PATTERN THRESHOLDS FOR MOVING AND STATIONARY GRATINGS DURING SMOOTH EYE MOVEMENT

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(Received 29 November 1976; in revised form 7 July 1977)

Abstract—The influence of smooth pursuit eye movements on the visibility of stationary and moving objects was investigated by measuring eye movements and contrast thresholds for moving bright and dark bars of a 7 cycle/degree drifting grating in three different viewing conditions: (1) subjects maintained fixation, without saccades, on a 20-degree target while the gratings were presented at a constant speed across six fovea, (2) subjects smoothly pursued the 20-degree target superimposed on the qualifying grating and moving with it, and (3) subjects smoothly pursued the 20-degree target track and forth across the stationary grating.

It was found that: (1) inaccuracies of smooth pursuit eye movements produce substantial impairments of retinal image motion for target velocities greater than 1/3"/sec; (2) contrast thresholds during smooth pursuit were equal to contrast thresholds during maintained fixation when equal amounts of retinal image motion were present, (3) self-imposed and externally-imposed retinal image motions have equal effects on contrast detection; (4) improvements in contrast sensitivity were accomplished by improvements in smooth pursuit accuracy.

These results imply that (1) Visual sensitivity is not reduced by smooth pursuit eye movements, (2) The visibility of moving objects is primarily limited by velocity errors of smooth pursuit eye movements for the range of target velocities studied (49-2070")/sec.

INTRODUCTION

When an object we wish to see moves through our visual field we track the moving object with our eyes. We do this in an attempt to maintain fixation of the moving object and thereby maximize its visibility. Of course, the improved visibility of the moving object is obtained at the cost of reduced visibility of the stationary background. This occurs because the eye movements themselves produce movement of the retinal image of the stationary background. Seeing and tracking moving objects are tasks that confound visual and oculomotor systems frequently in everyday life. Despite this fact a number of questions remain unanswered concerning the influence of smooth pursuit eye movements on the visibility of stationary and moving objects.

The Paper addresses these of these questions. These are:

1. How well do smooth pursuit eye movements maintain fixation of moving targets?

2. In visual sensitivity reduced by smooth pursuit eye movements as it is by saccadic eye movements?

3. Do visual pattern analyzers respond differentially to self-imposed and externally-imposed retinal image motions?

Experimental studies to date have been limited to the investigation of the visibility of classical acuity targets in motion. Most of what we know is based on only two publications (Ludvigh and Miller, 1955; Miller, 1958). In these two publications Ludvigh and Miller review a decade of their work concerning a variety of aspects of dynamic visual acuity. Their primary findings were that: (1) dynamic visual acuity decreases with increases in the angular velocity of the target even when subjects are permitted to track the moving objects with their eyes, (2) rotation of a subject reduces his acuity for stationary objects, and (3) the function relating acuity to the angular velocity of the target is similar in form to the function relating acuity to the angular velocity of the subject.

Ludvigh and Miller concluded from these findings that reductions in visual acuity during the pursuit of moving objects result from imperfect pursuit movements of the eye because when the eyes do not move at the same speed as the target, the image of the target on the retina is smeared which reduces its contrast and therefore, its visibility.

This conclusion implies that eye velocity does not match target velocity during tracking. Is this true? Ludvigh and Miller could only speculate that it was because they did not measure tracking eye movements and very little quantitative information about such eye movements was available 20 years ago. Since then, this capacity has been studied by several investigators but it is still impossible to give an unequivocal answer.
Highlights in this research are as follows: investigators, concentrating on pursuit of single spot targets moving at relatively low velocities (less than 15 deg/sec) through small distances (less than 10 degrees), have reported conflicting results. Namely, Rabinovich (1983) concluded that (1) pursuit velocity is linearly related to target velocity for target velocities less than 10 degrees/sec; (2) pursuit velocity equals target velocity 400 msec after the target is set and motion, and (3) retinal image velocity during sustained pursuit of constant velocity targets equals retinal image velocity during maintained fixation of stationary targets. However, Puckett and Steinman (1972) found that (1) mean pursuit velocity was always less than target velocity, (2) pursuit velocity was not linearly related to target velocity, and (3) retinal image motion during pursuit was substantially greater than retinal image motion during maintained fixation. The Puckett and Steinman results support Ludwig and Miller's speculation because they suggest that oculomotor capacity could determine the limits of dynamic visual acuity. Unfortunately, however, Puckett and Steinman did not measure visual acuity during pursuit so to strictly. The only studies found that DVA declined with increase in target velocity but perhaps could predict the decline from their eye movement records. Furthermore, once again, there is disagreement about oculomotor system capacity. Ludwig, like Rabinovich, reported that the eye matches the velocity of the target during pursuit (1972) found, like Puckett and Steinman but unlike Rabinovich and Ludwig, that, on the average, smooth pursuit velocity was lower than target velocity. For consistency and clarity, velocity threshold measured by Puckett and Ludwig during pursuit of moving targets were higher than would be predicted from their measurements of retinal image motion during pursuit, particularly in Barneck's experiment where it was claimed that the eye matched the velocity of the target. Both experiments suggest that some factor or factors other than imperfect pursuit influence dynamic visual acuity. One possibility is that visual sensitivity is reduced by activities in the oculomotor system itself. For nearly a century, investigators have reported a decrease in visual sensitivity during scotopic eye movements—the phenomenon called "scotopic suppression" (see Milam, 1974, for a review) and recent Riga's (1982) reported suppression of electro- physiological responses during scotopic eye movements made in total darkness which lends strong support to the hypothesis (of oculomotor activity) can affect visual sensitivity. If smooth pursuit eye movements had significant effects, this could account for the unexpected loss of acuity found by Barneck and Brown (1972).

