Reprinted from Journal of the Optical Society of America A

Saccadic localization of eccentric forms

Peiyuan He

Department of Biomedical Engineering, Rutgers University, Piscataway, New Jersey 08854

Eileen Kowler

Department of Psychology, Rutgers University, New Brunswick, New Jersey 08903

Received January 5, 1990; accepted July 31, 1990

Saccades made to outline drawings of eccentric forms were compared with saccades made to single-point targets. Saccades could be directed to designated locations within eccentric forms nearly as accurately and precisely as they could be directed to single points. Saccades directed to the form as a whole landed at consistent locations near the center of the form. These results show that contour information is sufficient for accurate computation of a saccadic command and that this computation is constrained by the internal coding of the shape. A serial two-stage process, voluntary selection followed by a weighted-averaging process, is proposed for computation of the saccadic command based on information provided by shape.

INTRODUCTION

When human beings inspect natural visual environments they use saccadic eye movements to bring the line of sight to one or another selected object in the visual field. By contrast, most laboratory studies of saccades use a visual target consisting of only a single point. The difference between these two types of target, object and point, is crucial. When the target is a single point, the desired endpoint of the saccade is clearly marked on the visual display, and its retinal location can be represented unambiguously by the visual system. When the target is a spatially extended visual object, on the other hand, the desired endpoint of the saccade is not marked and must be computed by using the information in the visual contour as a reference. The problem investigated in the present paper is to discover how this computation is carried out. This problem has been largely ignored in vision research, in which, with rare exceptions,[1,2] interest has focused on how the coding of visual forms or objects serves pattern recognition rather than how it serves oculomotor localization. This is a serious limitation. Pattern recognition and oculomotor localization are distinct tasks with different visual demands. These differences raise the possibility that the visual representations that serve one may not be adequate or appropriate for the other.[3]

There are two views of how the visual configuration of a spatially extended target can influence saccades. One view is that the visual configuration of the target will place little or no constraint on saccades, so that any saccadic landing position within the target can be selected simply by using the contour as a reference. This view derives from demonstrations that stable gaze [standard deviation (SD) less than 3 arcmin] can be maintained at various places along or within the contour of simple forms regardless of target size[4,5] or shape,[6] provided that targets are confined to the fovea. (Stability declines somewhat for extrafoveal targets.[7]) However, the processes that keep gaze stable[8,9] might not be of much relevance to the control of saccades. Saccades are responsible for shifts in gaze rather than for maintaining the line of sight in a given position.

An alternative view is that the visual configuration of a spatially extended target will place strong and unavoidable constraints on saccades. This view has appeared in several recent studies of saccades made to visual targets presented with irrelevant visual backgrounds. These studies described tendencies of subjects to direct saccades to the center of the entire visual stimulus array (target + background).[10–12] These so-called centering (or averaging) tendencies have been attributed to a fast, reflexive saccadic subsystem that averages all elements in the visual field in order to determine the saccadic endpoint.[11,13] According to this view, subjects make saccades to the center of the stimulus array, even when the intended target for the saccade is located somewhere other than at the center. The job of reaching the designated saccadic goal is left to a second, voluntary saccadic subsystem, which is assumed to be able to override centering tendencies under special circumstances, e.g., if the subject delays responding long enough for this voluntary subsystem to act.[11]

Recently He and Kowler[14] rejected the two-subsystem idea described above and questioned the plausibility of automatic centering tendencies. They noted that such tendencies were prominent only when target locations varied randomly so that subjects were uncertain regarding which location in the stimulus array contained the target and which contained irrelevant visual backgrounds. (See also Ref. 12.) He and Kowler[14] showed that, when subjects were uncertain regarding the true target location, saccades were directed toward the location in which the target was most likely to appear. This means that centering tendencies are more likely to be the result of visual search strategies based on expectations regarding the likely location of the target rather than the result of low-level visual or visuomotor averaging.

The use of random target locations in the prior research, and the resulting confusion of visuomotor processes with the subjects' strategies, means that basic properties of saccades to spatially extended stimuli remain unexplored. The goal of the present experiments was to answer a fundamental

0740-3232/91/020440-10$05.00

question regarding saccades to spatially extended stimuli, namely, are spatially extended stimuli effective targets for saccades? In these experiments, unlike the previous research on centering tendencies described above, target locations were not selected at random. Instead, subjects were told precisely where, within or along the contour of a simple form, to try to direct the line of sight. This approach minimizes the confusion of strategies with oculomotor capacities. This confusion was prominent in the prior studies of centering tendencies.

We compared the accuracy and precision of saccades directed to locations within a spatially extended stimulus (i.e., an outline drawing of a form) with the accuracy and precision of saccades directed to a presumably less ambiguous target, namely, a single point. The single point was presented alone and located at the same eccentricities as the form. Our main interest was in finding out whether a saccadic target, defined solely by reference to the information in the contour of the form, would be as effective as a single point or whether spatially extended targets would lead to a greater scatter among saccadic endpoints or to the line of sight's being drawn to a particular location within the form. We also examined saccades made under the instruction to look at the whole form, an instruction that seemed to us to resemble what people often try to do when they scan natural, patterned environments.

We found that saccades could be directed to a designated location within a form nearly as well as they could be directed to a single point. Nevertheless there was evidence obtained under the whole form instruction for natural or preferred saccadic endpoints. This suggests that the internal coding of shape places some (but certainly not inviolate) constraints on the saccadic pattern.

METHODS

Eye-Movement Recording

Two-dimensional movements of the right eye were recorded by a Generation IV SRI double Purkinje image tracker.[15] The left eye was covered, and the head was stabilized by a dental biteboard.

