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SLOW OCULOMOTOR CONTROL IN THE PRESENCE OF MOVING BACKGROUNDS

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Abstract—Subjects were able to use slow control to maintain a steady line of sight for 4·5 sec on a stationary point in the center of a 4° dia field containing a high contrast squarewave grating that moved horizontally at either 5′, 48′ or 480′/sec. A small (<6%) influence of the grating movement on drift velocity was observed. It was reduced by more than a factor of 2 when the point was replaced by an annulus (26′ dia). These results were not restricted to brief exposures to the moving grating. Drifts were still largely independent of the background movement after 3 min of exposure. Subjects could also switch at will between keeping the eye in place and tracking the moving grating. Our results are consistent with the hypothesis that there is a single low velocity eye position control subsystem. We conclude that the input to this subsystem is determined by choice and attention and not by the nature of the stimulus.

Images are always moving on the retina either because of movements of the stimulus or drifts of the eye. In both cases the eye uses smooth movements to keep the image relatively stationary. It follows moving targets with smooth pursuits and keeps the line of sight on stationary targets with slow control (Steinman, Haddad, Skavenski and Wyman, 1973). The present research shows that humans have almost complete freedom to pursue or to stay virtually in place when both stationary and moving targets are present in the visual field at the same time.

METHOD

Recording

Horizontal movements of the right eye were recorded by means of an electronic contact lens optical lever whose output was used to make analog and digital records of eye position (Haddad and Steinman, 1973). The recording limit of the instrument as used in the present experiments was 4°, permitting resolution of eye position to about 15″. The left eye was closed and covered and the head was supported by an arcylic dental biteboard.

Stimuli

The stimuli were generated electronically on two oscilloscope displays, one directly in front of the subject's right eye and the other perpendicular to his line of sight. One oscilloscope displayed a 4° bluish-green (P-1 phosphor) 1·25 c/deg high contrast (78%) squarewave grating whose average luminance was 1·7 cd/m^2. The grating was produced by modulating the intensity (Z-axis) of a homogeneous raster. The other oscilloscope displayed either a yellowish (P-20 phosphor) diffraction-limited point or an equally bright 26′ or 147′ dia annulus. The point and annuli were 10 times as intense as the average luminance of the grating. The two oscilloscope displays (1·3 m from the eye) were superimposed by a pellicle beam-splitter.

On a given trial the grating was moved either to the left or to the right at a known constant velocity by time-locking a sawtooth waveform to the Z-axis signal, adding it to a second sawtooth, and triggering the sweep with their sum. The velocity of the moving grating is determined by the slopes of the two sawteeth. Three velocities were used: 5′, 48′ and 480′/sec. The slowest was chosen to be near drift velocity and the others are low and high in the range frequently used in studies of smooth tracking. Only the experimental stimuli could be seen in an otherwise dark room.

Subjects

Four subjects participated in the experiments. They were chosen because they differed both in experience and in the effectiveness of slow control on the horizontal meridian. Two were highly experienced eye movement subjects. One, RS, maintains a steady line of sight on a stationary target when he suppresses saccades. The other experienced subject, GH, drifts slowly (2′/sec) to the right when she suppresses saccades. The other two subjects were inexperienced. They were running in their first eye movement experiment. Their prior experience consisted of a single brief recording session in which their slow control characteristics were observed. One, BW, like RS, has completely effective slow control. The other PM, does not. She, like GH, tends to drift to the right but at a higher velocity (9·5′/sec).

EXPERIMENTS

Slow control maintains the line of sight on a stationary target when the background moves

Both subjects with effective slow control were asked to suppress saccades and maintain the line of sight on a centered stationary point while the grating moved either to the right or to the left in the background. The subject started each trial, causing the moving grating to appear for 4·5 sec after which the grating was replaced by a homogeneous field of the same space average luminance. The homogeneous field and point remained in view during intertrial intervals. Trials were also run with the homogeneous field as the background to permit an estimate of slow control characteristics when the moving background was not present. The effect of the moving grating on drift eye movements was determined by comparing digitized eye position samples from the beginning and from the end of each saccade-free 4·5-sec trial. These measures were used to calculate drift velocity.