The results may be accounted for by the following reasons: First, the purpose of smooth pursuit eye movements is to reduce the retinal image motion of a moving target thereby maintaining visibility. Suppression of visual sensitivity during smooth pursuit could be counterproductive to this process. Second, Start, Angel and Yeates (1969) found that visual sensitivity is markedly reduced by saccadic eye movements (as many prior investigations have found) but sensitivity was not reduced by smooth pursuit eye movements. This was the first study of visual suppression by smooth pursuit, however, making it premature to rule out the possibility completely.

The research picks up the problems with modern psychophysical and eye monitoring methodology and shows Ludwig and Miller's hypotheses is correct. Proof includes demonstrating that:

1. Smooth pursuit velocity does not match target velocity

2. The contrast threshold for patterns during pursuit of a moving object is equal to the contrast threshold for patterns during maintained fixation when equal amounts of retinal image motion are present.

3. There is no visual suppression during smooth pursuit.

4. Self-induced retinal image motions of equal velocity have equal effects on the visibility of objects.

5. Improvements in dynamic visual acuity largely reflect improvement in oculomotor and not in sensory performance.

METHODS

Visual stimulation

The stimuli were generated electronically on the faces of two Tektronics 605A displays (0-45 microsec). The subject viewed a black stimulus that covered the edges of the two displays. The location of one of the displays was partially occluded by a black mask that had a rectangular aperture 1.36 by 1.36 degrees wide. The aperture was filled with a microsecond that had 1.36 microsecond modulation signal allowing both the subject and the experimenter to control the contrast and phase of the image. The modulation signal was a rectangular pulse of 1.36 microsecond duration and 1.36 microsecond width. Two 0.25-micron phototubes were connected to the x-axis modulation signals allowing both the subject and the experimenter to control the contrast and phase of the image. The mean luminance of the grating was measured using a light-stimulated phototube and the mean luminance of the grating 0.04 microsec at the eye. Such stimuli stimulate minimally brightness contrasts and other artifacts produced by luminance steps at the edge of gratings (Scher and Cummins, 1976).

The second display contained a 100-point target that provided a visual stimulus for smooth pursuit and the maintained fixation. The intensity of the points was one log unit greater than that of the target. A 200-point target was used to help maintain proper law accommodation and provided the subject with a criterion for normal vision through the full range of amplitudes of motion. The vertical sensitivity of the points was chosen empirically to be the tallest perceivable one. It was the same for

β
both subjects (4.3). The two-point target, like the grating, could be moved horizontally by driving the x-axis of its display with the same low frequency triangle wave that moved the grating. A switch permitted the experimenter to move either one or both of the targets, so both kept both of them stationary. The extent of the movement of the two-point target and the gratings were matched at 1.48° so that the subjects could not observe any relative motion when the two were moved together.

Eye-movement recording and analysis

Horizontal movements of the right eye were monitored by means of an electronic contact lens optical lever. The left eye was closed and covered with an eye patch and the scleral shell was stabilized by means of an acrylic dental binder. The contact lens optical level instrument provided a voltage analog of eye position that was recorded on magnetic tape for subsequent computer analysis (for details of the optical level instrument see Hinshelwood and Summner, 1971).

The analysis was performed in a time by a program that sampled the analog every 3 sec, converted this sample to a 12-bit digital code, and stored the digital information model for the computation of eye and stimulus velocities. The sensitivity of the measurement and recording instruments permitted resolution of eye and stimulus position to better than 0.5°. Eye and stimulus velocities were computed by measuring the time taken in one direction to traverse a specified region (described below). On each traverse of the eye in a given direction, the first digital eye position that fell within the specified region and the corresponding stimulus position were stored and the millisecond clock was started. The first digital eye position that fell outside of the specified region and the corresponding stimulus position were stored and the elapsed time recorded.

