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PATTERN THRESHOLDS FOR MOVING AND STATIONARY GRATINGS DURING SMOOTH EYE MOVEMENT[1]

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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 seeing bright and dark bars of a 7 cycle (5.14 c/deg) sine grating in three different viewing conditions: (1) Subjects maintained fixation, without saccades, on a stationary 2-point target while the grating oscillated at a constant speed across the fovea, (2) Subjects smoothly pursued the 2-point target superimposed on the oscillating grating and moving with it, (3) Subjects smoothly pursued the 2-point target back and forth across the stationary grating.

It was found that: (1) Inaccuracies of smooth pursuit eye movements produce substantial amounts of retinal image motion for target velocities greater than 1°/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 accompanied 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 (49–420′/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 confront our 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.

This paper addresses three of these questions. These are:

1. How well do smooth pursuit eye movements maintain fixation of moving targets?
2. Is 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, 1958; 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 eye does not move at the same velocity 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.

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Highlights of this research are as follows: investigators, concentrating on pursuit of single point targets moving at relatively low velocities (less than 15 degarc/sec) through small distances (less than 10 degrees), have reported conflicting results. Namely, Rashbass (1961) 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 into motion, and (3) retinal image velocity during sustained pursuit of constant velocity targets is equal to retinal image velocity during maintained fixation of stationary targets. However, Puckett and Steinman (1969) repeated Rashbass' experiment and 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 Ludvigh 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 once again we can only speculate because confirmation requires measurement of visual, as well as oculomotor function.

To date there have been only two studies of DVA in which both eye movements and acuity were recorded (Barmack, 1970; Brown, 1972). Both of these authors found that DVA declined with increases in target velocity but neither could predict the decline from their eye movement records. Furthermore, once again, there is disagreement about oculomotor system capacity. Barmack, like Rashbass, reported that the eye matches the velocity of the target during pursuit. Brown (1972) found, like Puckett and Steinman but unlike Rashbass and Barmack, that, on the average, smooth pursuit velocity was lower than target velocity.

Acuity threshold measured by Barmack and Brown during pursuit of moving targets were higher than would be predicted from their measurements of retinal image motion during pursuit, particularly in Barmack'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 smooth 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 been reporting a decrease in visual sensitivity during saccadic eye movements—the phenomenon called "saccadic suppression" (see Matin, 1974, for a review) and recently Riggs (1976) reported suppression of electrical phosphenes during saccadic eye movements made in total darkness which lends strong support to the hypothesis that oculomotor activity can affect visual sensitivity directly. If smooth pursuit eye movements had similar effects, this could account for the unexplained loss of acuity found by Barmack and Brown.

This seems unlikely for the following reasons: First, the purpose of smooth pursuit eye movements is to reduce the retinal image motion of a moving target thereby sustaining its visibility. Suppression of visual sensitivity during smooth pursuit would be counterproductive to this process. Second, Starr, Angel and Yeates (1969) found that visual sensitivity is markedly reduced by saccadic eye movements (as many prior investigators 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.

This research picks up the problems with modern psychophysical and eye monitoring methodology and shows that Ludvigh and Miller's hypothesis is correct. Proof includes demonstrations that:

1. Smooth pursuit velocity does not match target velocity.
2. The contrast threshold for pattern during pursuit of a moving object is equal to the contrast threshold for pattern during maintained fixation when equal amounts of retinal image motion are present.
3. There is no visual suppression during smooth pursuit.
4. Self-imposed 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 Tektronix 604 displays (P-4 phosphors). The subject viewed a beam splitter that combined the images of the two displays. The face of one of the displays was partially occluded by a black mask that had a rectangular aperture 1.36° high by 5.38° wide. The aperture was filled with a raster that had 130 vertical lines/degree and a refresh rate of 1000 Hz. A small portion of the raster was intensity modulated (z-axis) to produce a vertically oriented grating 1.36° high by 1.36° wide. Two 10-turn potentiometers were connected to the z-axis modulation signal, allowing both the subject and the experimenter to control the contrast of the grating. Grating contrast was defined conventionally, *i.e.* $(L_{max} - L_{min})/(L_{max} + L_{min})$. The grating was composed of 7 sinusoidal cycles and therefore had a spatial frequency of 5.14 cycles/degree.