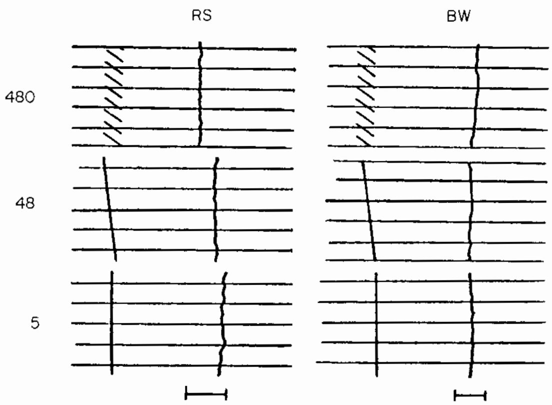

Fig. 1. Three representative records of horizontal eye movements of subjects RS and BW using slow control to maintain the line of sight on a stationary point located at the center of a 4° dia field containing a grating moving to the left at 5′/sec, 48′/sec, and 480′/sec. The eye trace is on the right of each record and grating velocity is proportional to the slope of the trace on the left of each record. Records are read from bottom to top. Horizontal lines are 1-sec time-markers. The bar below each subject's records represents a 1° arc rotation.

The effects of background motion on slow control were modest. The moving background increased the probability of drifting in the direction of the target motion and increased the velocity of the drifts that went in the same direction as the grating. But, the fastest mean drift velocity (3·0′–3·2′/sec) in the direction of the grating motion was less than 6% of the velocity of the most influential background (48′/sec). At this grating velocity 81–90% of the drifts were in the direction of grating motion but the velocity of the eye was very much slower than the velocity of the grating. These results are illustrated in Fig. 1 and summarized in Table 1.

Table 1. The percentage ($\%_{in}$) of trials in which drifts moved the line of sight in the DIRECTION of a grating that moved at 5′/sec, 48′/sec, 480′/sec, or moved the line of sight to the left (%L) when the stationary point was seen at the center of a homogenous field (HOMO) for subjects RS and BW

	Direction		Velocity	
	N	$\%_{in}$	In	Opposite
Subject RS				
5′/sec	68	51	1·0 (0·9)	1·1 (0·7)
48′/sec	69	90	3·0 (1·8)	1·0 (0·8)
480′/sec	64	78	2·5 (1·4)	1·1 (0·9)
Homo	*N*	%L	Left	Right
	31	39	0·8 (0·5)	1·0 (0·5)
Subject BW				
5′/sec	33	73	1·4 (0·9)	0·4 (0·5)
48′/sec	27	81	3·2 (2·9)	2·3 (2·3)
480′/sec	30	77	1·8 (1·3)	1·4 (0·9)
Homo	*N*	%L	Left	Right
	33	55	1·8 (1·6)	1·0 (0·8)

The total number (*N*) of trials recorded under each condition and the mean drift velocities (VELOCITY) IN and OPPOSITE to the direction of grating motion are shown with their standard deviations given in parentheses. Drift velocity is given in min arc/sec

The results summarized in Table 1 were taken from saccade-free trials. Drift velocity was also measured for a random sample of trials containing "spontaneous" saccades (saccades made despite an explicit effort to suppress them) in order to be sure that the selection of saccade-free trials did not bias our estimate of slow control characteristics. Only drifts prior to the first saccade were measured because the subjects knew that the trial would be of little interest if they made a saccade and they did not attempt to maintain the instruction after a spontaneous saccade had occurred (such saccades are easily detected; Haddad and Steinman, 1973). Drift samples were at least 190 msec long and a period of 140 msec preceding saccade-onset was not included in the measurement of drift velocity to allow for saccadic latency (Nachmias, 1959).

Proportions of drifts in the direction of grating motion were not statistically different from proportions observed on saccade-free trials. Drift velocities for the period preceding spontaneous saccades were also not statistically different from drift velocities calculated from a sample of drifts of the same duration taken from the saccade-free trials summarized in Table 1.

The presence of a clearly visible stationary target is essential for effective slow control

The experiment was repeated without the stationary point. The only stationary visible reference was the vague outline of the 4° dia circular aperture that surrounded the field of moving bars which moved to the left on all trials.

Both subjects' lines of sight were dragged in the direction of the moving grating on every trial. Mean drift velocities were about 7–8 times faster than those observed when a stationary centered point was visible. Once again the 48′/sec grating velocity had the largest influence on drifts of the eye. Representative records are reproduced in Fig. 2 and drift velocities are summarized in Table 2.

