of the target for smooth eye movements on visual search performance could be determined independently of either effects of shifts in criteria for detection, or effects of retinal speed. This was accomplished in the following ways:

(1) The perceptual task was visual search rather than detection. A detection task was *not* used because, as described above, improved detectability as a function of attentional instructions can be accounted for by shifts in decision criteria (Shaw, 1983). Performance on the visual search task we used (finding a numeral from among letters) would not be expected to be influenced by a shifting detection criterion because the letters and numerals will be well above detection threshold. The errors in visual search performance, therefore, would not result from failure to detect the presence of a stimulus, but rather from the failure to identify or recognize those stimulus features that distinguish the numeral from the surrounding letters. See Kowler and Sperling, 1983, for further discussion of the distinction between energy-limited processes, such as detection, and time-limited processes, such as visual search.*

(2) Search performance on the target and on the background will be compared for instances in which their retinal speeds are the same. Instances of equal retinal speed are expected because the velocity of target and background will differ by no more than 50′/sec, and because smooth pursuit eye movements are neither perfectly accurate (Puckett and Steinman, 1969; Collewijn and Tamminga, 1984) nor perfectly precise (Kowler and McKee, 1987). Any improved visual search for the target can be attributed to the operation of the selective mechanism, and not to lower retinal speed, when the retinal speed of the target is the same as the retinal speed of the background.

The experiments to be described show that visual search peformance was superior for the target for smooth eye movements. This result was not due either to differences in retinal speed or to shifts in a detection criterion. The superior performance for the target suggests that smooth eye movements and perception share a common selective mechanism.

A clarification of terminology is in order before proceeding to details of methods and results. We will be using the term "attention" to refer to the voluntary selection of some stimulus or some portion of the visual field for enhanced processing. This usage is consistent with current practice. For example, previous studies have reported that simple instructions to attend a particular portion of the visual field resulted in improved identification or recognition of stimuli in the attended location at the expense of the identification or recognition of stimuli in other, unattended locations (e.g. Sperling and Melchner, 1978; Shaw, 1980, 1982; Reeves and Sperling, 1986). Labelling this selective process

*These considerations need not imply that the superior performance found for pursuit targets by Kowler and Zingale (1985) was due to a lowered detection criterion. In fact subsequent experiments we performed employing conventional signal detection techniques suggest that the superior performance for the target in Kowler and Zingale's task was due to changing thresholds and not to changing criteria.

"attention", however, should not be taken as an explanation of how it works. For example, questions about the level of visual processing at which attention operates, the kinds of visual judgements which are susceptible to the influence of attention, and the way in which attention affects processing are all the subject of current research (e.g. Sperling, 1984; Reeves and Sperling, 1986; Treisman and Gelade, 1980; Kahneman and Treisman, 1984).

METHOD

Eye movement recording

Two-dimensional movements of the right eye were recorded by a Generation IV SRI Double Purkinje Image Tracker (Crane and Steele, 1978). The left eye was covered and the head was stabilized on a dental biteboard.

The voltage output of the tracker was fed on-line through a low pass 50 hz filter (8-pole Bessel) to a 12-bit analog to digital coverter (ADC). The ADC, under control of a computer (*Plessey* LSI 11/23), sampled eye position every 10 msec. The digitized voltages were stored for subsequent analysis.

Tracker noise-level was measured with an artificial eye after the Tracker had been adjusted so as to have the same first and fourth image reflections as the average subject's eye. Filtering and sampling rate were the same as those used in the experiment. Noise level, expressed as a standard deviation of position samples, was 0.4 min arc for horizontal and 0.7 min arc for vertical position.

Recordings were made with the Tracker's automatically movable optical stage (auto-stage) and focus servo disabled. These procedures are necessary with Generation IV trackers because motion of either the auto-stage or the focus-servo introduces large artifactual deviations of Tracker output. The focus-servo was used, as needed, only during intertrial intervals to maintain subject alignment. This can be done without introducing artifacts into the recordings or changing eye position/voltage analog calibration. The auto-stage was permanently disabled because its operation, even during intertrial intervals, changed the eye position/voltage analog calibration.

Subjects

Two subjects were tested. E.K. was an experienced eye movement subject and psychophysical observer. B.K. had neither been an eye movement subject nor participated in any previous psychophysical experiments.

Stimuli

The stimulus was generated on a display monitor (*Tektronix* 608, P-4 phosphor) located directly in front of the subject's right eye. The display consisted of a 4×4 array of alphanumeric characters. Characters were comprised of discrete points located within a 7 by 10 matrix subtending a visual angle of 16′ horizontally and 23′ vertically. The center-to-center separation of the characters was 48′ horizontally. The center-to-center separation vertically was 33′ between row 1 (the top row) and row 2 (second from the top), and between row 3 (third from the top) and row 4 (the bottom row). Between rows 2 and 3 was a gap which subtended 43′ vertically. The total array subtended 192′ horizontally and 155′ vertically.

The characters were illuminated briefly (<1 msec) to a luminous directional energy (LDE) of 0.15 cd-μsec/point (see Sperling, 1971). Characters contained between 14 and 31 points; thus the LDE/flash for a character ranged between 2.1 and 4.7 cd-μsec/character. The characters were seen against a dim background (0.7 cd/m^2) produced by the faint glow of the display's phosphor produced by the beam when it was moved off the display face between refreshes.

The entire display was refreshed every 40 msec. This rate was too rapid for individual refreshes to be discerned. The display was viewed in a dark room through a collimating lens which placed it at optical infinity. Appropriate negative lenses were placed between the collimating lens and the Tracker's optics so that the subjects (both of whom were myopic) could see all displays in sharp focus.

Two types of character arrays were presented on each trial. The first type consisted of 16 letters (see the example in Fig. 1). The second type consisted of 14 letters and 2 numerals (see Fig. 2). This array served as the stimulus for the visual search task. One of the numerals always appeared in rows 1 or 3 and the other in rows 2 or 4. Any numeral from 0 through 9 could appear. Any letter could appear in either array except B, I, O, Q and Z. These were excluded because of their close resemblance to the numerals 3, 1, 0 and 2.