The z-axis modulation was produced by a generator that was triggered by the sweep signal provided to the x-axis of the display. The grating could be moved horizontally. Movement was produced by changing the position of the modulated portion of the raster by adding a low-frequency triangle wave to the signal that triggered the generator modulating the raster. The mean luminance of the grating pattern was equal to that of the homogeneous raster that filled the rest of the aperture. This assured that the grating would always be moved onto retina adapted to the mean luminance of the grating (0.43 cd/m^2 at the eye). Such stimulation eliminates illusory brightness contours and other artifacts produced by luminance steps at the edge of gratings (Estevez and Cavonious, 1976).

The second display contained a two-point target that provided a vivid stimulus for smooth pursuit and for maintained fixation. The intensity of the points was one log unit greater than that of the raster. A two-point target was used to help maintain proper lens accommodation and provided the subjects with a criterion for normal vision throughout recording and psychophysical sessions. The vertical separation of the points was chosen empirically to be the smallest perceptible gap. It was the same for both subjects (4.7′). 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, or keep both of them stationary. The extent of the movement of the two-point target and the grating were matched at 3.48° 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 subject's head was stabilized by means of an acrylic dental bitebar. 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 Haddad and Steinman, 1973).

The analysis was performed in real time by a program that sampled the analog record every 3 msec, converted this sample into a 12-bit digital code, and stored the digital information needed 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 msec 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 specific 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 time and distance (0.5%), 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. Velocity measurements were retained only if tracking through the specified region was saccade-free. This criterion did not require rejection of many tracks. Subjects frequently sustained pursuits for more than 20 sec without making any saccades. They sometimes made a saccade when they reversed the direction of eye rotation but generally they tracked for many cycles without making any.

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

The criteria for accepting a velocity measurement were contained in the digitizing and analysis programs. However, the judgements made by the software were checked by hardnosed human observers working from 2 analog records made on a *Visicorder* (1508) light-writing oscillograph. One 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 movement 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 windows (vertical lines) superimposed on the synthesized eye trace show the region over which eye velocity was computed. The vertical line on the far left of the synthesized record was displaced to the right when the program detected a saccade occurring within the window. On this trial tracks 1, 13, and 30 were excluded from the analysis because of saccades. Tracks 19 and 20 were eliminated because the eye turned around too close to the edge of the window. The saccades at the beginning of track 14 and at the end of track 28 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-

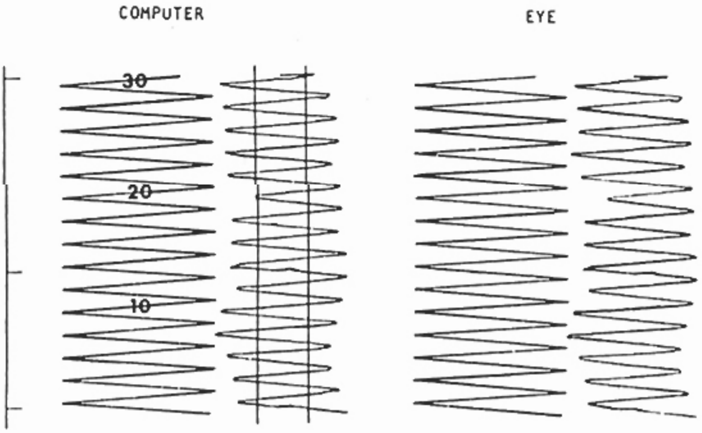

Fig. 1. A representative record of eye and stimulus movement (on right) and its computer synthesized copy (on left). The subject was *EK* and the frequency of the two-point tracking target was 0.55 Hz. Its peak-to-peak amplitude was 3.48°. See text for a description of this figure.

ments had been recorded. Subject *EK* was not an experienced 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 procedures, imposed by the eye movement recording method and the psychophysical criterion used, were common to all experiments. These were:

(1) The method of adjustment was used to set the contrast of the grating to the threshold for distinguishing bright and dark bars. It was essential to use a rapid psychophysical procedure because the tight-fitting scleral contact lens used for recording eye movements cannot be worn for longer than 40 minutes or more than once a day. The convenience and flexibility of the method of adjustment are obtained at the risk that the subject reproduces potentiometer position 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 his potentiometer to remove any correlation between the position of the subject's potentiometer and the contrast of the grating.

(b) Three successive settings were made with each stimulus condition and their median was used in the subsequent analyses.