The voltage output of the tracker was fed on line through a low-pass 50-Hz filter to a 12-bit analog-to-digital converter. The analog-to-digital converter, under the control of a computer (LSI 11/24), sampled eye position every 10 msec. The digitized voltages were stored for later analysis.

The tracker's 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 rates were the same as those used in the experiment. Noise level, expressed as a SD of position samples, was 0.4 arcmin for horizontal and 0.7 arcmin for vertical positions.

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

Subjects

The authors (EK and PH) were subjects in the experiments. EK is an experienced subject, and PH had never served as a subject before in eye-movement or psychophysical experiments.

Stimuli

There were two types of display. In one the target of the saccade was a form. In the other it was a point.

The display in which the target was the form is shown in Fig. 1 (top). It consists of two right triangles, a central triangle located near the subject's line of sight and an eccentric triangle that served as the target for the saccade. The central triangle contained two points, one serving as a fixation point and the other serving as a target marker. The target marker indicated where, within the eccentric target triangle, the subject was to try to direct the saccade. We refer to this location within the eccentric triangle as the designated target location.

Four designated target locations were tested, as shown in Fig. 1 (bottom): A, the symmetric point of the triangle[16]; B, the midpoint of the base; C, the location aligned horizontally

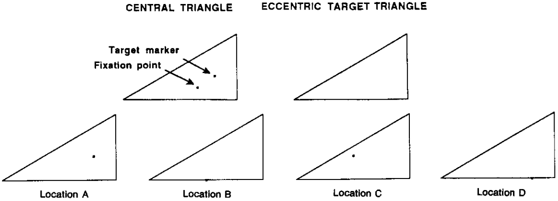

Fig. 1. Stimuli used in the experiments. The definitions of each component of the stimuli are on the top, and the four possible locations of the target marker are on the bottom.

with the symmetric point and vertically with the midpoint of the base; D, the location aligned vertically with the symmetric point and horizontally with the midpoint of the base. The horizontal distance between the midpoint of the base and the symmetric point was 18 arcmin. The vertical distance between the midpoint of the base and the symmetric point was 12.8 arcmin. The fixation point was located in the center of the four designated target locations.

The base of the central and target triangles was 60 arcmin, and the height was 35 arcmin. The triangles were oriented so that the 90-deg angles were either on the left or on the right. The eccentric triangle was located either to the left or to the right of the central triangle. The distance between the fixation point of the central triangle and the designated target locations of the eccentric triangle ranged between 63 and 99 arcmin.

In the second type of display the target was a single point. In these displays the eccentric target triangle was not shown. Instead, only a single eccentric point was presented at one of the four designated target locations.

The contour of each triangle was actually composed of 28 closely spaced (6 arcmin apart) points. The luminous directional energy of each point was 0.21 cd/μsec.[17] The target marker was three times as intense as the fixation point so that it would be easily distinguishable. Displays were refreshed every 20 msec, a rate high enough to prevent visible flicker.

The stimuli were seen against a dim (0.25 cd/m^2), homogeneous background produced by a raster on a second display monitor located perpendicular to the first. The views of the two displays were combined by a pellicle beam splitter. The combined displays were viewed in a dark room through a collimating lens that placed them at optical infinity. Appropriate negative lenses were placed between the subject's eye and the collimating lens so that the stimuli appeared in sharp focus for each subject.

Procedure

Before each trial the central triangle containing the fixation point and the target marker was presented. The subject was told to take note of the location of the target marker. The subject looked at the fixation point and started the trial by pressing a button when ready. Two hundred msec later, either the eccentric target triangle or the eccentric point appeared. The central triangle was not removed.

The subject was instructed to make a single saccade to the target, which was either the designated target location within the eccentric target triangle or the single eccentric point. The instruction to make a single saccade (rather than multiple saccades) was used because we wanted to investigate how saccades are programmed to selected locations at known eccentricities, rather than how the final target position can eventually be reached by a series of corrective saccades. To help subjects follow the instruction to make a single saccade, the experimenter told the subject after each trial the number of saccades that had been made. This feedback was effective in reducing the number of trials with multiple saccades. Trials with multiple saccades were discarded. Subjects were also instructed to try to make the saccade as accurately as possible and not to sacrifice accuracy in order to achieve a shorter latency.[9,18] This instruction was given because the object of the experiment was to estimate the capacity to look at designated locations within forms. Attempts to sacrifice saccadic accuracy to achieve a shorter latency would lead to underestimating this capacity.

The entire display remained on for 1300 msec following the appearance of the target and was then removed. Five hundred msec later the central triangle, the fixation point, and the target marker reappeared, signaling that the subject could begin to prepare for the next trial.

The nature of the target (form or point) and the location of the target marker were each selected randomly and independently before each trial. The probability of selecting either target type was 0.5, and the probability of selecting any of the four designated target locations was 0.25. The subject was shown the target marker inside the central triangle before the trial but was not told whether the target would be the form or the point.

Experimental Sessions

Each eye-movement recording session contained 100 trials and lasted approximately 20–30 min. Each subject was tested in a total of six–ten sessions for the basic experiment described above. An additional 22–26 sessions were run for each subject in which stimuli and instructions were changed. Details regarding these sessions will be presented below with the results.

Analysis of Eye-Movement Data

The data to be reported consist of the size and the latency of the first saccade made to the target. Saccades were detected by means of a computer program employing an acceleration criterion. The criterion was determined for each subject by examination of a large sample of analog records of eye position in which the saccades detected by the algorithm were marked. Saccades as small as the microsaccades that may be observed during maintained fixation[9] could be reliably detected by the algorithm.