The region through which eye and stimulus velocities were measured was chosen by the following criteria: (1) it was within the linear region (1°) of the measuring instruments, (2) it was large enough to permit adequate measurement of velocity and distance (10.5°) and (3) it was in the center of the path traveled by the eye. This excluded from analysis changes in eye velocity that might occur with changes in the direction of the stimulus. Thus, these measurements of smooth pursuit eye velocity represent an estimate of the average steady state velocity attained while tracking a target. Very brief movements were retained only if tracking through the specified region was successful. This criterion did not require retention of many tracks. Subjects had usually sustained pursuits for more than 20 sec without making any saccades. They sometimes made a pause when they relaxed the direction of eye movement that generally they tracked for many cycles without making any.

In experiments in which subjects were asked to maintain steady eye position while a grating moved across the screen, eye velocity was computed by measuring the difference in eye position during the time taken for the stimulus to pass across the central 2° of the fovea. Once again, only sacadic-free tracks were accepted for analysis and this criterion did not require retention of many tracks.

The criteria for accepting a velocity measurement were contained in the digitizing and analysis programs. However, its judgments made by the software were checked by human observers working from 2 analog records made on a Lissander (1950) light-writing oscillograph. Our record was made directly from tape recordings prior to their being digitized while the other record was synthesized from the digital eye and stimulus position samples. The synthesized record also includes windows showing the region over which eye velocity was computed on a given trial. The people who checked the records were not informed of the aims of the present study and were not familiar with any previous eye movement research but had been carefully trained to discriminate saccades from smooth pursuits. See Fig. 1 for a representative eye movement record and its computer synthesized copy.

The records are read from bottom to top and the tracks are numbered consecutively. In both records the eye movements trace is shown to the right of the stimulus trace. The record on the right was made directly from the analog tape recording. The record on the left shows the synthesized stimulus and eye traces made from the digitized samples. The window (vertical line) superimposed on the synthesized eye trace show the region over which eye velocity was computed. The vertical line on the left of each of the synthesized records is displaced to the right where the program detected a saccade occurring within the window. On the trial tracks 1, 13, and 30 - eye movements were occluded from the analysis because of saccades. Tracks 19 and 20 were eliminated because of the presence of eye movements and the stimulus at the beginning of track 20 at the end of track 36 did not interfere with the analysis and were, therefore, ignored.

Subjects

Both subjects had participated in previous eye movement experiments. Subject RS was a highly experienced psychophysical observer and had participated in several prior experiments in which his smooth pursuit eye move-
ments had been recorded. Subject EK was not an experi-
enced psychophysical observer and had never attempted
periodic smooth pursuit in a laboratory setting.

Procedure
The stimulus configuration and mode of eye movement
behavior required of the subjects varied from experiment
to experiment. Certain psychophysical tasks depend on
the eye movement recording method and the psychophysical
criteria used, were common to all experiments. These were:
(1) The method of adjustment was used to set the con-
trast of the gratings so that the threshold contrasts for bright and dark bars was to use a rapid psy-
chophysical procedure because the rigid lifting order con-
cept, target lasting for longer than 40 min or more. The con-
veniences and flexibility of the method of adjustment
were obtained at the risk that the subject reproduces poten-
tially positional errors rather than stimulus appearance which could result in precise but inaccurate estimates of contrast sensitivity.

To minimize this risk the following procedures were adopted:
(a) Before each trial the experimenter varied the position of the subject's head or the contrast of the grating.
(b) Three successive settings were made with each stimu-
lus condition and their mean was used in the subsequent analyses.
(c) Experimental sessions were of two kinds. Half were devoted exclusively to psychophysical threshold measure-
ments. The other half combined psychophysical and eye movement recording. This strategy was adopted because it made possible an extensive series of psychophysical measurements which would not have been feasible if data had been obtained only during the eye movement record-
ning sessions. By alternating the extensive psychophysical sessions with brief sessions in which eye movements were also recorded a good estimate of both contrast sensitivity and ocular motor performance could be obtained.