(2) Experimental sessions were of two kinds. Half were devoted exclusively to psychophysical threshold measurements. 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 recording 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 oculomotor performance could be obtained.[3]

(3) The psychophysical "threshold" adopted by both subjects throughout these experiments was the "just visible pattern of bright and dark bars". This threshold, rather than a smudge (frequently described as "inhomogeneity of the display") was employed for two reasons. First, classical DVA experiments required the subject to discern details in the target rather than merely detect its presence. A relatively high threshold criterion was chosen to make the present experiments comparable to the classical work despite the use of modern methods. Second, this classical requirement has the virtue of making the laboratory task similar to the visual demands of everyday life where the individual frequently needs to see details of some moving object and not merely detect its presence in the visual field.

(4) Most of the results to be reported are based on psychophysical and eye movement measurements made under two conditions: (1) the eye stayed in place while the grating moved and (2) the eye tracked a target superimposed on the moving grating. The results of these manipulations will be reported as separate experiments but both kinds of measurements were actually made in every session thereby facilitating comparisons between them uncontaminated by daily fluctuations in contrast sensitivity. All stimulus velocities, as well as both modes of eye movement behavior, were employed at every session.

EXPERIMENTS

Experiment 1. Imperfections of smooth pursuit, resulting retinal image slip, and its effect on contrast sensitivity.

The two-point target was superimposed on the grating and both were moved to the left and to the right at constant velocities. Subjects tracked the two-point target and adjusted the contrast of the grating 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 frequently interrupted by saccades. Frequent saccades were undesirable for two reasons: (1) Accurate estimates of smooth pursuit velocity required long saccade-free periods because of the accuracy of the clock (1 msec), and (2) saccades have a detrimental influence on visual sensitivity—the phenomenon called saccadic suppression (described above).

The velocity of the eye does not match the velocity of the target. Stimulus and pursuit 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. Equivalence 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 proponent of velocity matching, asserted that the velocity of the eye matches the velocity of the target only to within the error of the oculomotor system. He estimates oculomotor system error from drift velocities reported during maintained fixation of a stationary target. Fixation drift velocity (on a single meridian) is about 5′/sec—an order of magnitude greater than experimental error in the present experiments. If Rashbass' criterion is 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 is not a characteristic of smooth pursuit as was concluded by Rashbass (1961) and reiterated by Robinson (1965) and Barmack (1971). It is, however, consistent with the results of Puckett and Steinman (1969), Steinman, Skavenski, and Sansbury (1969), 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 visible for short periods of time. The present results extend this finding to the tracking of prolonged (40 sec) periodic movement of the stimulus.

Smooth pursuit velocity, on the average, was less than target velocity. Subject *EK* exceeded target velocity (>5′/sec) on only 20% of her tracks but was slower (>5′/sec) on 63% of her tracks. *RS* exceeded target velocity on 18% and was slower on 66% of his tracks. Quantitative details of tracking performance are summarized in Table 1 and illustrated in Figure 2 where

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[3] Contrast thresholds for patterns measured during sessions in which eye movements were recorded fell within the distribution of thresholds measured during purely psychophysical sessions. On the average thresholds during eye movement sessions were slightly lower. This shows that the tightly-fitted scleral contact lens, which was sucked on to the eye, did not impair vision—a finding of some interest to investigators desirous of making "natural" psychophysical observations concurrent with accurate eye 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

	Stimulus (min arc/sec)	Eye (min arc/sec)	N
Subject *RS*			
	51.5 (0.1)	46.3 (4.24)	52
	141.5 (0.4)	137.9 (9.8)	77
	232.4 (0.8)	219.1 (21.8)	115
	322.5 (1.2)	288.5 (34.2)	139
	412.3 (2.4)	354.4 (51.8)	159
Subject *EK*			
	49.5 (2.1)	48.8 (7.0)	47
	138.1 (5.1)	129.6 (21.0)	83
	226.0 (9.3)	204.4 (34.9)	79
	311.5 (16.0)	255.7 (56.5)	85
	402.5 (19.5)	326.9 (63.5)	97

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/target velocity) as a function of stimulus speed. Errors bars show plus and minus one standard deviation about the mean.