The letters, the numerals, and their locations were selected randomly, independently and with replacement. The selection of characters and

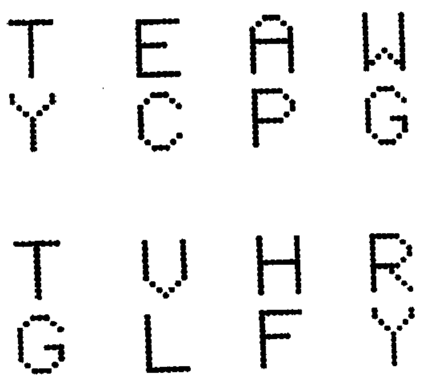

Fig. 1. An example of the first character array presented in a trial. The array appeared after the subject pressed the start button and stayed on until the eye had reached approximately the center of the gap.

locations for each type of array was carried out independently. This meant that during a trial the contents of the first array and the contents of the second array would not (except in the case of a chance correspondence) be the same.

The letters moved rightward at a constant velocity. Characters moved within the confines of the 192′ width of the display. Thus, when any portion of a character reached the right margin of the display it disappeared and reappeared at the left margin.

Pairs of rows (rows 1 and 3 or rows 2 and 4) shared the same velocity. Four kinds of displays were tested, differing in the velocities of the rows. These displays were: (1) rows 1 and 3 moved at 25′/sec and rows 2 and 4 at 50′/sec; (2) rows 1 and 3 moved at 50′/sec and rows 2 and 4 at 25′/sec; (3) rows 1 and 3 moved at 50′/sec and rows 2 and 4 at 100′/sec; (4) rows 1 and 3 moved at 100′/sec and rows 2 and 4 at 50′/sec.

Procedure

Before each trial the display contained a single point. Its location corresponded to the leftmost edge of the character array and the vertical center of the gap. The subject fixated the point. She pressed a button when ready to begin a trial. Seventy msec later the point disappeared and the first character array, containing moving letters, appeared. The purpose of this array was to initiate smooth pursuit. Specifically, the subject was instructed to maintain vertical eye position in the gap between the second and third rows while matching horizontal eye velocity to either the slow or the fast pair of rows. When the display was on long enough so that the eye would have reached the approximate center of the display window, the array of letters was replaced by the stimulus array for the visual search task. The approximate time to reach the center (3.8 sec for the 25′/sec, 1.9 sec for the 50′/sec and 0.96 sec for the 100′/sec row velocities) was estimated by assuming accurate pursuit. However, inaccurate pursuit, if and when it occurred, would not affect the relative performance on target and background because the location of target and background numerals was random.

The characters in the array for the visual search task appeared in the same position that the characters in the first array had vacated. This meant that the transition from the first array to the visual search array took place without any interruption in the motion of the characters. The visual search array was presented for 200 msec. Then, it was replaced by the original array of moving characters, again in the same positions so as to ensure smooth display motion. This array was on for 300 msec. Its purpose was (1) to ensure that subjects maintained pursuit during the visual search task (subjects slow down in anticipation of the cessation of motion, Kowler and Steinman, 1979b) and (2) to prevent vivid afterimages which otherwise would have appeared at the offset of the search array.

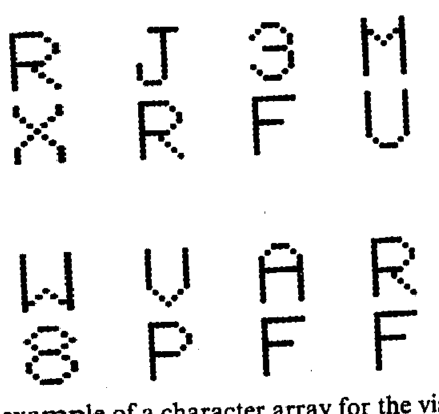

Fig. 2. An example of a character array for the visual search task. It contains 14 letters and 2 numerals. One numeral is always present in either row 1 (top row) or row 3 (third from the top) and the other in either row 2 (second from the top) or row 4 (bottom row).

After each trial the subject had to report (by pressing buttons) the identity of the numeral in the slow rows and the numeral in the fast rows and the particular row in which each numeral was located. Subjects were asked to report the identity and row location of the numeral occurring in the slow rows and in the fast rows. Subjects had to guess if uncertain about the answer. The probability of a correct report answer completely by chance was 0.05 because there were 10 possible numerals and 2 possible row locations for each numeral reported. "Illegal" responses, such as reporting a fast row when answering queries about the numeral in the slow rows, were eliminated. For E.K. 19 out of 400 trials (5% of the total trials) and for B.K. 9 out of 600 trials (2% of the total trials) were eliminated for this reason. After the subjects had responded they were shown the search array for 1.5 sec so that they would know the correct answer.

Sessions

Each session consisted of 100 trials. Instructions to pursue either the slow or the fast rows were alternated in blocks of 10 trials. The order of testing conditions was haphazard. Testing of these conditions was interleaved with testing of other conditions to be described later. E.K. was tested on a total of 4 sessions, 2 with the rows moving at 25 and 50′/sec, and 2 with the rows moving at 50 and 100′/sec. B.K. was tested on 6 sessions, 4 with rows moving at 25 and 50′/sec and 2 with rows moving at 50 and 100′/sec.

Data analysis

Eye movements were measured from the onset of the visual search array until the end of the trial. Horizontal eye velocity for each trial was computed as the difference in horizontal eye position at the onset and offset of the search array divided by the presentation time (200 msec) of the visual search array.

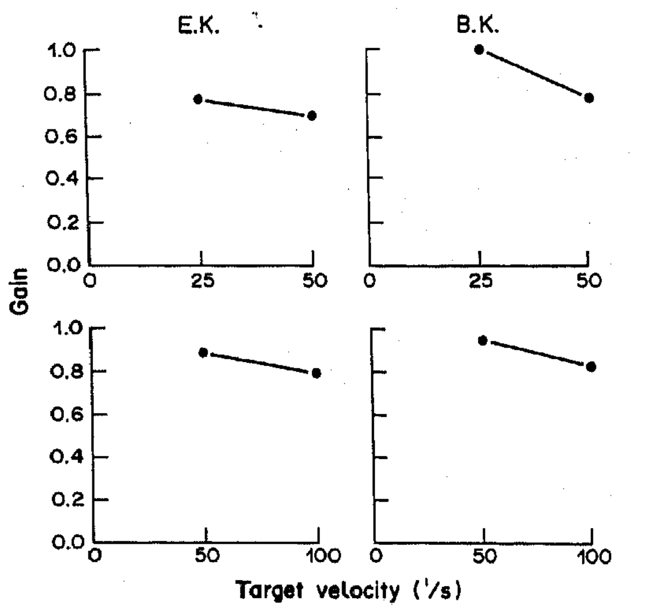

Fig. 3. Average pursuit gain (eye velocity/target velocity) as a function of target velocity during the 200 msec presentation of the visual search array. Each datum point is based on 72–97 trials for E.K., and 68–172 trials for B.K. Standard errors are smaller than the plotting symbols.