(3) The psychophysical "threshold" adopted by both observers (for these experiments was the "just visible pattern of bright and dark bars"). This threshold, rather than zero and the use of a psychophysical display was employed for two reasons. First, classical alphanumeric tasks (frequently described as "identification of the display") was employed for two reasons. First, classical th
The velocity of the eye does not match the velocity of the target. Stimulus and pursuit eye velocities were measured on 391 tracks for subject EK and 542 tracks for subject RS. Smooth pursuit velocity matched target velocity to within experimental error (± 0.5 sec) on 2% of the trials for both subjects. Equi-
valence of stimulus and eye velocities to within experimental error is arbitrary and for present purposes seems unnecessarily stringent because Rashbass (1961), the most often cited proponents of velocity matching, asserted that the velocity of the eye matches the velocity of the target only to within the error of the ocular system. He estimates ocular system error from drift velocity studies during maintained fixation of a stationary target. Fixa-
tion drift velocity (on a single meridion) is about 5 sec—an order of magnitude greater than experimental error in the present experiments. If Rashbass' criteria are used, then subject EK matched target velocity on 16% of her tracks and RS on 16% of his tracks. This result suggests that velocity matching between the eye and target stimulus was included by Rashbass (1961) and reiterated by Robin-
son (1965) and Bermark (1971). It is, however, consist-
ent with the results of Puecket and Steinmann (1969), Steinmann, Skavanski, and Sansbury (1960), and Brown (1972). N.B. Prior reports that eye and target velocity do not match during pursuit were based on the tracking of non-repetitive ramp stimuli not viable for the short periods of time. The present results extend this finding to the tracking of prolonged (40 sec) periodic stimuli.

Smooth pursuit velocity, on the average, was less than target velocity. Subject EK extended target velocity (≥ 5 sec) only on 20% of her tracks but was slower (≥ 5 sec) on 62% of her tracks. RS exceeded target velocity on 39% and was slower than target velocity 6% of the time. Quantitative details of tracking performance are sum-
mariated in Table 1 and illustrated in Figure 2 where

EXPEDMENTS

Experiment 1. Imperfections of smooth pursuit, resultant retinal image slip, and its effect on contrast sensi-
tivity. The two-point target was superimposed on the retinal image slip, and the two-point target was ad-
justed to the contrast of the gratings until they could just discern its bright and dark bars. The velocity of the targets ranged from 49/sec to 420/sec. This range of target velocities was chosen because, in preliminary experiments, it was found that with higher target velocities smooth pursuit was fre-
frequently interrupted by saccades. Frequent saccades were undetermined for two reasons: (1) the accurate esti-
mates of smooth pursuit velocity required long saccad-
esecond per because of the accuracy of the click (1 msec), and (2) saccades have a detrimental influence on visual sensitivity—the phenomenon said called saccadic suppression (described above).

The velocity of the eye does not match the velocity of

References

[1] Contrast thresholds for patterns measured during ses-
sions in which eye movements were recorded fell within the
distribution of thresholds measured during purely psy-
chophysical sessions. The average number of trials that
eye movements were slightly lower. This shows that the right-sided occipital contrast tract, which was weaned on the eye, did not impair vision—a finding of some inter-
rest to investigators working with the "natural" psychophysical observations concurrent with accurate eye move-
movement recordings.
Table 1. Mean stimulus and eye speed of subjects RS and EK smoothly pursuing a 2-point target superimposed on the center of a moving grating

<table>
<thead>
<tr>
<th>Subject RS</th>
<th>Eye (mm arc/sec)</th>
<th>Stimulus (mm arc/sec)</th>
<th>N</th>
</tr>
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<tbody>
<tr>
<td>54.5 (0.1)</td>
<td>45.3 (4.24)</td>
<td>52</td>
<td></td>
</tr>
<tr>
<td>141 (0.4)</td>
<td>137 (2.6)</td>
<td>77</td>
<td></td>
</tr>
<tr>
<td>232 (0.7)</td>
<td>216 (2.19)</td>
<td>115</td>
<td></td>
</tr>
<tr>
<td>322.5 (2.2)</td>
<td>288 (3.42)</td>
<td>139</td>
<td></td>
</tr>
<tr>
<td>412.5 (2.4)</td>
<td>354 (4.36)</td>
<td>159</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Subject EK</th>
<th>Eye (mm arc/sec)</th>
<th>Stimulus (mm arc/sec)</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>49.5 (2.1)</td>
<td>48.5 (7.0)</td>
<td>47</td>
<td></td>
</tr>
<tr>
<td>138 (5.1)</td>
<td>129.6 (21.0)</td>
<td>83</td>
<td></td>
</tr>
<tr>
<td>236 (0.9)</td>
<td>204.8 (3.40)</td>
<td>79</td>
<td></td>
</tr>
<tr>
<td>311.5 (16.0)</td>
<td>255.7 (34.5)</td>
<td>85</td>
<td></td>
</tr>
<tr>
<td>405.5 (19.5)</td>
<td>326.0 (33.7)</td>
<td>97</td>
<td></td>
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</table>

*The number of tracks (N) are shown as well as the standard deviations which are given in parentheses.

oculomotor performance is shown graphically as gain (eye velocity/stimulus velocity) as a function of stimulus speed. Errors bar show plus and minus one standard deviation about the mean.