Retinal image slip—velocity vs 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 eye does 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 machinery, 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 faster or slower 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 Steinman's (1969), Steinman's *et al.* (1969), and Brown's (1972) all showed a number of tracks in which velocity over-shooting 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.[4]

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 they did when the grating was stationary. This is a striking result—a 15-fold increase in retinal image speed raised pattern thresh-

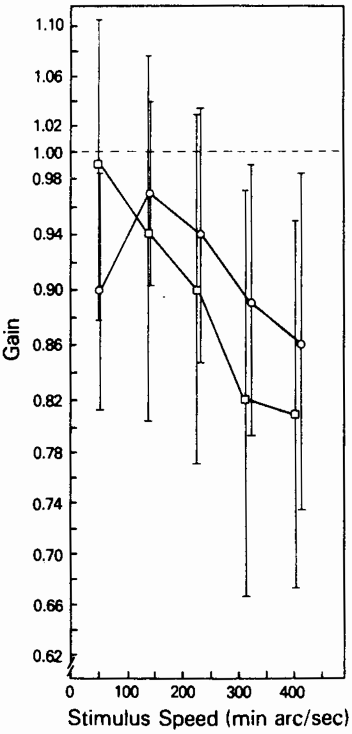

Fig. 2. Mean smooth pursuit gain (eye velocity/stimulus velocity) as a function of stimulus speed. Circles represent subject *RS*, squares subject *EK*. The dashed horizontal line represents velocity matching (gain = 1). Gain was calculated for individual tracks and the values shown in this figure differ 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.

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[4] The variability of stimulus speed arose from two sources, i.e. (1) drift in the signal generators within each session and (2) the ability of the experimenter to reproduce each frequency during the course of each session.

Table 2. Mean pattern threshold contrast (%) and retinal image speed of subjects *RS* and *EK* during smooth pursuit of targets moving at several speeds (*stimulus*)

	Stimulus (min arc/sec)	%	*N*	Image (min arc/sec)	*N*
Subject *RS*	0	2.4 (0.6)	18		
	51.1	3.1 (0.3)	10	5.4 (3.4)	52
	141.5	3.5 (0.4)	10	8.6 (6.9)	77
	232.4	3.6 (0.4)	10	21.6 (16.0)	115
	322.5	3.8 (0.2)	10	38.1 (23.7)	139
	412.4	4.6 (0.6)	10	63.3 (36.4)	159
Subject *EK*	0	3.9 (1.2)	21		
	49.5	3.8 (1.3)	12	4.7 (3.2)	47
	138.1	3.2 (0.8)	12	15.8 (11.2)	83
	226.0	3.7 (1.1)	12	27.0 (18.0)	79
	311.6	5.2 (1.8)	12	56.0 (36.7)	85
	402.4	5.5 (1.4)	12	76.7 (46.0)	97

The number of median thresholds (*N*) averaged is shown as well as their standard deviations, given in parenthese. See Table 1 for estimates of the variability of stimulus speed. The number (*N*) of tracks is also shown.

olds by less than a factor of two. This psychophysical 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 visibility of its pattern during smooth pursuit. However, there is evidence that those changes in contrast sensitivity that did occur during pursuit were caused primarily by retinal image motion produced by imperfections of the oculomotor response. The inexperienced subject, *EK*, showed marked improvement of smooth pursuit during the four weeks of data collection (*viz.* overall mean image speed for week 1 = 61.8′/sec, SD = 42.9; week 2 = 45.9′/sec, SD = 43.9; week 3 = 27.2′/sec, SD = 32.6; week 4 = 31.1′/sec, SD = 34.4). Her contrast thresholds during pursuit showed similar improvement (*viz.* overall mean % contrast in week 1 = 5.2, SD = 1.8; week 2 = 4.6, SD = 1.6; week 3 = 3.6, SD = 0.7; week 4 = 3.0, SD = 0.7). The experienced subject, *RS*, did not show improvement in his smooth pursuit performance during the four weeks of the experiment. His contrast thresholds also remained unchanged. The good correspondence between the oculomotor and psychophysical performances for each subject suggests that retinal image motion could be an important determiner of contrast sensitivity.

Note, however, that *EK*'s psychophysical 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 slip may not be the whole story.

Experiment 2. The influence of retinal image slip on contrast for pattern 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 detail. 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 this 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).