Saccades were detected from the original eye position records by a computer algorithm using a velocity criterion. The algorithm was checked by inspection of analog eye movement records in which flags marked the saccades detected by the algorithm. Trials in which saccades were detected were eliminated. One out of E.K.'s 400 trials (0.25%), and 54 out of B.K.'s 600 trials (9%) contained a saccade. Trials were also discarded if vertical drifts had taken the eye outside of the gap between rows 2 and 3. Thirty-three out of 400 trials (8%) for E.K., and 80 out of 600 trials (13%) for B.K., contained vertical drifts sufficient to take the eye outside the gap. On the whole 13% of E.K.'s trials and 24% of B.K.'s trials were removed from the analysis because of saccades, vertical drifts or illegal responses (see above).

RESULTS

1. *Visual Search During Smooth Pursuit*

Subjects could pursue eccentric targets within the gap as instructed

Figure 3 shows average pursuit gain (eye velocity/target velocity) as a function of the velocity of the rows being pursued. Average gains decreased as the velocity of the target increased. Pursuit also depended on context, that is, on the velocity of the targets that were tracked in the other trials of the experimental session. Specifically, when the 50′/sec rows were pursued in the context of faster 100′/sec rows, average gain was about 20% higher than when the same target velocity was pursued in the context of the slower 25′/sec rows.

The results reported above, namely, average gains of less than one which decreased with increasing stimulus velocity, are consistent with previous observations using different stimuli (single points of light) (Puckett and Steinman, 1969; Murphy, 1978; Kowler *et al.*, 1978; Collewijn and Tamminga, 1984). Also, Winterson and Steinman (1978), who used a perifoveal point target, reported average gains of 0.6 to 0.9, similar to the range of gains found in the present experiment. Finally, Kowler and McKee (1987) reported effects of velocity-context on gain. This similarity between the present results and prior work shows that representative smooth pursuit performance was, in fact, achieved with the present stimuli, which are somewhat different from the stimuli typically studied.

Performance in the visual search task was better for target rows

Performance in the visual search task is shown in Fig. 4. Percent correct on the slow rows is on the abcissa and percent correct on the fast rows is on the ordinate. The solid circle represents performance when the faster pair of rows was the target, the open circle when the slower pair was the target. If the attempt to pursue the target did not affect the accuracy of search, then the solid and open circle would coincide.

Consider the performance when the slow rows moved at 25′/sec and the fast rows moved at 50′/sec. When E.K. pursued the faster rows, she got 55% correct on the target and only 17% correct on the background. When she pursued the slower rows she got 60% correct on the target and 26% on the background. Results were about the same for B.K., and similar when the slow rows moved at 50′/sec and the fast rows at 100′/sec. Averaged across subjects and row velocities, performance on the pursued target was about 35% better than that on the back- about 35% better than that on the background.

Since both identity and location judgments were made, it is reasonable to ask whether better performance on the target was due to improved identity judgments, or to improved location judgments, or to both. Averaged across subjects and row velocities, identification judgments (regardless of the report of location) made about the pursued target were 33% better than those about the background. Similarly, location judgments (regardless of the report of the numeral) made about the target were 24% better than those about the background. So, smooth pursuit affected both identity and location judgments.

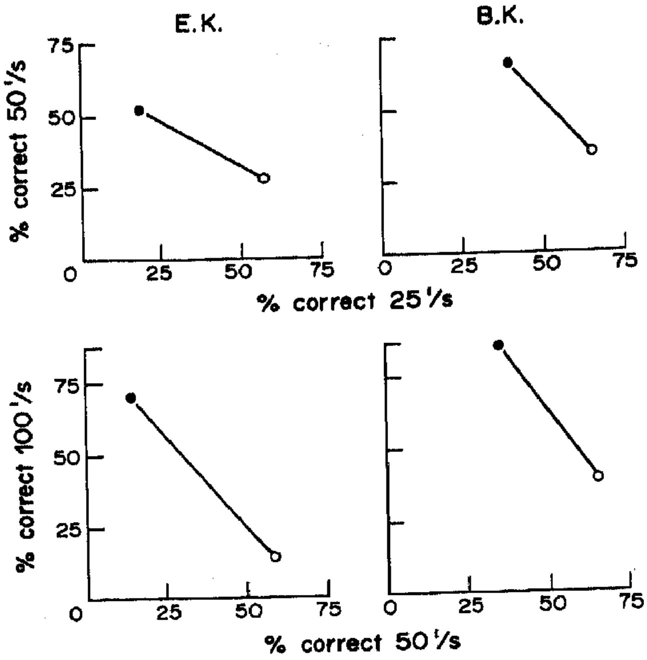

Fig. 4. Visual search performance in the form of Attention Operating Characteristics (AOCs) while subjects tried to pursue either the slow pair of rows (open circle) or the fast pair of rows (solid circle). Percent correct on slow rows is on the abscissa and percent correct on the fast rows is on the ordinate. Each datum point is based on 72–97 trials for E.K. and 68–172 trials for B.K.

Allocating processing capacity between target and background

The line connecting the pair of data points in each graph of Fig. 4 represents an "Attention Operating Characteristic", or AOC (Sperling and Melchner, 1978; Kinchla, 1980; Sperling, 1984). The AOCs drawn show the performance would be expected if performance on one of the row pairs could be sacrificed for an equivalent improvement in performance on the other row pair. Later (Fig. 9) we will provide evidence that such a trade-off can occur with our task by showing that performance lies approximately on the AOC when subjects are encouraged to move some of their attention from the target to the background rows. At this point, however, we will assume that the effect of the pursuit instructions was to encourage the subjects to trade performance on one pair of rows for performance on the other, and ask how this trade-off may have been achieved.