The main results to be presented consist of the size and the latency of the first saccade that occurred at least 100 msec after the onset of the target. Trials containing more than one saccade (13% for subject EK and 17% for PH) were not analyzed because, as noted above, these represented a different strategy in which the first saccade would be directed to the approximate target location and subsequent corrective saccades used to clean up errors. Saccades occurring earlier than 100 msec (less than 2% for both EK and PH) were omitted because their latencies were so short that it was not likely that their programming was affected appreciably by information in the current stimulus display.

Saccadic latency was determined by calculating the time between the onset of the target stimulus and the onset of the first saccade. Saccade size was calculated from the difference between the steady-state eye position after the saccade and the steady-state eye position at the start of the trial (average of the first 50 msec) for each meridian.

Perceptual Localization

Using the same stimuli as those described above, we also tested how well subjects could perceptually locate the four designated target locations. Only if the target locations could be perceived accurately and precisely would it be reasonable to test whether the subjects can make saccades to the designated locations. Otherwise it would be hard to determine whether any difficulties in saccadic control were due to limitations of visual resolution or to limitations of saccadic programming.

The subject's task was to look at the fixation point while setting the position of a test point within the eccentric target triangle to the designated target location. The procedure was as follows. The central triangle containing the fixation point and the target marker was presented before the trial. Five hundred msec after the subject started a trial the eccentric target triangle containing the test point was presented briefly (100, 200, or 400 msec). These brief presentations approximated the processing time preceding saccades. Each brief presentation was followed by a random-dot mask lasting 1 sec. The location of the test point was adjusted by the subject after each brief presentation. The subject then repeated the procedure until he or she was sure that the test point in the eccentric triangle was at the designated target location. Then the subject ended the trial. The eccentricity of the target triangle was varied randomly within a range of ± 10 arcmin in both up–down and left–right directions from one brief presentation to the next in order to encourage the subject to make the judgment by using only the triangle's contour as a reference. In the perceptual experiment the average horizontal distance from the fixation point to the nearer pair of designated target locations was 81 arcmin and to the more distant pair of designated target locations was 99 arcmin. The target triangle was located to the right of the central triangle, and it was oriented with the 90-deg angle on the right.

RESULTS

Perceptual Localization

Perceptual localization will be considered first because, as noted in the Methods section, saccadic localization is interpretable only after we have established that the four designated target locations tested were perceptually distinguishable.

There were no systematic effects of the duration of presentation in the range (100–400 msec) tested. The average positions of the test point, pooled across durations, are plotted in Fig. 2. The average errors (the absolute difference between the perceived and the actual target location, averaged over the four locations) were small (1.7 arcmin for EK and 2.9 arcmin for PH). The errors were smaller for the nearer locations (0.6 arcmin for EK and 0.2 arcmin for PH) than for the more distant locations (2.9 arcmin for EK and 5.5 arcmin for PH). The errors for the more distant locations were underestimates of the target locations. The mean horizontal separation between the perceived location of the horizontally adjacent targets was 15 arcmin for EK and 12 arcmin for PH, somewhat less than the actual horizontal separation (18 arcmin) of the adjacent designated target locations.

Perceptual localization, in addition to being quite accurate, was also very precise. SD's of the judgments were 2–4 arcmin. The symmetric point was judged more precisely (horizontal SD of 1.9 arcmin for EK and 2.0 arcmin for PH) than the other locations (SD of 3.5 arcmin for EK and 3.0 arcmin for PH). The results show that the perceptual localization of the designated locations in the eccentric form were both accurate and precise. This makes it reasonable to ask how well the same locations could serve as targets for saccades.

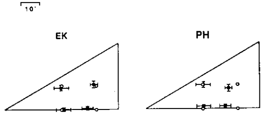

Fig. 2. Mean settings (±1 SD) in the perceptual localization task averaged over presentation durations (100–400 msec) relative to the contour of the eccentric target triangle. Each datum point is based on 44–58 observations. Open circles indicate the four designated target locations, which were not displayed during the experiment.

Saccades to Locations within Forms versus Saccades to Points: The Basic Experiment

For this experiment comparing saccades made to locations within forms with saccades to points, the target triangle was located to the right of the central triangle. Two orientations of the triangle (90-deg angle on the right or on the left) were tested for subject EK and one (90-deg angle on the right) for subject PH. The distance between the fixation point and the two nearer target locations was 81 arcmin and between the fixation point and the two more distant target locations was 99 arcmin. These distances define the expected sizes of accurate saccades.

The average endpoints of saccades (± 1 SD) relative to the position of the targets are shown in the top two rows of Fig. 3. These endpoints were based on the measured sizes of saccades, assuming that the eye was on target (that is, looking at the fixation point) at the start of the trial.[19] The horizontal size and the latency of the saccades are shown in Table 1.

In general saccades were fairly accurate. Saccades to the point targets, when no eccentric form was presented, were more accurate than saccades to the locations within forms. The average error, defined as the absolute difference between the observed and the expected saccade sizes averaged over the four designated target locations, was 4.6 arcmin for forms and 3.9 arcmin for points for EK and 8.8 arcmin for forms and 6.6 arcmin for points for PH. The directions of the errors were somewhat different for the forms and the points. With the form targets, EK tended to overshoot the nearer locations and undershoot the more distant locations. This pattern was less pronounced with the point targets for which overshoots were more common regardless of the target location. PH always overshot the targets, whether they were forms or points.