Retinal image slip—velocity to speed? Neither subject showed perfect smooth pursuit. Generally, they pursued more slowly than the target moved, occasionally they went faster, but seldom matched target velocity. Whenever the eyes do not move at the same velocity as the target, the image of the target moves on the surface of the retina. The nature of the mismatch is important for understanding the oculomotor mechanism, but not for understanding how smooth pursuit limits the visibility of moving objects. Movement of the image on the retina could affect vision regardless of whether retinal image slip results from the eye going slower or faster than the target. A reasonable estimate of retinal image motion, then, must describe its speed, not its velocity, because mean velocity could equal zero when retinal image velocities on individual tracks were not zero. This distinction is not trivial. The present subjects, as well as Puckett and Steamans' (1969), Steamans et al. (1969), and Brown's (1972) all showed a number of tracts in which velocity overshooting occurred. There are no quantitative reports of smooth pursuit that have failed to note the occasional tendency of the eye to go faster than the target.

The retinal image slipped during smooth pursuit. The average speed of the retinal image during pursuit was comparable to the average speed of the retinal image during maintained fixation of a stationary target only when the target moved less than 1/sec. Retinal image motion increased rapidly with increases in target velocity. When targets moved 7/sec, the mean retinal image speed was high (64.6/sec for RS and 76.7/sec for EK). See Table 1 and Figure 3 for a summary of this functional relationship. Pattern threshold increased modestly during smooth pursuit despite large increases in retinal image slip. Both subjects required less than 2.5% more contrast to distinguish the bright and dark bars of the grating when it moved at 7/sec than when the grating was stationary. This is a striking result—a 15-fold increase in retinal image speed raised pattern threshold.

Fig. 2 Mean smooth pursuit gain (eye velocity/stimulus velocity) as a function of stimulus speed. Circles represent subject RS squares subject EK. The dashed horizontal line represents velocity matching (gain = 1). Gain was calculated for individual tracks and the values shown in the figure differ slightly, therefore, from estimates of gain that might be made from the eye and stimulus speeds summarized in Table 1. Error bars show plus and minus one standard deviation about the mean.

*The variability of stimulus speed arose from two sources, i.e. (1) drift in the signal generators within each session and (2) the inability of the experimenter to reproduce each frequency during the course of each session.
| Stimulus | % | N | Image
<table>
<thead>
<tr>
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<th></th>
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</thead>
<tbody>
<tr>
<td>Subject RS</td>
<td>31.00</td>
<td>18</td>
<td>5.4 (3.4)</td>
</tr>
<tr>
<td>51.2</td>
<td>3.0 (0.0)</td>
<td>10</td>
<td>0.5 (0.0)</td>
</tr>
<tr>
<td>32.5</td>
<td>3.0 (0.0)</td>
<td>10</td>
<td>0.5 (0.0)</td>
</tr>
<tr>
<td>32.5</td>
<td>3.0 (0.0)</td>
<td>10</td>
<td>0.5 (0.0)</td>
</tr>
<tr>
<td>4.2</td>
<td>4.0 (0.0)</td>
<td>10</td>
<td>0.5 (0.0)</td>
</tr>
</tbody>
</table>

| Subject EK | 3.9 | 21 | 7.5 |
| 4.0 | 3.6 | 12 | 5.1 |
| 3.9 | 3.0 | 12 | 2.0 |
| 3.9 | 3.0 | 12 | 2.0 |
| 3.9 | 3.0 | 12 | 2.0 |

The number of median thresholds (N) averaged in parentheses. See Table 1 for estimates of RS

The table shows as well as their standard deviations, the variability of stimulus speed. The number of trials is also shown.

old by less than a factor of two. This physiophotical result is summarized in Table 2 and Figure 3. This result suggests that there is not a strong relationship between the speed of the retinal image and the variability of its pattern during smooth pursuit. However, there is evidence that these changes in contrast sensitivity that did occur during pursuit were caused primarily by retinal image motion produced by imperfections of the ocularmotor response. The inexperienced subject, EK, showed marked improvement of smooth pursuit during the four weeks of data collection (e.g., overall mean image speed for week 1 = 619/sec, SD = 429; week 2 = 459/sec, SD = 439; week 3 = 272/sec, SD = 52; week 4 = 311/sec, SD = 344). Her contrast thresholds during pursuit showed similar improvement (e.g., overall mean % contrast in week 1 = 5.2, SD = 15; week 3 = 5.0, SD = 0.7). The experienced subject, RS, did not show improvement in his smooth pursuit performance during the four weeks of the experiments. His contrast thresholds also remained unchanged. The good correspondence between the ocularmotor and physiophoticle performance for such subject suggests that retinal image motion could be an important determinant of contrast sensitivity.