Sperling and Melchner (1978) proposed a contingency analysis to determine how trade-offs of performance on one task for performance on another may be achieved. If trade-offs were achieved by "sharing", that is, changing the relative proportion of one's processing capacity (i.e. "attention") devoted to target and background, then a correct response on the target would not be correlated with the response on the background. If trade-offs were achieved by "switching", on the other hand, the reports would be correlated because the subject could be in only one of two (or many) attentional states. And, being in one state would necessitate not being in any other. To discriminate these alternatives, Sperling and Melchner (1978) did a χ^2 contingency analysis for independence of responses. We did the same analysis to determine whether visual search with the moving stimuli was similar to visual search observed previously with stationary characters. The 2×2 contingency tables are shown in Tables 1 and 2. The χ^2 statistics were significant

Table 1. The 2 × 2 contingency table for subject E.K. Cell entries are the observed frequencies when the subject was correct on both target and background, on target only, on background only and on neither target nor background. Parenthesized cell entries are the expected frequencies. The total number of observations (N) is also shown

		Background	
		Correct	Incorrect
Target	Correct	22 (38)	185 (169)
	Incorrect	42 (26)	98 (114)

$N = 347$

at the 0.005 level. This means that on trials in which the subject responded correctly on the target, she was less likely to have responded correctly on the background. These results are similar to those reported by Sperling and Melchner (1978), who used static displays of characters and instructions to allocate different amounts of attention to different portions of the displays in the absence of smooth pursuit eye movements. Thus, visual search performance during smooth pursuit was similar to visual search performance with a static display in the sense that in both cases subjects may be allocating attention between target and background by means of a "switching" strategy.

The results reported thus far show that the smooth pursuit and the visual search observed in the present task were similar to prior observations when these two tasks were tested separately. Also, search performance on the target for smooth eye movements was better than that on the background. Before concluding that a common selective attentional mechanism accounted for the better search performance on the target for smooth eye movements, it is necessary to rule out explanations involving changes to the position or the speed of the retinal image.

Table 2. The 2 × 2 contingency table for subject B.K. Cell entries are the observed frequencies when the subject was correct on both target and background, on target only, on background only and on neither target nor background. Parenthesized cell entries are the expected frequencies. The total number of observations (N) is also shown

		Background	
		Correct	Incorrect
Target	Correct	96 (114)	213 (195)
	Incorrect	72 (54)	76 (94)

$N = 457$

The role of retinal position

The stimuli were designed so that any change in vertical eye position would not favor the target rows over the background rows. For example, if the subject drifted downward when instructed to match eye velocity with rows 1 and 3, then performance on row 3 might improve but at the expense of performance on row 1. To verify that this experimental strategy was successful, we examined the performance in each row separately and found that each row of a pair benefited by being part of the target. Specifically, rows both above and below the gap were affected almost equally by the pursuit instructions. Search performance on the inner rows (2 and 3) was 39% higher when they were the target instead of background. Performance on the outer rows (1 and 4) was similarly increased by 32% when they were target rather than background. This shows that the effects of selection were distributed among all rows, and the superior performance on the target rows was not due to shifts in vertical eye position.

Vertical position did influence the results in that search performance was on the average 29% better on the inner rows than on the outer rows. But this did not affect the test of the hypothesis because one inner row was a target while the other was background. An analogous argument can be made for the horizontal position. Numerals that were presented nearer to the horizontal center of the display were likely to be at an advantage for search performance. But, once again, since horizontal position was randomly assigned, its effects were distributed equally across target and background. Thus, the position of the retinal image did not provide an alternative explanation for the improved performance with the target for smooth pursuit.

The role of retinal speed

Suppose that the differences in the search of the target and background rows was not due to attention but to the quality of imaging of the stimulus on the retina. A stimulus that remains relatively stationary on the retina might allow for better perceptual judgments; a stimulus that is moving at a high retinal velocity might suffer retinal smearing, and, thus, hamper good perceptual judgments. If the visual search task were sensitive to changes in retinal image speed in the ranges that were tested, perceptual judgments about the target could be better because of its lower retinal speed relative to that of the background. At the outset, this explanation seems unlikely given that a stationary retinal image is not a prerequisite for good visual acuity. Westheimer and McKee (1975) found that resolution thresholds for Landolt C's and vernier acuity judgments remained the same regardless of the target being stationary or moving as fast as 2.5°/sec. Also, Murphy (1978) and Steinman *et al.* (1985) found no effect on contrast thresholds with retinal image speeds up to about 100′/sec. But since the requirements of our search task were not exactly the same as those in an acuity or contrast sensitivity task, retinal image motion deserves consideration.

Figure 5 shows visual search performance as a function of mean retinal speed. Mean retinal speed was computed as the absolute difference between eye velocity and stimulus velocity averaged over trials. At retinal speeds between 10 and 20′/sec, performance on the target rows was 2–3 times better than performance on the background. The retinal speed hypothesis would argue that if the retinal image speed of the background were equal to that of the target, then the difference in performance should disappear. Since this was not the case, the difference in the visual search performance on target and background was not due to retinal speed.

Figure 5 also shows that for both subjects, performance on the target improved from about 60 to 80% correct as retinal speed increased from about 17 to 21′/sec. This might suggest that higher retinal speeds were helpful. But this conclusion is not supported by the performance on the background which hardly varied as a function of retinal speed over a wider range (10–60′/sec).

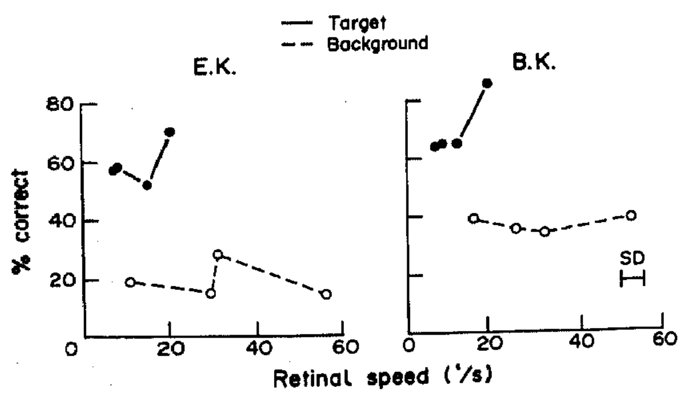

Fig. 5. Visual search performance on the target (solid line) and background (dashed line) as a function of mean retinal speed. Mean retinal speed is the absolute difference of eye velocity and stimulus velocity averaged over trials. Each datum point was based on 72–97 trials for E.K. and 68–172 trials for B.K. The error bar is the average standard deviation of retinal speed. S.D.'s range from 5.1 to 10.0′/sec.