Another way to evaluate saccadic accuracy is to look at the horizontal separation of the saccadic endpoints (Fig. 3). These horizontal separations tell us how distinguishable the saccadic endpoints were when the saccades were directed to different locations. The endpoints of saccades to the locations within forms were closer together than the endpoints of saccades to the points. The mean horizontal separation of saccadic endpoints for adjacent horizontal target locations was 8.7 arcmin for forms and 13.8 arcmin for points for EK and 10.7 arcmin for forms and 15.6 arcmin for points for PH. Note that for both forms and points the observed horizontal

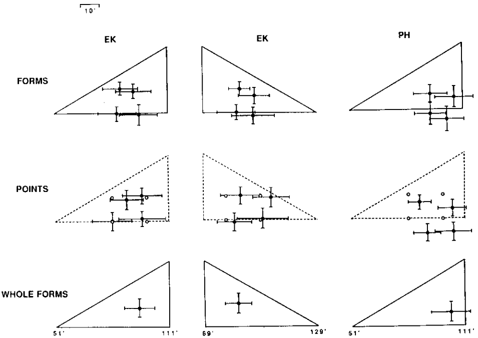

Fig. 3. Mean endpoints of saccades (±1 SD) for subjects EK and PH to locations within forms, to points, and to the whole form. Endpoints are shown relative to the contour of the eccentric target triangle. The distance from the fixation point to the left and the right ends of the base of the triangle are shown in minutes of arc in the bottom row of triangles. For saccades to point targets the eccentric triangle was not displayed; the dotted line shows its usual position and the open circles show the position of the point targets. Each datum point is based on 33–70 observations. All targets were to the right of the fixation point.

Table 1. Comparisons of Saccades to Designated Locations within Forms with Saccades to Points for Subjects EK and PH[a]

		Subject EK				Subject PH	
	Saccadic	90-deg Angle on the Right		90-deg Angle on the Left		90-deg Angle on the Right	
Location	Measures	Form	Points	Form	Points	Form	Points
A	Size (SD)	92.7 (9.3)	96.8 (10.4)	88.4 (5.7)	88.4 (10.5)	106.1 (10.3)	104.2 (7.4)
	Error	−6.3	−2.2	7.4	7.4	7.1	5.2
	Latency (SD)	279 (46)	334 (65)	243 (35)	268 (51)	262 (37)	272 (56)
	N	33	47	41	67	47	42
B	Size (SD)	83.9 (10.0)	80.8 (10.5)	95.4 (11.4)	100.2 (13.5)	93.4 (8.4)	90.6 (7.2)
	Error	2.9	−0.2	−3.6	1.2	12.4	9.6
	Latency (SD)	265 (76)	303 (71)	277 (40)	309 (35)	254 (50)	291 (54)
	N	55	69	43	50	56	59
C	Size (SD)	85.8 (9.4)	88.6 (8.9)	96.1 (8.2)	104.7 (9.7)	93.4 (8.9)	86.9 (5.9)
	Error	4.8	7.6	−2.9	5.7	12.4	5.9
	Latency (SD)	260 (69)	283 (80)	267 (63)	288 (40)	260 (39)	273 (40)
	N	57	62	42	50	64	39
D	Size (SD)	95.4 (10.1)	96.5 (12.4)	86.6 (10.0)	85.2 (9.0)	102.1 (9.1)	104.5 (9.8)
	Error	−3.6	−2.5	5.6	4.2	3.1	5.5
	Latency (SD)	291 (68)	311 (85)	248 (55)	278 (46)	260 (46)	274 (55)
	N	50	37	54	43	70	47

[a] Location A is the symmetric point of the triangle, location B is the midpoint of the base, location C is aligned vertically with the symmetric point and horizontally with the midpoint of the base, location D is aligned vertically with the midpoint of the base and horizontally with the symmetric point. Perfectly accurate saccades to the two nearer locations would be 81 arcmin, to the two further locations would be 99 arcmin. Horizontal saccade sizes and errors (saccade size − target eccentricity) are shown in minutes of arc. Latencies are in milliseconds.

separation of saccadic endpoints was less than the expected separation, which was 18 arcmin.

The SD of the saccade sizes was small. The average SD for EK was 9.3 arcmin for forms and 10.6 arcmin for points and for PH was 9.2 arcmin for forms and 7.6 arcmin for points (see Table 1). These values were approximately 13% of the saccade size, which is in line with previous reports of the SD's of saccades during target step tracking.[20] Precision did not differ systematically among the four target locations (see Table 1).

The average saccadic latency was shorter with the form than with the point targets. Average latency was 266 msec for forms and 297 msec for points for EK and 259 msec for forms and 278 msec for points for PH (see Table 1). EK's latencies were slightly longer for the more distant targets. PH's latencies did not differ systematically among the four target locations.

These results show that the subjects could make saccades to designated locations within forms based on the information in the contour. The saccades made to the points were more accurate than the saccades made to the locations within forms. These differences, however, were sufficiently small (<5 arcmin in average saccade size) to have trivial visual consequences.

The results also show that there was no apparent advantage for saccades directed to the symmetric point of the triangle because these saccades were comparable in accuracy, precision, and latency with the saccades made to the three other locations.

Were Learned Saccadic Programs, Learned with Point Targets, Responsible for the Highly Accurate Saccades to the Form Targets?

In the above experiment, trials in which targets were locations within forms were randomly mixed with trials in which targets were points. It was therefore possible that the good performance with the forms was due to the use of saccadic programs learned from the trials with the point targets. To determine whether trials with points taught trials with forms, we ran a new experiment in which the locations within forms were tested first and the point targets were tested afterward. The stimuli were different from those used in the above experiment so that subjects could not rely on any previously developed saccadic programs. In this experiment the targets were located to the left of the central triangle (instead of to the right). Also, the distance between the fixation point and the nearer target locations was reduced to 63 arcmin (from the 81 arcmin used above), and the distance between the fixation point and the more distant target locations was reduced to 81 arcmin (from the 99 arcmin used above). The triangle was oriented with the 90-deg angle on the right.

Figure 4 shows the results. The levels of accuracy and precision were quite similar to those in the above experiment, indicating that the accuracy and precision achieved in the form trials were not due to saccadic programs learned in the point trials.