Note, however, that EK's physiophotical performance continued to improve beyond the time that her smooth pursuit and retinal image speed had reached asymptote—a fact which suggests that retinal image size may not be the sole story.

Experiment 2. The influence of retinal image size on contrast for patterns during maintained fixation of a stationary target.

Subjects fixated the stationary two-point target in the center of the display and adjusted the contrast of a moving grating until they could distinguish its details. The grating was moved to the left and to the right at constant velocities. The velocities ranged from 27/sec to 177/sec, the highest velocity at which the subjects could make out bars in a moving pattern whose maximum available contrast was 77.5%. The moving grating did not interfere with the ability to maintain a steady line of sight. This is summarized in Table 3, where it can be seen that there was little relationship between the velocity of the target and the velocity of the eye. Both subjects tended to drift in the direction of the grating but drift velocity was negligible and did not vary with the velocity of the grating.

This result means that in the experiment where the subject fixated a stationary target, retinal image velocity was approximately equal to grating velocity. It was only necessary to subtract the negligible drift velocity from grating velocity to know the velocity of the image of the grating across the retina. This finding was not surprising because it had already been shown that the eye is not captured by moving gratings providing a stationary fixation target is present (Murphy, Kowler and Steinman, 1975).

![Fig. 3. M Orch retardal image speed during smooth pursuit as a function of stimulus speed. Circles represent subject RS, squares subject EK.](image-url)
Contrast thresholds were not strongly affected by retinal image motions of less than 100/sec. They rose sharply with increases in retinal image motion above this velocity. This is summarized in Fig. 4 and Table 4. N.B. Subject SK, whose contrast thresholds during pursuit fell as pursuit improved, did not show any improvement in the experiment which was conducted in the same animals (i.e., overall mean ± 1/2 contrast for week 1 = 59, SD = 11.6; week 2 = 11.65, SD = 12.8; week 3 = 12.3, SD = 11.7; week 6 = 12.6, SD = 14.1.1) A result which once again suggests that contrast sensitivity for moving objects is determined by oculomotor skill.

Experiment 3. Contrast sensitivity to stationary objects during smooth pursuit

So far, it seems that the ability to see details of an object in motion is limited by the speed of its image across the retina. Is this also true when the object is stationary and the eye is in motion? This is an easy question to answer experimentally.

In a first attempt to answer this question subjects were asked to track the two target crosses across a stationary grating and adjust the contrast of the grating as they did in Experiments 1 and 2. This did not work. Subjects frequently switched to and paused at the stationary grating. Furthermore, subjects reported that they were not aware of making this saccade and were not able to modify their behavior appreciably even after they were informed of their prior performance. This difficulty was circumvented by modifying the experimental design. Modifications included: (i) switching to a yes-no signal detection procedure; and (ii) presenting the grating in 100 msec flashes. This duration was long enough to produce smear of the retinal image when the velocity of the two-point target was 140/sec and still short enough to prevent the subjects from making a saccade when the grating appeared.

Subjects tracked the two-point target back and forth across the homogenous field (E's mean eye speed = 120.5/sec, SD = 12.8, N = 45, RS's mean eye speed = 121.0/sec, SD = 15.7, N = 127) once during each cycle they lasted 4-100 msec bsp and made a judgment as to the presence or absence of the grating. Presentation probability was 0.5 and grating and blank trials were presented randomly. Grating contrast was fixed at 10%, which allowed 75% correct detections by subject SK and 76% by RS.

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1 Thresholds in the highest stimulus velocities are not included in the overall means because these endpoints on the functions were determined by fixing grating contrast at its maximum and having subjects adjust the grating velocity until they could just discern the bright and dark bars of the grating pattern.

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Table 3. Mean stimulus and eye velocities of subjects RS and SK when fixation was maintained on a stationary target and the grating moved