In summary, visual search performance was better on the smoothly pursued target than on the background. The difference between target and background was not due to differences in either retinal position or retinal speed.

The results thus far suggest that smooth eye movements and perception share a common selective mechanism. That is, once a pair of rows is selected as a target for smooth pursuit, it is also selected for enhanced perceptual processing. The next step was to determine whether subjects *had* to attend to the same target they were told to pursue, or whether they simply chose to do so. In the next 2 experiments, conducted to address this issue, subjects were instructed to make one stimulus the target for smooth pursuit and another stimulus the target for perceptual attention.

2. *Visual Search of Moving Characters During Fixation of a Stationary Point*

In this experiment subjects were asked to maintain a stable line of sight while attending either the slow rows or the fast rows. The stimulus was exactly the same as that used in the first experiment, except that a central stationary point was present in the middle of the gap. If the subjects could maintain a stable line of sight while attending to moving targets then: (1) visual search should be the same as that in the first experiment, and (2) smooth eye movements should be able to provide a stable line of sight on the point. Such results would suggest separate selective mechanisms for smooth eye movement and perception.

E.K. was tested on 4 sessions and B.K. on 8 sessions of 100 trials each. In half of these sessions the row velocities were 25 and 50′/sec and in the other half they were 50 and 100′/sec.

The following trials were eliminated for reasons described in the Methods for the prior experiment: for E..K.: 2% of the trials removed because of saccades, 20% for vertical drifts, 3% for pressing illegal response buttons. For B.K.: 1% for saccades, 5% for vertical drifts, 3% for illegal button presses.

Performance in the visual search task was better on the attended rows

Performance in the visual search task is shown in Fig. 6. For comparison the performance from the first experiment is shown as well.

E.K. on the average did 32% better on the attended target than on the unattended back-

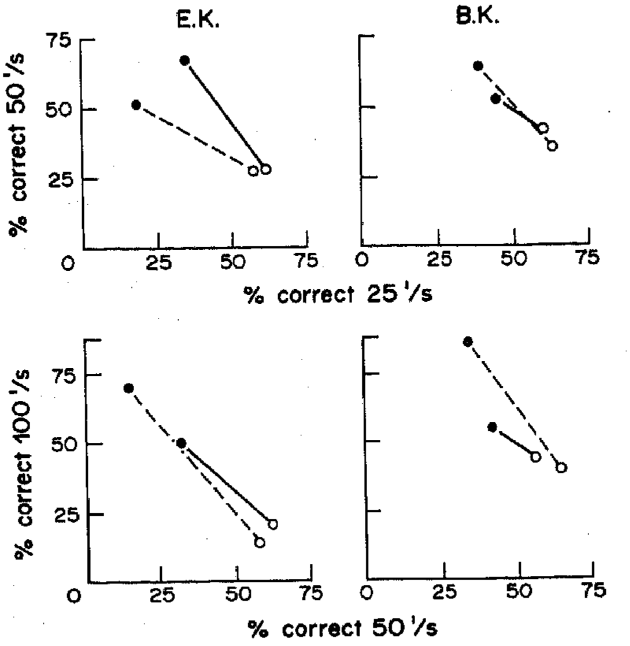

Fig. 6. Visual search performance in the form of Attention Operating Characteristics (AOCs). Percent correct on the slow rows is on the abscissa and percent correct on the fast rows is on the ordinate. The solid line connects the data points obtained while subjects maintained the line of sight on a stationary point while attending either the slow rows (open circle) or the fast rows (solid circle). The dashed lines show performance reproduced from Fig. 4 from the first experiment when subjects pursued either slow (open circle) or fast (solid circle) rows. Data points joining the solid lines are based on 68–92 trials for E.K. and 174–191 trials for B.K. Data points joining the dashed lines are based on 72–97 trials for E.K. and 68–172 trials for B.K.

ground. Similarly B.K. did 14% better on the target than the background. E.K.'s performance was about the same as her performance in Experment 1. B.K.'s was not the same in that there was a smaller difference between performance on the target and that on the background. This reduced difference between target and background for B.K. indicated that she had more difficulty in attending separately to the target and background rows.

Averaged across subjects and movement parameters, identification judgments (regardless of the report of location) on the attended target were 20% better than on the unattended background. Similarly, location judgments were better by 19%.

Both subjects' search performance was sufficiently similar to their performance in the initial experiment that it might seem that it was possible to maintain a stable line of sight while attending to moving eccentric targets. But the smooth eye movements associated with the search performance, described below, argue against this interpretation.

Subjects had difficulty maintaining the line of sight

Figure 7 shows eye velocity as a function of the velocity of the *attended* rows. Eye velocity increased in proportion to the velocity of the attended rows. Drifts were more pronounced for E.K. These results show that she achieved good search performance, which was comparable to that in the first experiment, at the expense of the stability of her line of sight. B.K. did maintain a fairly stable line of sight. However, her search performance indicated that she was not very successful at distinguishing the rows via attention. So, both subjects appear to have been unable to fixate the stationary point while attending the moving background.

Visual search as a function of row location

E.K.'s performance for all rows was 25–35% better when the rows were attended as opposed to unattended. B.K.'s performance differed in that she averaged only 16% better on rows 1, 2 and 4 when asked to attend to them. For row 3 she did equally well (82% correct) whether she was instructed to attend the row or not. Thus, for subject B.K. rows below the gap were favored for visual search regardless of attentional instruction. This is another indication that B.K. was less successful at attending one pair of the moving rows during fixation of the stationary point than during pursuit.