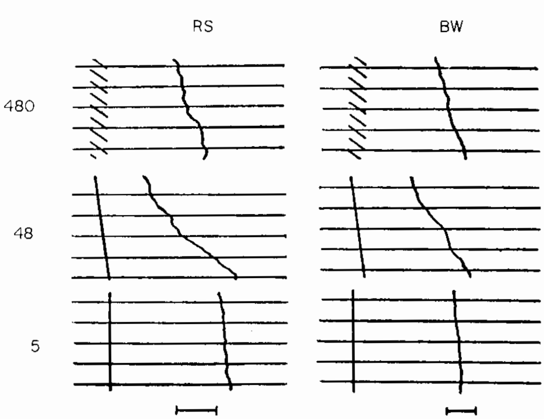

Fig. 2. Three representative records of horizontal eye movements of subjects RS and BW trying to maintain the line of sight with slow control at the center of a 4° dia field containing only a grating moving to the left at 5′/sec, 48′/sec and 480′/sec. The eye trace is on the right of each record and grating velocity is proportional to the slope of the trace on the left of each record. Records are read from bottom to top. Horizontal lines are 1-sec time-markers. The bar below each subject's records represents a 1° arc rotation.

Table 2. The percentage ($\%_{oin}$) of trials in which drifts moved the line of sight in the direction of a moving grating when no stationary target was visible (NONE) and when a LARGE or SMALL stationary annulus was visible for subjects RS and BW

	Direction N	$\%_{oin}$	Velocity In	Opposite
Subject RS				
None				
5′/sec	13	100	3·2 (1·1)	*
48′/sec	13	100	25·2 (3·5)	*
480′/sec	14	100	9·5 (2·8)	*
Large				
48′/sec	16	100	6·0 (1·5)	*
Small				
48′/sec	13	77	1·2 (0·8)	0·4 (0·4)
Subject BW				
None				
5′/sec	15	100	3·0 (1·7)	*
48′/sec	15	100	28·0 (3·2)	*
480′/sec	16	100	14·6 (2·1)	*
Large				
48′/sec	15	100	2·8 (2·8)	*
Small				
48′/sec	15	80	1·6 (0·8)	0·4 (0·3)

The total number (N) of trials recorded under each condition and the mean drift velocities (VELOCITY) IN and OPPOSITE to the direction of grating motion are shown with their standard deviations given in parentheses. Drift velocity is given in min arc/sec

* Drift velocity could not be calculated because all drifts were in the direction of grating motion.

The influence of background motion on slow control depends on the nature of the stationary target

Subjects were asked to suppress saccades and maintain a steady line of sight in the center of a stationary annulus matched in brightness to the point used in the initial experiment. The annulus (either 26′ or 147′ dia) was located at the center of a grating moving to the left at 48′/sec—the velocity that had the largest effect on drifts in the previous experiments.

The large annulus, although better than the vague outlines of the 4° dia field, was found to be less effective in maintaining the line of sight than the point that had been used initially. The eye drifted in the direction of grating motion on all trials for both subjects. The small annulus, however, was found to be a particularly effective target for slow control. Although the proportion of drifts in the direction of grating motion was about the same as with the point, drift velocity in the direction of grating motion decreased by more than a factor of 2, making it barely above the drift velocity observed with a point in a homogeneous field (see Table 1). The finding that a small annulus is particularly effective when used to hold the eye in place is not surprising because it has already been shown that such forms are more effective stimuli for slow control than a small point (Murphy, Haddad and Steinman, 1974). The results of this experiment are summarized in Table 2.

Subjects can switch readily between slow control and smooth pursuit

Subjects, on alternate trials, were asked to suppress saccades and maintain a steady line of sight on the centered stationary small annulus or to track a grating that was moving in the background at either 5′, 48′ or 480′/sec.

Both subjects were able to switch between slow control and smooth tracking with ease as is illustrated in Fig. 3. Note that tracking was brisk, much faster than slow control captured by the grating in the absence of a visible stationary target (see Fig. 2).

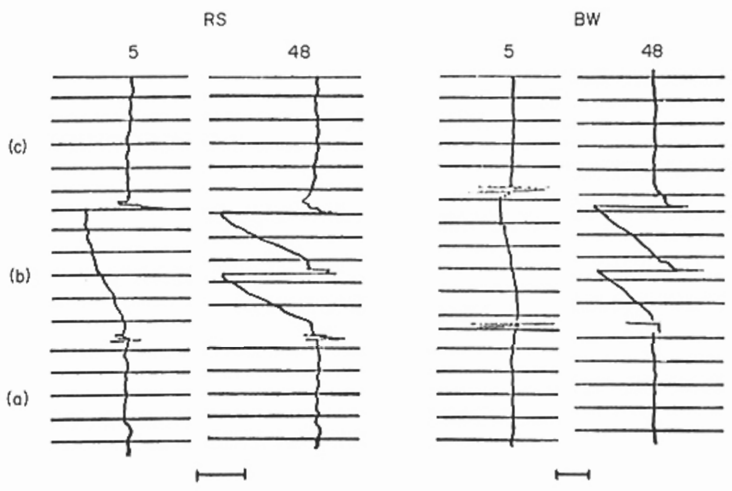

Fig. 3. Three representative consecutive records of horizontal eye movements of subjects RS and BW under instructions to use slow control (a), followed by a trial during which they were asked to track (b) the moving grating, followed by a trial during which they were asked to use slow control once again (c). The stimulus consisted of a 26′ dia annulus located at the center of a 4° dia field containing a grating moving to the left at 5′/sec and 48′/sec. The large right-going saccade, shown by each subject in the middle of the trials in which they tracked the grating moving at 48′/sec, was made in response to a specific instruction to return to the center when they reached the edge of the 4° dia field. Records are read from bottom to top. Horizontal lines are 1-sec time-markers. The bar below each subject's records represents a 1° arc rotation.