In this experiment EK was slightly more accurate with the forms than with the points. The average error, defined as the absolute difference between the observed and the expected saccade sizes, was 5.6 arcmin for forms and 7.5 arcmin for points. PH was more accurate with points, with the difference between actual and expected saccade sizes 8.6 arcmin for the forms and 3.4 arcmin for the points. The mean horizontal separation between saccadic endpoints for adjacent horizontal target locations was 13.7 arcmin for forms and 12.8 arcmin for points for EK and 8.9 arcmin for forms and 13.2 arcmin for points for PH. In general, both subjects' saccades tended to be too short. (In the above experiment saccades were either too short or too long, depending on the target location; see Fig. 3.)

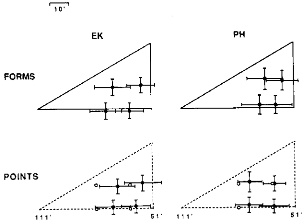

Fig. 4. Mean endpoints of saccades (±1 SD) for subjects EK and PH to locations within forms and to points, when forms were tested before points. Endpoints are shown relative to the contour of the eccentric target triangle. The distance from the fixation point to the left and the right ends of the base of the triangle are shown in minutes of arc in the bottom row of the triangles. For saccades to point targets the eccentric triangle was not displayed; the dotted line shows its usual position and the open circles show the position of the point targets. Each datum point is based on 35–71 observations. All targets were to the left of the fixation point.

The standard deviation of saccade size was smaller for forms (8.2 arcmin) than for points (9.0 arcmin) for EK and larger for forms (9.1 arcmin) than for points (6.9 arcmin) for PH.

Average latencies were approximately 30–80 msec shorter in this experiment, in which form and point trials were tested separately, relative to the above experiment, in which form and point trials were randomly intermixed. The average latency in form trials (194 msec) was again shorter than in the point trials (234 msec).

Could Accurate Saccades be Programmed without the Eccentric Target Triangle?

In a separate session, EK was instructed to make saccades to the estimated location of the eccentric target without either the eccentric target form or the eccentric target point being present. This was done to determine the contribution of factors other than the contour of the target triangle to the programming of saccades. These factors might include other visible references, such as the central triangle, or any saccadic programs memorized after only a few trials. In this experiment a block of 10 trials in which the eccentric target triangle was present alternated with a block of 10 trials in which the eccentric target triangle was not present. Five blocks of each type were tested. The central triangle was always presented in each kind of block. For trials in which no eccentric target triangle was presented, the subject had only the central triangle, the faint glow of the cathode-ray-tube display, and the memory of prior saccades to guide the saccade to where she estimated the target might be.

Performance when the eccentric target triangle was present was almost identical to performance measured in the above experiment in which a triangle of the same eccentricity and orientation was tested (see Fig. 4). Performance was different, however, when the target triangle was not present.

First, the average sizes of saccades were 10–20 arcmin larger than saccades made when the target triangle was present. Second, saccades always overshot the target location. These results are consistent with previous reports of increased sizes of saccades to remembered, rather than visible, target locations.[21,22] Also, endpoints of saccades without the target triangle were more widely scattered. The average SD of the saccades was 16.5 arcmin, approximately twice the average SD (8.4 arcmin) of saccades made in the presence of the eccentric triangle in the same experimental session.

This result shows that the good performance achieved in directing saccades to the locations within forms was not due to extraneous factors. Information in the contour of the eccentric form was essential for producing the accurate and precise saccades observed.

Equating the Latency of Saccades to Forms and to Points

In the above experiments the endpoints of saccades to adjacent horizontal locations within forms were, in general, closer together (by approximately 5 arcmin) than the endpoints of saccades to points. Also, the latency of saccades to the locations within forms was shorter (by approximately 20–35 msec) than the latency of saccades to the points. In this experiment we encouraged subjects to adopt the same saccadic latency in form trials and in point trials to see whether this would improve the accuracy of saccades to forms relative to saccades to points. Subjects were instructed to adopt a latency that seemed long enough (320 msec for EK and 300 msec for PH) to ensure good saccade accuracy for both form and point trials. We measured saccadic latency on line and told the subject the latency immediately after each trial in order to help them achieve the instructed latency.

EK was tested with the 90-deg angle of the triangle on the left and PH with the 90-deg angle on the right. The distance between the fixation point and the target locations was the same as in the basic experiment. The trials with saccades to the locations within forms and to points were randomly mixed within a session.

Subjects were able to adjust saccadic latency in the direction indicated by the instructions. Latencies increased, and the difference between latencies with form and point trials was smaller than in the basic experiment. For EK the mean latency was 314 msec for saccades to locations within forms and 339 msec for saccades to points, and for PH the mean latency was 276 msec for forms and 282 msec for points.

Saccades to locations within forms were nearly as accurate as saccades to points (see Fig. 5 and Table 2). The average difference between the observed and the expected saccade sizes was 3.8 arcmin for forms and 4.4 arcmin for points for EK and 6.6 arcmin for forms and 4.6 arcmin for points for PH. The improvement in the accuracy of saccades to locations within forms in this experiment is also apparent in the analysis of the mean separation of the endpoints of saccades to adjacent horizontal target locations. This separation was 10.3 arcmin for locations within forms versus 11.4 arcmin for points for EK (compared with 8.7 arcmin versus 13.8 arcmin in the basic experiment) and 15.3 arcmin for locations within forms versus 16.3 arcmin for points for PH (compared with 10.7 arcmin versus 15.6 arcmin in the basic experiment). The average SD for EK was 6.6 arcmin for forms and 7.3 arcmin for points and for PH was 9.1 arcmin for forms and 7.8 arcmin for points, which were similar to the SD's in the basic experiment.