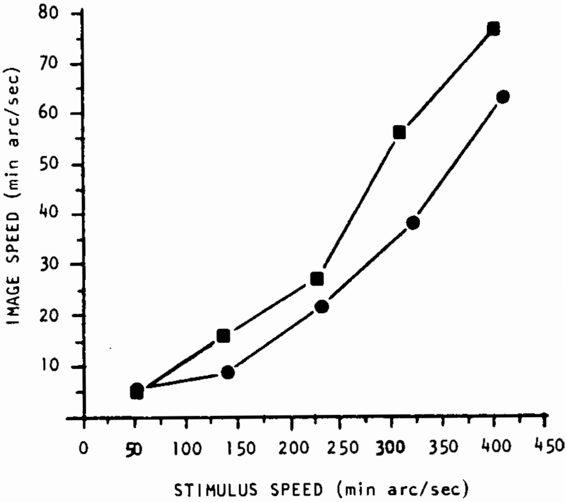

Fig. 3. Mean retinal image speed during smooth pursuit as a function of stimulus speed. Circles represent subject *RS*, squares subject *EK*.

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

	Stimulus (min arc/sec)	Eye (min arc/sec)	*N*
Subject *RS*	−28.8 (1.8)	0.0 (2.7)	26
	28.2 (1.8)	2.4 (2.9)	27
	−51.3 (0.6)	−0.2 (3.7)	24
	50.6 (1.3)	3.9 (4.3)	14
	−99.4 (17.6)	−2.4 (5.4)	30
	98.9 (19.3)	3.9 (4.0)	24
	−141.3 (0.9)	0.0 (5.1)	26
	140.9 (1.0)	1.8 (4.6)	23
Subject *EK*	−28.6 (0.2)	−1.2 (2.6)	14
	28.1 (0.2)	−0.9 (2.8)	20
	−53.6 (30.1)	−1.2 (3.6)	19
	52.6 (28.5)	0.1 (4.0)	22
	−99.4 (21.7)	−0.1 (6.0)	17
	98.9 (20.6)	−1.9 (5.4)	19
	−142.1 (0.9)	−0.4 (4.6)	21
	132.8 (19.3)	2.0 (6.0)	26

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

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 *EK*, whose contrast thresholds during pursuit fell as pursuit improved, did not show any improvement in this experiment which was conducted in the same sessions (*viz.* overall mean % contrast for week 1 = 9.9, SD = 11.6; week 2 = 11.65, SD = 12.8; week 3 = 12.3, SD = 11.7; week 4 = 12.6, SD = 14.1).[5] 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 not an easy question to answer experimentally.

In a first attempt to answer this question subjects were asked to track the two-point target 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 saccaded to and paused at the stationary grating. Furthermore, subjects reported that they were not aware of making these saccades 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: (1) switching to a yes-no signal detection procedure; and 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 homogeneous field (*EK*'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 heard a 100 msec beep and made a judgement 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 73% correct detections by subject *EK* and 74% by *RS*.

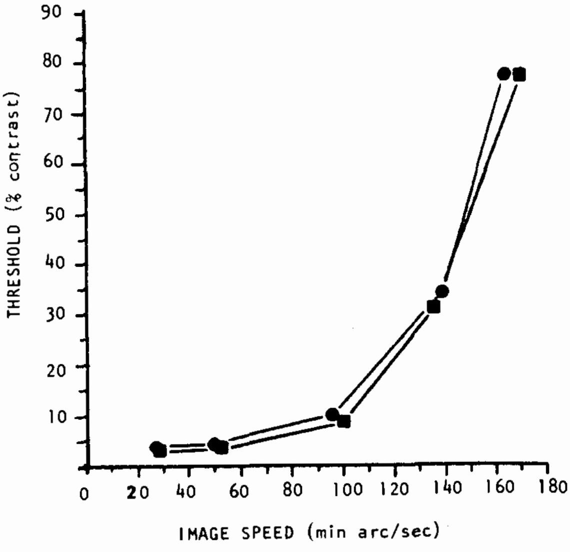

Fig. 4. Mean contrast threshold for pattern as a function of mean retinal image speed when fixation was maintained on a stationary target and the grating moved. Circles represent subject *RS*, squares subject *EK*.

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[5] Thresholds at 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's pattern.