Visual search as a function of retinal speed

Figure 8 shows search performance on the target and background for both subjects as a

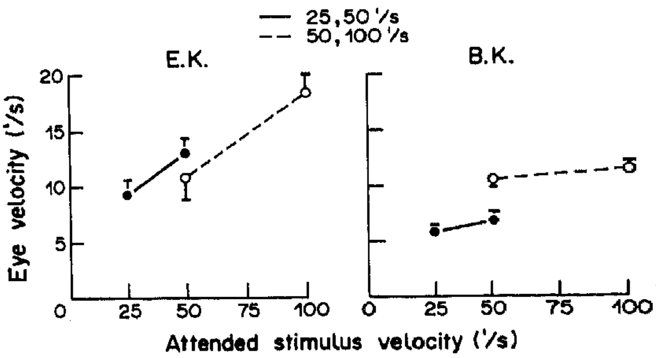

Fig. 7. Mean eye velocity as a function of the velocity of the attended stimulus while subjects were instructed to maintain a stable line of sight on the central stationary point while attending the moving rows. The solid lines show performance when the slow pair of rows moved at 25 and the fast pair at 50'/sec. The dashed lines show performance when the slow pair of rows moved at 50'/sec and the fast at 100'/sec. Each datum point is based on 68–92 trials for E.K. and 174–191 trials for B.K. Vertical bars represent ·1 SE.

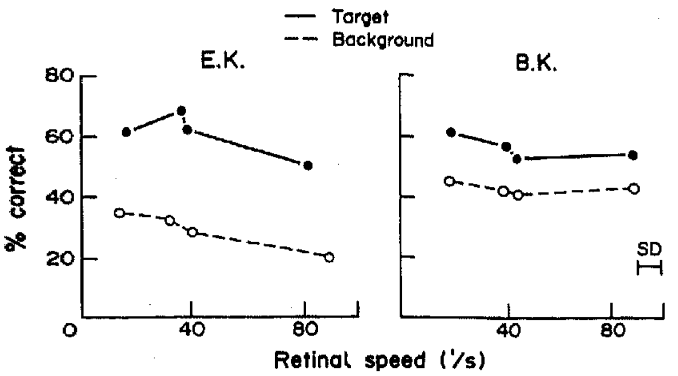

Fig. 8. Visual search performance on the target (solid line) and background (dashed line) when subjects were instructed to maintain a stable line of sight on a central stationary point and attend to the moving rows, as a function of mean retinal speed. Mean retinal speed is the absolute difference of eye velocity and stimulus velocity averaged over trials. Each datum point was based on 68–92 trials for E.K. and 174–191 trials for B.K. The error bar is the average standard deviation of retinal speed. SD's range from 7.5 to 18.5'/sec.

function of average retinal speed. E.K.'s performance for target and background tended to fall with increased retinal speed; B.K.'s fell slightly for the target but not for the background. Most important for the present experiment is the finding that visual search of the target was better than the search of the background across all retinal speeds.

In summary, the results with the stationary point support a shared selection process. B.K. maintained a relatively stable line of sight, but could not selectively attend to one of the pairs of rows as well as she did when she pursued the rows. E.K., on the other hand, could allocate attention as well as when she pursued the rows, but she could not maintain a stable line of sight.

3. *Visual Search While Pursuing One Target while Trying to Attend Another*

In this experiment subjects were instructed to match horizontal eye velocity with one pair of rows (either the slow or the fast) while attending the other pair. Trials were also run in which subjects were told both to pursue and to attend the same pair of rows, just as in the first experiment. The procedures were the same as in the first experiment, except that sessions consisted of 50 trials in which the instruction remained the same throughout. The 25 and 50'/sec pairs of rows were tested.

Trials were removed for the conventional reasons: for E.K.: 24% for vertical drifts and 4% for illegal button presses. For B.K.: 8% for saccades, 20% for vertical drifts, and 1% for illegal button presses.

Smooth pursuit performance

Average eye velocity was affected only very slightly by the attempt to shift attention to untracked rows. For example, E.K.'s mean eye velocity when she pursued and attended the slow rows was 20.8'/sec ($SD = 7.3$, $N = 73$). This increased to a mean of 21.0'/sec ($SD = 9.1$, $N = 68$) when she tried to pursue the slow rows while attending the fast rows. Thus, there was a small influence of the attempt to shift attention to the fast rows on both the average smooth eye velocity and on the variability of smooth eye velocity. A similar effect of the attempt to shift attention was observed when the fast rows were pursued. E.K.'s mean eye velocity was 31.5'/sec ($SD = 8.3, N = 81$) when she pursued and attended the fast rows. This decreased to a mean of 31.0'/sec ($SD = 9.7, N = 68$) when she pursued the fast rows while trying to attend the slow.

B.K.'s pattern of pursuit performance was similar. Her mean eye velocity when she pursued and attended the fast rows was 38.5'/sec ($SD = 8.5, N = 74$). When she tried to pursue the fast rows while attending the slow, mean eye velocity decreased to 35.9'/sec ($SD = 9.7, N = 86$). This was a larger change in mean eye velocity than observed for E.K. The reduction for B.K. was statistically reliable ($t = 1.8$, d.f. $= 158$, $P < 0.05$). But B.K.'s performance was different when she was told to pursue the slow rows. Her mean eye velocity was 26.8'/sec ($SD = 7.2$, $N = 57$) when she both pursued and attended the slow rows. Eye velocity actually fell slightly, to a mean of 26.2'/sec ($SD = 8.1$, $N = 67$), when she was told to attend the fast rows while pursuing the slow. Note that for B.K., like E.K., variabilitly was greater when the subject was instructed to pursue one pair of rows while attending the other.

In summary, subjects followed the pursuit instructions. Only small effects of the instruction to attend the background rows on eye velocity was observed.

Visual search performance

Both subjects' visual search performance, when asked to pursue and attend the same pair of rows (see Fig. 9), was nearly the same as that observed in the first experiment under the same instructions (see Fig. 4). On the average, they both did better on the target than on the background by 27%.