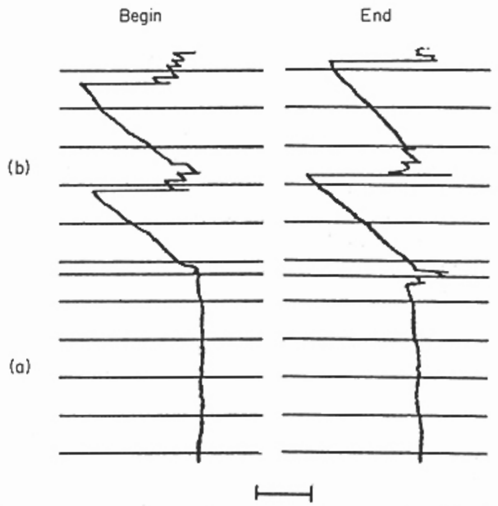

Fig. 4. Two representative consecutive records of horizontal eye movements of subject BW at the beginning (BEGIN) and END of a continuous 3-min exposure to a grating moving to the left at 48′/sec. The instructions were to use slow control (a) on the first trial, followed by a trial during which she was asked to track (b) the moving grating. The stimulus consisted of a 26′ dia annulus located at the center of a 4° dia field containing a grating moving to the left at 48′/sec. The large saccade shown in the middle of both tracking trials occurred when the subject reached the edge of the 4° dia field and saccaded back to her starting position near the center as she had been instructed to do. Records are read from bottom to top. Horizontal lines are 1-sec time-markers. The bar below the subject's records represents a 1° arc rotation.

The ability to maintain the line of sight on a stationary target is not restricted to brief exposures to the moving background

Long trials (3 min) were run during which subjects continuously viewed the grating moving left at 48′/sec. A tone, sounded every 30 sec, instructed the subject to record a pair of alternating 4·5-sec trials—suppressing saccades and maintaining a steady line of sight on a centered 26′ annulus on one trial and tracking the moving grating on the other trial.

Prolonged exposure to the moving grating did not alter the results previously obtained with 4·5-sec exposures to the moving grating. Representative records are reproduced in Fig. 4.

In summary, when subjects with effective slow control were asked to maintain a steady line of sight on a central stationary reference, a grating moving in the background had only a negligible influence on oculomotor performance. However, when they tried to maintain a steady line of sight without a visible central stationary reference, the line of sight was always captured by the moving grating but drift velocity was negligible compared to the velocities observed when the subjects were explicitly asked to track the moving background. Smooth pursuit and slow control are quite independent oculomotor options providing there are both appropriate stationary as well as moving stimuli in the visual field.

These results are not restricted to subjects with effective slow control. They can be demonstrated even more dramatically with subjects who show tendencies to systematic drift when they suppress saccades and try to keep the line of sight in place. Two subjects (GH and PM), who drift to the right when they suppress saccades while viewing a stationary point seen alone in the dark, were asked to maintain the line of sight when the point was seen at the center of a stationary 1·25 c/deg grating. They still drifted to the right. Removal of the point did not change their tendency to drift to the right. These results are illustrated in Fig. 5.

Their rightward drifts could be stopped by moving the grating to the left. GH required a grating velocity of 8′/sec and PM required 26′/sec to stabilize the eye. However, when they were asked to maintain a steady line of sight on the stationary point at the center of the same moving grating, their characteristic drift to the right returned. This is also shown in Fig. 5. These subjects, despite their tendency to drift to the right when the point was visible on a background moving to the left, had no difficulty tracking a grating moving to the left when instructed to do so despite the pres-