Table 4. Mean pattern threshold contrast (%) and retinal image speed when fixation was maintained on a stationary target and the grating moved

	Image (min arc/sec)	%	*N*
Subject *RS*	27.3	3.9 (1.3)	12
	49.5	4.9 (1.9)	12
	96.1	10.2 (5.5)	12
	140.3	34.1 (12.8)	12
	165.0	77.5 (*)	
Subject *EK*	28.3	3.2 (0.4)	11
	52.5	3.8 (0.6)	11
	100.0	8.6 (1.4)	11
	135.7	31.7 (9.3)	11
	169.6	77.5 (*)	

The number of median thresholds (*N*) averaged is shown 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°/sec, the stimulus speed which produced the same proportion of correct detections was determined when the subjects fixated stationary points and the moving grating was flashed for 100 msec. Threshold grating speed was 103′/sec for subject *EK* and 108′/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 of 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 activities of the oculomotor 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 oculomotor 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 (Skavenski, Haddad, and Steinman, 1972). If this were the case, it would be expected 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 pattern thresholds during fixation (Table 4) shows that they are equal when retinal image speed was equal. This finding confirms Starr *et al.* (1969). There are now two reports that visual sensitivity is not reduced by activities of the oculomotor 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: $EK = 4.2\%$, $RS = 2.5\%$; grating with points: $EK = 3.9\%$, $RS = 2.6\%$). 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 edges 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 40′ from the center of the grating. Also, measurements made during pursuit matched those made during fixation where the grating always oscillated at the center of fovea.

Neither oculomotor 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-shooting, was substantial 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 Ludvigh and Miller (1958) suspected. Also, as they suspected, the loss of acuity with increases in target velocity can be predicted from the amount of resulting image motion. A comparison of the pattern thresholds 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 subject showed substantial improvement of pursuit during 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 oculomotor methodology, it was possible to show that dynamic visual acuity is not more difficult to understand than Ludvigh 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 simple fact, a more complex problem emerged. We see exceedingly well despite the presence of considerable retinal image motion. Look at Fig. 4 and note that gratings moving less than 2°/sec, which is more than 20 times fixation drift velocity, 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 see too well.

This is not the first report that the visual pattern analyzers have a high tolerance for retinal image motion. Westheimer and McKee (1975) reported "super-acuity" for moving Vernier-offset and Landolt ring targets. Interestingly enough, acuity thresholds for these targets, like the pattern thresholds measured in the present experiments, were not markedly influenced by retinal image motions of 2°/sec or less. Perhaps, this resilience to retinal image motion should not be surprising. It makes sense teleologically because bitebars and chin-rests 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 circumstances we even hold our breath. However, it has recently been shown that all such strategems do not immobilize the head or keep the retinal image from moving, motions as fast as 2°/sec are frequently observed when the head is not supported artificially (Winterson, Steinman, Skavenski, Hansen and Robinson, 1975; Steinman, 1975; Steinman, 1976).

Subjective reports by these authors suggest that the visual world looks much the same under natural conditions as it does when the head is supported on a biteboard. The psychophysical measurements reported in this paper confirm their subjective observations. It is possible to see patterns clearly despite appreciable retinal image motion. How this is accomplished by the visual system must now be explained.

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OBITUARY

Brian J. Murphy died of cancer on January 5, 1978. His untimely death cut short a very promising career in visual science—a career that was undertaken under unusual and difficult circumstances.

Brian was born on October 31, 1944 and contracted retinal blastoma in his fifth year, which necessitated removal of one eye and radiation therapy of the remaining eye. This left him almost completely blind—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 impeded but did not prevent his education and he received the Bachelor of Science degree from Hobart College in 1971, graduating *magna cum laude* after election to the *Phi Beta Kappa* Society. He entered the graduate program in the Department of Psychology at the University of Maryland as a Woodrow Wilson Fellow and demonstrated exceptional aptitude as a student, teacher, and researcher during his graduate education. As a graduate student he published research concerned with motor theories of form perception [*Percept. Psychophys.* (1974) **16,** 557–563] and with the effects of moving backgrounds on slow oculomotor control [*Vision Res.* (1975) **15,** 1263–1268] as well as the doctoral thesis research summarized in this paper.

Since completing his Ph.D. in 1976, Dr Murphy was a postdoctoral fellow in the Department of Psychology at the University of Pennsylvania where he was engaged in research on spatial and temporal factors in vision. He was able to complete some of this research before his death which means that, although we have lost a valuable colleague, we will continue to benefit from his efforts in future publications. Unfortunately, we will not be able to benefit from his continuing participation as a visual scientist. In this we have suffered a great loss. Brian J. Murphy was a very talented man.

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