The results show that by making the latencies of saccades to locations within forms and to points longer and more similar, the difference between accuracy of saccades to locations within forms and to points was reduced.

Saccades to the Whole Form

We instructed subjects to direct the saccade to the whole form, rather than to a designated location within it. Trials in which the targets were points were also tested in the same session. The subject knew whether the point or the whole form would be the target before the trial because the target marker was present only when the points would be the targets. The orientation and the distance of the triangle were the same as in the basic experiment.

Saccades to the whole form tended to land inside the form near the symmetric point (Fig. 3, bottom row). The horizontal distances between the saccadic endpoints and the symmetric point were 3–5 arcmin; the vertical distances were 1–5 arcmin. The SD of the saccade size was 7.5 arcmin for EK and 10.5 arcmin for PH. These SD's were slightly smaller for EK and nearly the same for PH than the SD's of saccades to the locations within forms and saccades to the points (see Table 1). Saccadic latencies were 229 and 177 msec for EK for the two types of triangle (90-deg angle on the left and on the right) and 246 msec for PH. These values were substantially shorter (30–100 msec) than the latencies of saccades to the locations within forms or to the points.

Saccades to the Whole Form with Varied Eccentricities

It was surprising to see that saccades landed consistently at the same location in the form with such a short latency when the form as a whole was the target. To make sure that this

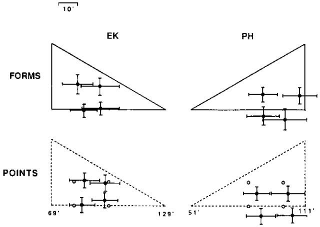

Fig. 5. Mean endpoints of saccades (±1 SD) for subjects EK and PH to locations within forms and to points with approximately equal saccadic latencies. Endpoints are shown relative to the contour of the eccentric target triangle. The distance from the fixation point to the left and the right ends of the base of the triangle are shown in minutes of arc in the bottom row of triangles. For saccades to point targets the eccentric triangle was not displayed; the dotted line shows its usual position and the open circles show the position of the point targets. Each datum point is based on 40–80 observations. All targets were to the right of the fixation point.

Table 2. Comparison of Saccades to Designated Locations within Forms with Saccades to Points for Subjects EK and PH When Subjects Were Under Instructions to Equate Saccadic Latencies for Form and Point Targets[a]

		Subject EK 90-deg Angle on the Left		Subject PH 90-deg Angle on the Right	
Location	Saccadic Measures	Form	Points	Form	Points
A	Size (SD)	82.7 (8.1)	86.4 (8.1)	108.1 (9.1)	101.6 (8.8)
	Error	1.7	5.4	9.1	2.6
	Latency (SD)	290 (52)	321 (48)	279 (41)	287 (36)
	N	40	80	58	51
B	Size (SD)	94.6 (9.9)	97.0 (6.8)	88.9 (8.6)	87.5 (7.6)
	Error	−4.4	−2.0	7.9	6.5
	Latency (SD)	340 (55)	362 (63)	263 (43)	273 (42)
	N	48	57	66	49
C	Size (SD)	94.5 (10.2)	97.2 (7.8)	88.7 (7.4)	85.4 (7.0)
	Error	−4.5	−1.8	7.7	4.4
	Latency (SD)	329 (71)	345 (49)	263 (42)	272 (33)
	N	48	46	62	42
D	Size (SD)	85.8 (7.0)	85.0 (6.6)	100.1 (11.4)	103.8 (7.9)
	Error	4.8	4.0	1.1	4.8
	Latency (SD)	297 (40)	329 (53)	298 (82)	294 (33)
	N	66	78	56	41

[a] Location A is the symmetric point of the triangle, location B is the midpoint of the base, location C is aligned vertically with the symmetric point and horizontally with the midpoint of the base, location D is aligned vertically with the midpoint of the base and horizontally with the symmetric point. Perfectly accurate saccades to the two nearer locations would be 81 arcmin, to the two further locations would be 99 arcmin. Horizontal saccade sizes and errors (saccade size − target eccentricity) are shown in minutes of arc. Latencies are in milliseconds.

performance was not due to the constant eccentricity of the triangle, we varied the eccentricity of the target triangle in this experiment. The eccentricity was randomly selected on each trial to be 70, 80, 90, 100, or 110 arcmin, where eccentricity refers to the distance between corresponding locations in the central and the eccentric target triangle. We also tested a triangle at a fixed eccentricity of 90 arcmin in a separate experimental session. The triangles were oriented with the 90-deg angle on the left. The target triangle was located to the left of the central triangle. The subjects were instructed to make a single saccade when the eccentric target triangle appeared. They were told to be sure to wait until the target triangle appeared so as to reduce any errors that might be caused by anticipation of the triangle's location. This instruction would be expected to prolong saccadic latencies. This was not troublesome because the main interest in the experiment was in achieving best possible saccadic accuracy and precision.

Saccades landed in the same place with respect to the contour of the target triangle in spite of the varied eccentricity (Fig. 6). Precision was nearly the same for fixed and varied eccentricities. Latencies were relatively long (358 msec for EK, 352 msec for PH), as is expected given our instruction to emphasize accuracy and avoid anticipating the target location. As shown in Fig. 7, the endpoints of horizontal saccades increased linearly as the eccentricity of the form increased.