If subjects could pursue one pair of rows and

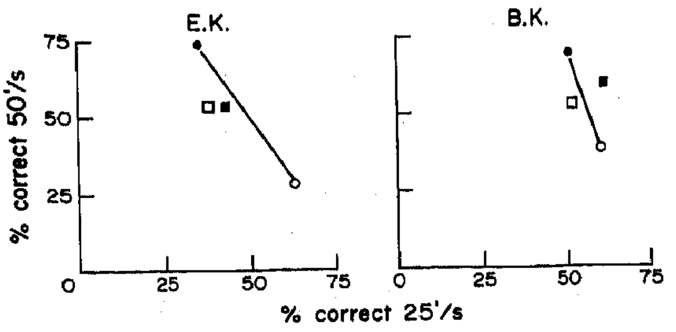

Fig. 9. Visual search performance when the subjects tracked one target and attended another in the form of Attention Operating Characteristics. Percent correct on the slow rows is on the abscissa and percent correct on the fast rows is on the ordinate. The solid circles represent performance when the faster pair of rows was both tracked and attended, the open circles when the slower pair of rows was both tracked and attended. The solid squares represent performance when subjects were instructed to track the fast rows while trying to attend the slow rows. The open squares represent performance when the subjects were instructed to track the slow rows while trying to attend the fast rows. Each datum point was based on 68–91 trials for E.K. and 57–86 trials for B.K.

attend the other (untracked) rows, then their search performance for the untracked rows should be the same as it was when these rows were the target for smooth eye movements.

Figure 9 shows that subjects were only partially successful at attending the untracked rows. For example, consider first E.K.'s performance when she pursued the fast rows. Performance on the fast target rows was 73% correct and on the slow, background rows was 35% correct. When she tried to maintain pursuit while shifting attention to the slow, untracked rows, performance on the fast rows decreased to 54% correct and performance on the slow rows increased to 43% correct. If E.K. had been fully successful at shifting attention, then performance on the slow, untracked rows should have improved to 63% correct, which was the percentage correct reports observed on the slow rows when they were the targets. The failure to reach 63% correct indicates that E.K. was only partially successful at shifting attention from the tracked fast rows to the untracked slow rows.

Evidence for a partial, rather than complete, shift of attention to untracked rows was also observed for both E.K. and B.K. when the slow rows were targets. Performance on the untracked, but attended, rows was poorer than performance on these rows when they were both pursued and attended.

In one case there was evidence that might seem to suggest an ability to pursue one pair of rows while attending the other. This occurred when B.K. pursued the fast rows and tried to attend the slow rows. In that case performance on the slow rows (62% correct) was about the same as performance when the slow rows were both attended and pursued (60% correct). However, this was also the case in which the largest (and only statistically reliable) change in mean eye velocity, accompanying the shift of attention to the untracked rows, was observed (see above section). Thus, B.K.'s high level of search performance with the untracked slow rows may *not* have been due to an ability to pursue the fast rows while attending the slow. Instead, her high level of search performance may have resulted from a substantial number of trials in which she actually was pursuing the slow rows.

In summary, the results described above show that subjects were not able to pursue one target while fully attending another. They were able to improve performance of the untracked rows, but this improvement fell short of the values observed when the rows were the targets for smooth eye movements.

DISCUSSION

In the present experiments subjects were asked to smoothly pursue a target consisting of 2 rows of eccentric, moving alphanumeric characters. Also present were 2 rows of other, background characters moving at a different velocity. Concurrent with the pursuit task, the subjects had to make perceptual judgments about both the moving target characters and the background characters. The judgment was to identify and locate the single numeral present in the target rows and the single numeral present in the background rows. We found that subjects were able to pursue the target rows while making the judgments. They were more successful at finding the single numeral in the target rows than in the background. This superior performance for the target rows was not due to the difference in the retinal speed of the target and background. When the retinal speed of the target and background rows was equal, a phenomenon made possible by the fact that pursuit velocity was seldom exactly the same as the target velocity, judgments about the target were 2–3 times more accurate than those about the background. We conclude that the improved perceptual performance for the target was due to the attention required to pursue the target.

This conclusion was further supported by the results of additional experiments in which subjects were asked to pursue one target while attending another. For example, in one of the experiments subjects were asked to maintain a stable line of sight on a central stationary point while simultaneously attending to one pair of moving rows. The attempt to do so led either (1) to drifts of the eye in the direction of the attended rows, or, (2) to poor search performance while the eye remained stationary. Also, in another experiment subjects were asked to smoothly pursue one pair of rows while trying to attend to the other, background rows. Visual search performance for the attended—but untracked—rows was considerably poorer than the performance observed when the same rows were both attended *and* tracked.

These results, taken together, offer support for a single selective mechanism which serves both the smooth oculomotor subsystem and the perceptual system. In other words, our perceptual attention is devoted to the stimulus we pursue, and not to other, background stimuli.

Other investigators have suggested that attention contributes to smooth pursuit (e.g. Murphy *et al.*, 1975; Cheng and Outerbridge, 1975; Dubois and Collewijn, 1979; Kowler *et al.*, 1984). These conclusions were based on oculomotor experiments in which subjects were to able to pursue moving targets superimposed on stationary backgrounds, or maintain the line of sight on stationary targets superimposed on moving backgrounds. These demonstrations of the ability to attenuate the influence of backgrounds on smooth eye movements shows that some selective mechanism contributes to smooth eye movements. The nature of the selective mechanism, however, was not revealed by these experiments. For example, the term "attention" was often used to describe the selection. However, it was not clear as to whether this "attention" was the same as that typically referred to in perceptual experiments employing such tasks as identification or location of target stimuli (Sperling and Melchner, 1978; Treisman and Gelade, 1980; Shaw, 1982; Reeves and Sperling, 1986). The present work directly addressed the question and shows that the selective attention for smooth pursuit eye movements and selection for visual processing are the same.

The shared selective mechanism has the following implications for smooth pursuit and perception:

First, in psychophysical experiments, retinal speed is often controlled by asking subjects to fixate a stationary point while making judgments about moving backgrounds (or in some cases to pursue a moving point while making judgments about stationary backgrounds e.g. Arend, 1976). This procedure assumes that whatever processes are required to perform the fixation task will have no consequences for the performance of the particular visual task under investigation. The results of the present experiments show that this assumption is false. Fixation of a stationary point in the presence of moving stimuli requires attention to the point. This attention to the point takes away attention from the moving backgrounds. Thus, the procedure of fixating a stationary point in the presence of moving stimuli may lead to underestimates of perceptual performance. So, the attentional consequences of fixation instructions used during psychophysical experiments must be evaluated in order to interpret perceptual performance correctly.