<table>
<thead>
<tr>
<th>Stimulus (min/sec)</th>
<th>Eye (min/sec)</th>
<th>N</th>
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<tbody>
<tr>
<td>Subject RS</td>
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<td></td>
</tr>
<tr>
<td>-28.0 (3.8)</td>
<td>0.0 (2.7)</td>
<td>26</td>
</tr>
<tr>
<td>26.0 (1.8)</td>
<td>2.4 (2.9)</td>
<td>27</td>
</tr>
<tr>
<td>50.6 (3.0)</td>
<td>-0.2 (3.7)</td>
<td>24</td>
</tr>
<tr>
<td>50.6 (1.3)</td>
<td>3.9 (4.3)</td>
<td>14</td>
</tr>
<tr>
<td>-99.4 (7.6)</td>
<td>-2.4 (5.4)</td>
<td>39</td>
</tr>
<tr>
<td>-99.4 (6.3)</td>
<td>-3.9 (5.9)</td>
<td>24</td>
</tr>
<tr>
<td>-143.1 (9.7)</td>
<td>0.0 (5.1)</td>
<td>26</td>
</tr>
<tr>
<td>140.9 (1.8)</td>
<td>1.8 (4.3)</td>
<td>23</td>
</tr>
<tr>
<td>Subject SK</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-28.0 (6.2)</td>
<td>-1.2 (2.6)</td>
<td>14</td>
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<tr>
<td>28.0 (10.2)</td>
<td>-0.9 (2.0)</td>
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<td>-33.6 (8.1)</td>
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<td>-99.4 (21.7)</td>
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<tr>
<td>99.4 (20.6)</td>
<td>-1.2 (5.4)</td>
<td>19</td>
</tr>
<tr>
<td>-142.0 (9.6)</td>
<td>0.0 (4.4)</td>
<td>21</td>
</tr>
<tr>
<td>132.6 (9.3)</td>
<td>2.0 (6.0)</td>
<td>26</td>
</tr>
</tbody>
</table>

The number of trials (N) is shown as well as standard deviations, given in parentheses. Negative velocities signify movements to the left.

Fig. 4. Mean contrast threshold for pattern as a function of mean retinal image speed when fixation was maintained on a stationary target and the grating moved. Circles represent subset RS, squares subset SK.
Table 4. Mean pattern threshold contrast (\%T) and retinal image speed when fixation was maintained on a stationary target and the grating moved.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Image (min arc/sec)</th>
<th>%T</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>RS</td>
<td>27.3</td>
<td>3.9 (3)</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>49.5</td>
<td>4.9 (3)</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>96.1</td>
<td>10.2 (3.5)</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>140.0</td>
<td>13.1 (3.1)</td>
<td>12</td>
</tr>
<tr>
<td>165.0</td>
<td>17.5 (4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subject</td>
<td>EK</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>28.3</td>
<td>3.2 (0.4)</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>52.5</td>
<td>3.8 (0.6)</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>100.0</td>
<td>8.9 (1.4)</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>153.7</td>
<td>11.0 (1.4)</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>169.6</td>
<td>17.5 (4)</td>
<td>11</td>
</tr>
</tbody>
</table>

The number of median thresholds (%T) averaged as shown is as well as their standard deviations, given in parentheses. * This is maximum contrast for the grating. Here, grating speed was adjusted until the bars were visible. Settings for each subject were reproducible but the SD of contrast cannot be reported.

This design discouraged the subjects from making saccades. Occasionally, they stopped pursuing the two-point target and made a saccade to the center of the display in anticipation of the grating's appearance. The eye movement recordings and psychophysical responses made on these trials were disregarded.

Having determined the percent correct detections for a flashed stationary 10% contrast grating while the eye pursued across it at 2 arc/sec, the stimulus speed which produced the same proportion of correct detections was determined when the subjects fixated stationary patterns and the moving grating was flashed for 100 msec. Threshold grating speed was 103/sec for subject EK and 138/sec for RS. Both subjects were slightly more sensitive to externally imposed retinal image motion than to self-imposed retinal image motion, but these differences were not statistically or functionally significant.

Thus, contrast sensitivity is influenced by retinal image motion if a given velocity, equally, regardless of whether the image motion is produced by eye movements or movements of the stimulus object.

**DISCUSSION**

The purpose of this discussion will be to show that imperfections of smooth pursuit determine the capacity to see the spatial pattern of a moving object. It will be argued that mismatches between stimulus and pursuit velocity result in movement of the image of the object on the surface of the retina. It is this movement of the retinal image that makes it difficult to see details of moving objects. Furthermore, it will be argued that retinal image motion alone is sufficient to explain dynamic visual acuity without reference to (1) any direct influence of activity of the oculocephalic machinery, or (2) differences in visual sensitivity to pattern within the fovea. These two factors will be discussed first.

There are two ways in which activities of the oculocephalic machinery could influence the perception of moving patterns: (a) the visual system could compensate for retinal image motion produced by eye movements. It does this with respect to the perception of motion (Skavronska, Kludov, and Steinman, 1972). If this were the case, we would expect that acuity for the pattern of a stationary object, when the observer moves his eye, would be better than when he fixates a stationary object and the object moves through the visual field at the same speed. (b) Visual sensitivity to contrast could be reduced by smooth pursuit eye movements as it is reduced by saccadic eye movements.

I found no evidence that supports either possibility. Self-imposed and externally-imposed retinal image motions have equal influence on pattern threshold (see Exp. 3). Also, visual sensitivity was not reduced by smooth pursuit eye movements. A comparison of the pattern thresholds during pursuit (Table 2) with the patterns thresholds during fixation (Table 4) shows that they are equal when retinal image speed was equal. This finding confirms Start et al (1969). There are now two reports (that visual sensitivity is not reduced by activities of the oculocephalic machinery that controls smooth pursuit eye movement.