The average landing positions within the forms, shown in Fig. 6, were somewhat different from the landing positions shown in Fig. 3 (bottom graphs) discussed above. The landing position in Fig. 3 was near the symmetric point of the triangle, whereas the landing positions in Fig. 6 undershot the symmetric point by approximately 12 arcmin horizontally for EK and 14 arcmin for PH. The difference may have been due to the different directions of the saccades (for Fig. 6 the saccades were leftward, for Fig. 3 rightward) or due to different experimental contexts; i.e., the data in Fig. 6 were obtained when the saccades were made to the whole form on each trial, and the data in Fig. 3 were obtained when trials with saccades to forms were intermixed with trials with saccades to the single-target points.

The finding of consistent saccadic endpoints, despite random variation in eccentricity, shows that there are natural, or preferred, saccadic endpoints when one is attempting to look at entire forms. The endpoint is within the form and located near, but not precisely at, either the center of gravity or the symmetric point.

DISCUSSION

We found that subjects could direct saccades to designated target locations within simple forms with an accuracy, precision, and latency comparable with those of saccades directed to a single point. The finding suggests that subjects can use the information in the contour of a form to program saccades to a designated location within the contour. This capability is useful in everyday life because it permits us to direct the line of sight to specific locations of interest or importance without being compelled to certain endpoints by the structure of the visual environment. Of course, the visual environment is by no means irrelevant to saccadic programming because it provides necessary information for programming a single saccadic command to the desired location, even though there is no visible target available there.

We also found that saccades directed to a form as a whole, rather than to a designated location within it, tended to land

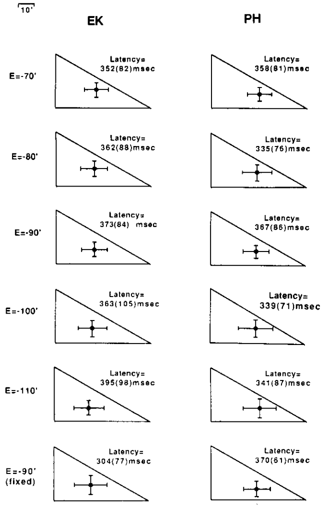

Fig. 6. Mean endpoints of saccades (±1 SD) for subjects EK and PH to the whole form with either varied eccentricities (top 5 rows) or constant eccentricity (90 arcmin, bottom row). The eccentricity *E* of the triangle in minutes of arc is shown on the left. Targets were to the left of the fixation point. The mean saccadic latencies and SD's (in parentheses) are given for each graph. Each datum point is based on 70–110 observations.

at a consistent location in the form. Precision was the same or better, and latencies were shorter, compared with those of saccades made either to designated locations within the forms or to a single target point. This finding suggests that a form may be a more effective target than a single point for saccadic programming.

How was the information contained in a contour transformed into the saccadic command that took the line of sight to a single endpoint? Our results permit us to reject previous suggestions of automatic centering tendencies, in which the eye lands at a location determined by averaging all the retinal positions stimulated by the contour, because we found that saccades were not compelled to land at a particular location in a form, such as the center of gravity or the symmetric point. Saccades landed at a particular location within the form only when the subject selected the whole form as a target. Even here, averaging of all available visual elements is an inadequate description of the control process because the landing position was affected by factors such as the location of the target (right or left) with respect to the line of sight and the experimental context (i.e., the nature of stimuli in surrounding trials).

Our results suggest that computing a saccadic command based on the information in the contour of a form requires at least two stages of processing, each introducing its own constraints. One stage consists of a voluntary selection process in which the subject biases the location of the endpoint of the saccade with respect to the contour by, perhaps, a selective (attentional) weighting of the visual information at various spatial positions in the contour. The second stage of processing uses these selected (weighted) visual signals in order to compute the saccadic endpoint, perhaps by a process akin to averaging of the weighted signals.

The suggestion of a single, two-stage serial process is different from prior suggestions of two parallel, independent saccadic subsystems, one voluntary and the other reflexive (see the Introduction), with the former subsystem directing the line of sight in some unspecified way to a chosen target position and the latter compelled to take the line of sight to one and only one endpoint. We propose instead that all saccades are controlled by a single subsystem with both voluntary (selective) and involuntary stages. A similar two-stage process has been proposed in the past to explain how

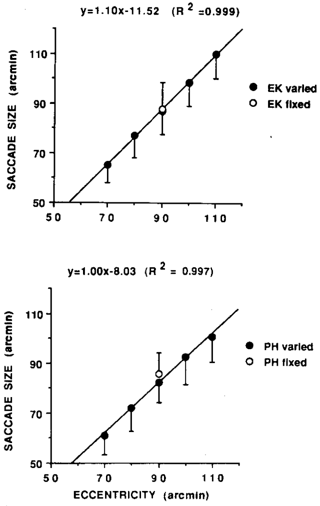

Fig. 7. Mean saccade size as a function of the eccentricity of the target triangle for EK and PH. Vertical bars show one SD. The data points for the targets at varied eccentricities were fitted by the linear function shown on the top of each graph.

smooth eye movements can be made to track selected targets in a field containing stimuli moving at various velocities.[23,24] These previous experiments also showed that the selection process (the first stage) is shared by smooth eye movements and by perception.[24] We propose here that the selection process is even more general. It is also shared by saccades.

The present results are analogous to the results of previous studies of eye movements in that they show considerable independence of oculomotor control from the configuration of the stimulus[4,5,6,9,25,26] and an apparently natural link between selective spatial attention and eye movements.[24] Both of these characteristics permit the line of sight to be directed to places of interest in the visual scene without specific effort to overcome fixation reflexes. This state of affairs is obviously useful, if not essential, for the effective processing of visual information. We also found that selection of the whole form as a target causes the eye to land near the center. The utility of this landing position for the processing of visual information, in contrast to alternatives, such as landing positions along the contour, remains to be determined.

ACKNOWLEDGMENTS

This research was supported by grant 88-0171 from the U.S. Air Force Office of Scientific Research to E. Kowler. A portion of these results was reported in Ref. 27. We thank J. Bergen and M. Leyton for useful discussions.