The second implication of finding a single, shared selection process for smooth pursuit and perception is that smooth eye movements become potentially valuable, overt indicators of attention. In the past saccadic eye movements have often been considered as overt indicators of attention (e.g. Just and Carpenter, 1975; Noton and Stark, 1971; Suppes *et al.*, 1983). However, two opposing points of view have arisen regarding the relationship of saccades with attention. One point of view is that saccadic eye movements are indicative of movements of attention. For example, Goldberg and Bruce (1985) have found cells in the frontal eye fields that respond with increased activity to a stimulus in their receptive field which is a target for saccadic eye movement. This enhancement was not observed when a saccade was made to another location or before saccades in the dark. The authors concluded that this neurophysiological event could be a neural correlate of attention. The other point of view is that saccades and attention shifts are controlled independently. Evidence for the independence viewpoint comes from work showing that visual attention can be shifted in the absence of saccades (Kowler and Steinman, 1977, 1979a; Klein, 1980; Reeves and Sperling, 1986) and that a single attention shift may be accompanied by more than one saccade (Kowler and Steinman, 1977). Thus, the role of saccades as overt indicators of attention is unresolved. Smooth eye movements, on the other hand, would be better overt indicators because the present results show that we attend what we pursue.

Such an overt indicator of attention might be of value in neurophysiological experiments. A measure of smooth eye velocity would reveal what visual stimulus the subject is attending while neural activity is measured. This technique would be useful, of course, only in the presence of different stimuli moving at different velocities. Changes in neural activity correlated with a change in smooth eye velocity might be attributable to a shift in attention from one stimulus to another.

Using smooth eye movements as indices of visual attention may also be of value in cognitive experiments. Smooth eye velocity might be used to obtain estimates of otherwise hidden attentional decisions made by subjects performing visual or cognitive tasks. Such estimates could than be used to develop models of these tasks and to determine the optimal attentional allocation strategies for task performance.

But the present results suggest that caution should be observed with regard to the use of eye movements as overt indices of attention. The present findings suggest a rather complicated relationship between smooth eye movements and attention. For example, in the last experiment subjects were asked to pursue a set of rows while trying to attend to the other. It was observed that a very small shift of mean eye velocity in the direction of the untracked rows was accompanied by a relatively large perceptual improvement on these rows. One might be tempted to conclude from this result that it is possible to dissociate perceptual attention from oculomotor attention, and that the subjects had decided to allocate oculomotor attention to one pair of rows and perceptual attention to the other. However, such a conclusion has an implicit assumption, namely, that smooth pursuit velocity and search performance were each unambiguous indicators of the amount of attention paid to a stimulus. Stated slightly more formally, the assumption is that both smooth pursuit and visual search are equally monotonic increasing functions of the amount of attention allocated to a stimulus [see Fig. 10(a)]. This need not be the case, and, in fact, is surely an implausible assumption. See, for example, Norman and Bobrow (1975) and Sperling (1984), for discussions of ways of describing the relationship between attentional decisions and performance for a variety of tasks.

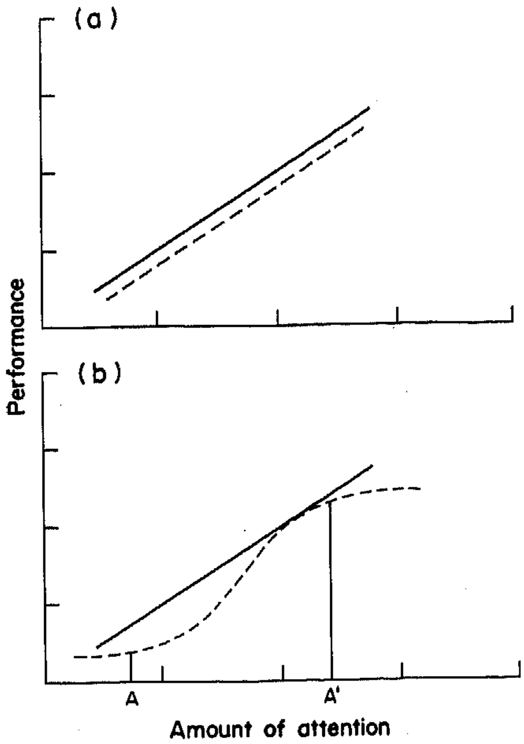

Fig. 10. (a,b) Hypothetical smooth pursuit (dashed line) and visual search (solid line) performance as a function of the amount of attention allocated to a stimulus. In (b) smooth pursuit is an s-shaped function of attention such that attentional inputs before A and beyond A′ are not reflected in the smooth pursuit performance. See text for further discussion.

Consider an alternative explanation for the observation of a large improvement in perceptual performance accompanied by a small shift in mean eye velocity. Suppose that the relationship between the amount of attention paid to a pair of rows in our task and the resulting performance was different for smooth pursuit and visual search. For example, in the hypothetical situation shown in Fig. 10(b), visual search performance is shown as a linear function, and smooth pursuit performance an s-shaped function, of the amount of attention allocated to the row pair. Points A and A′ are of particular interest. Before point A is achieved, increasing the attention paid to the rows does not result in better pursuit. Only after A does smooth eye movement performance benefit from additional attention. Similarly, beyond point A′ additional attention to the rows does not affect pursuit. Thus, taking attention away from a pair of rows beyond the point A′ would provide a situation similar to that observed, namely, little or no shift in mean eye velocity accompanied by a large improvement in visual search performance.

The above discussion suggests that in order to draw accurate inferences about attentional allocation from smooth eye movements one first needs to know: (1) the attentional decisions made by the subject, and (2) the consequences of these decisions for smooth pursuit (i.e. see Fig. 10). Measurement of eye movements alone, even smooth eye movements, which we have shown to be correlated with perceptual attention, will not suffice. These considerations illustrate how difficult it is in general to draw accurate inferences about mental processes from the measurement of motor performance.

The possibility of a nonlinear relationship between smooth eye movements and attention, illustrated in Fig. 10(b), has some fortunate consequences for our ability to move about natural visual environments. As we move about, images are in constant motion on the retina. The present results show that the eye will travel at a velocity that depends on how we have apportioned attention over the visual field. This means that spatially selective attention helps produce the retinal image velocities that are optimal for clear vision. We have argued that it may not be necessary to allocate all of one's attention to an object in order to pursue well enough to produce these velocities. This is a fortunate state of affairs. It allows us to maintain the line of sight on selected objects while preserving enough attention left over to make decisions, solve problems, or think.

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