The second factor considered was the variation in visual sensitivity to pattern within the fovea. The contribution of this factor was measured by having subjects fixate at the center of the display where they saw either the two-point target on the grating or the grating by itself. Contrast was set to threshold (grating only: EK = 42%, RS = 25%; grating with targets: EK = 39.5%, RS = 24%). Measurements were also made during fixation of the two-points at the center of the display with the center of the grating displaced 1.74° to the left and to the right of the visual axis. Contrast was set to threshold and the effect of retinal position proved to be small (EK: 5.4% and RS: 3.4%). Note that this loss of contrast sensitivity near the edge of the fovea did not contribute much to the functions obtained in these experiments because, although smooth pursuit was imperfect, the visual axis, on the average, during pursuit was never more than 4° from the center of the grating. Also, no measurements made during pursuit matched those made during fixation where the grating always oscillated at the center of fovea.

Neither oculocephalic activity nor retinal position.
were important to the visibility of the grating; retinal image motion was. Retinal image motion, resulting from velocity under-shooting and velocity over-shoot-
ing, was sub-tantial at all target velocities studied. During pursuit it was equal to retinal image motion of steady fixation only when the target moved less than 1°/sec. Image motion increased by more than an order of magnitude when the target moved at 7°/sec. Thus, Rashbass (1961) and Barmack (1970) were wrong. Smooth pursuit velocity does not match the velocity of the target. Rather, smooth pursuit is imperfect as Ludvig and Miller (1958) suspected. Also, they suspected the area of utility with increases in target velocity can be predicted from the amount of retinal image motion. A comparison of ring targets during pursuit (Table 2) with the pattern-thresholds during fixation (Table 4) shows that they were equal when retinal image speed was equal.

There is additional supporting evidence. One sub-
ject showed substantial improvement of pursuit dur-
ing the course of the experiment. The other subject did not. The subject who showed improvement in smooth pursuit also showed improvement in contrast sensitivity. The other subject did not.

So, by combining modern psychophysical and our-
loomor motility methods, it was possible to show that
dynamic visual acuity is not more difficult to under-
stand than Ludvig and Miller (1958) suspected. Details of objects are more difficult to see when they are moving than when they are stationary because our oculomotor skills, like all human activities, fall short of perfection.

But, having restored the explanation of dynamic visual acuity to a single simply well described problem emerged. We see exceedingly well despite the presence of considerable retinal image motion. Look at Figure 4 and note that gratings moving less than 2°/sec, which is more than 20 times fixation drift vel-
ocity, are almost as easy to see as gratings that are not moving at all. How does the visual machinery
tolerate such perturbations of its input? We seem to
don't care.

This is not the first report that the visual pattern analysts have a high tolerance for retinal image motion. Westheimer and McKee (1975) reported "super-acuity" for moving Verner-offset and Landolt ring targets. For Landolt targets with a 3° visual angle, the perceived acuity thresholds for these targets, like the pattern thresholds measured in the present experiments, were not markedly influ-
enced by retinal image motions of 2°/sec or less. Per-
haps, this resilience to retinal image motion should not be surprising. It makes sense teleologically because binocular and bin-esters are rarely available when we inspect the details of objects outside of the laboratory. There, we frequently find ourselves using

natural supports. We sit. We prop-up our elbows and support our head on our hands. In some circum-
stances we even hold our heads. However, it has been recently shown that all such strategies fail to immobilize the head or keep the retinal image from moving, motions as fast as 2°/sec are frequently observed when the head is maintained artificially (Winterston, Steinman, Skavenski, Hansen and Robo-


SUBJECTIVE reports by these authors suggest that the

visual world looks much the same under natural con-
ditions as it does when the head is supported on a

beehive. The psychophysical measurements reported in this paper confirm their subjective ob-

servations. It is possible to see patterns clearly despite appreciable retinal image motion. How this is accom-
plished by the visual system must now be explained.
OBITUARY

Brian J. Murphy died of cancer on January 5, 1976. He succumbed to a difficult illness while undergoing cancerous surgery. He was 50 years old.

Brian was born on October 31, 1925 and contracted retinal successfully in his fifth year, which necessitated removal of one eye and radiation therapy of the remaining eye. This left him almost completely blind, but his corrected visual acuity under high illumination did not exceed 20/800 in the small peripheral retinal area in which visual function remained. This disability led to a career in visual science—a career that was undertaken under unusual and difficult circumstances.

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Note: Dr. Murphy is a co-author of a Letter to the Editors on pp. 603-605 of this issue.