Address correspondence to E. Kowler.

REFERENCES AND NOTES

1. W. Richards and L. Kaufman, " 'Center-of-gravity' tendencies for fixations and flow patterns," Percept. Psychophys. 5, 81–84 (1969).
2. L. Kaufman and W. Richards, "Spontaneous fixation tendencies for visual forms," Percept. Psychophys. 5, 85–88 (1969).
3. There have been several well-known studies of saccades during the inspection of pictures: for example, A. L. Yarbus, *Eye Movements and Vision* (Plenum, New York, 1963); D. Noton and L. Stark, "Scanpaths in saccadic eye movements while viewing and recognizing patterns," Vision Res. 11, 929–942 (1971). Such studies were concerned with the choice of the target object and not with the major issue of this paper, namely, how the saccadic command is computed based on the information in a visual form. The earlier studies, unlike the present study, did not distinguish effects of decisions regarding where to try to direct the line of sight from the properties of the oculomotor mechanisms that carry out the decisions.
4. R. M. Steinman, "Effect of target size, luminance, and color on monocular fixation," J. Opt. Soc. Am. 55, 1158–1165 (1965).
5. J. J. Rattle, "Effect of target size on monocular fixation," Opt. Acta 16, 183–192 (1969).
6. B. J. Murphy, G. M. Haddad, and R. M. Steinman, "Simple form and fluctuations of the line of sight: implications for motor theories of form processing," Percept. Psychophys. 16, 557–563 (1974).
7. R. V. Sansbury, A. A. Skavenski, G. M. Haddad, and R. M. Steinman, "Normal fixation of eccentric targets," J. Opt. Soc. Am. 63, 612–614 (1973).
8. J. Nachmias, "Determiners of the drift of the eye during monocular fixation," J. Opt. Soc. Am. 51, 761–766 (1961).
9. R. M. Steinman, G. M. Haddad, A. A. Skavenski, and D. Wyman, "Miniature eye movements," Science 181, 810–819 (1973).
10. J. M. Findlay, "Global visual processing for saccadic eye movements," Vision Res. 22, 1033–1045 (1982).
11. F. P. Ottes, J. A. M. Van Gisbergen, and J. J. Eggermont, "Latency dependence of color-based target vs. nontarget discrimination by the saccadic system," Vision Res. 25, 849–862 (1985).
12. C. Coëffé and J. K. O'Regan, "Reducing the influence of nontarget stimuli on saccade accuracy: predictability and latency effects," Vision Res. 27, 227–240 (1987).
13. This view appeared originally in the 1960's in an attempt to explain why fixation stability is the same for point targets and for relatively large (87-arcmin-diameter) disks. It holds that "the error signal [for the eye movements] is the resultant of the direction and distance 'local signs' of all the signal elements stimulated by the edges of the target" (Ref. 4, p. 1165). This view predicts that the eye would be drawn to the center of the target, regardless of the initial fixation position. It was not supported by subsequent demonstrations that stable fixation can be maintained equally well at a variety of locations within or on the contour of a form.[6]
14. P. He and E. Kowler, "The role of location probability in the programming of saccades: implications for 'center-of-gravity' tendencies," Vision Res. 29, 1165–1181 (1989).
15. H. D. Crane and C. S. Steele, "Accurate three-dimensional eyetracker," Appl. Opt. 17, 691–705 (1978).
16. H. Blum, "Biological shape and visual science (Part 1)," J. Theor. Biol. 38, 205–287 (1973).
17. Luminous directional energy represents the luminous intensity, integrated over time, of a single intensification of a single point in the display. See G. Sperling, "The description and luminous calibration of cathode ray oscilloscope visual displays," Behav. Res. Methods Instrum. 3, 148–151 (1971).
18. P. Viviani and R. Swensson, "Saccadic eye movements to peripherally discriminated visual target," J. Exp. Psychol. Hum. Percept. Perform. 8, 113–126 (1982).
19. This is a reasonable assumption based on previous studies of the absolute stability of eye fixation.[4,9] It is necessary to calculate endpoints based on saccade sizes by using this assumption of initial on-target fixation with the Purkinje image tracker because this instrument is not capable of absolute calibration of eye position.
20. G. T. Timberlake, D. Wyman, A. A. Skavenski, and R. M. Steinman, "The oculomotor error signal in the fovea," Vision Res. 12, 1059–1064 (1972).
21. C. M. Zingale and E. Kowler, "Planning sequences of saccades," Vision Res. 27, 1327–1341 (1987).
22. W. Becker and A. F. Fuchs, "Further properties of the human saccadic system: eye movements and correction of saccades with and without visual fixation points," Vision Res. 9, 1247–1258 (1969).
23. E. Kowler, J. Van der Steen, E. P. Tamminga, and H. Collewijn, "Voluntary selection of the target for smooth eye movement in the presence of superimposed, full-field stationary and moving stimuli," Vision Res. 24, 1789–1798 (1984).
24. B. Khurana and E. Kowler, "Shared attentional control of smooth eye movement and perception," Vision Res. 27, 1603–1618 (1987).
25. B. J. Winterson and R. M. Steinman, "The effects of luminance on human smooth pursuit of perifoveal and foveal targets," Vision Res. 18, 1165–1172 (1978).
26. H. Collewijn and E. P. Tamminga, "Human fixation and pursuit in normal and open-loop conditions: effect of central and peripheral retinal targets," J. Physiol. (London) 379, 109–129 (1986).
27. P. He, E. Kowler, and M. Leyton, "Saccadic eye movement to simple forms," Invest. Ophthalmol. Vis. Sci. Suppl. 29, 135 (1988).