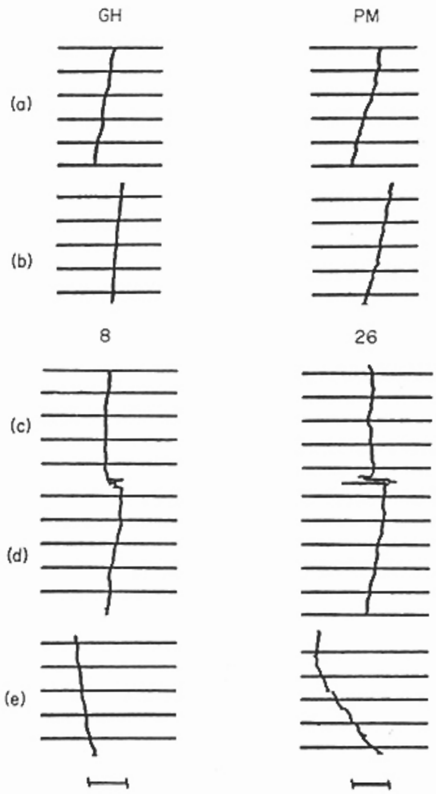

Fig. 5. (a) Representative records of horizontal eye movements of two subjects (GH and PM) who drift to the right when they use slow control to maintain the line of sight on a point located at the center of a 4° dia field containing a stationary grating. (b) Representative records of the same subjects attempting the same task when the point was not visible on the stationary grating and (c) when the grating moved to the left at 8′/sec for GH and 26′/sec for PM. In (d) the point was visible and the grating continued to move while (e) shows their response to a change in the instruction. They were asked to track the grating rather than to stay in place under the same stimulus conditions. Records are read from bottom to top. Horizontal lines are 1-sec time-markers. The bar below each subject's records represents a 1° arc rotation.

ence of the stationary point in their field of view. These results are also illustrated in Fig. 5.

DISCUSSION

Our results show clearly that the human being can keep his line of sight near stationary details in the presence of a moving background. Even a single stationary detail is sufficient to maintain the line of sight within a few minutes of arc when it is seen against a vivid highly structured moving background. Saccades are not required to stay in place and the fixation direction will not be disturbed appreciably over several seconds.

The fact that the line of sight is very much under the control of the subject regardless of the nature of the visual field is not news. This pervasive property of oculomotor performance has been demonstrated in recent years in a number of experiments with a variety of stimuli. Prior reports have included demonstrations that the size, shape, color and luminance of a stationary fixation target do not have important effects on the precision or on the accuracy of fixation. There have also been demonstrations that subjects can voluntarily track moving targets both with and without saccades (Puckett and Steinman, 1969) and also that they can smoothly pursue at specified fractions of target velocity (Steinman, Skavenski and Sansbury, 1969). Much of this research was reviewed recently by Steinman (1976) who also pointed out that such oculomotor independence from properties of the visual stimulus is useful to the organism.

The results of the present experiments are consistent with this pervasive property of oculomotor performance. They are also in accord with the conclusions of some prior investigators who used stimulus conditions similar to ours. Dodge and Fox (1928) found that the slow phase of optokinetic nystagmus "may be more or less completely inhibited by convergence, by fixating an accidental motionless object, by looking past the drum into distance, and to some degree at least by psychological indifference." (p. 823). Similar observations were subsequently made by Fischer and Kornmüller (1930) as well as by Stark (1971). All reported that drifts of the eye (slow phase OKN) are less influenced by moving visual backgrounds when a stationary reference is present than when it is not. The present study supports this general conclusion.

In fact it now seems appropriate to go further and say that slow control is virtually independent of background movement provided that two conditions are met, namely (1) an effective stationary stimulus for slow control is present in the field of view, and (2) subjects attend to the stationary stimulus and make a serious effort to maintain the line of sight. N.B. Our finding of virtually complete freedom of drifts from background movement under appropriate conditions was made with a recording technique that is 1–3 orders of magnitude more sensitive than the techniques employed in prior studies. Our result is new, therefore, because we used a recording method which could register the smallest drifts of the eye that could be produced by a moving background. Frankly, we were surprised that the conclusion drawn by Dodge and Fox many years ago would hold when it became possible to observe the finest features of oculomotor performance. (Dodge had an uncanny feel for what was really going on!)

Also of interest is our finding that smooth tracking and slow control can be activated by choice even when the velocity of the moving background is only 5′/sec—much less than 30′/sec—a typical "low" velocity stimulus studied in human eye tracking experiments (e.g. Rashbass, 1961; Puckett and Steinman, 1969). We know of only two prior reports of human tracking with targets as slow as those we used. Yarbus (1967) reported that smooth pursuit (drifts in the direction of target motion) began when "the speed of the object equals the speed of the irregular drift of the eye (always present during fixation)" (p. 162) and Cunitz (1970) showed, quantitatively, that smooth tracking can begin when target velocities are as low as 8′/sec.

We found that both the inexperienced as well as the experienced subjects, who had effective slow control (BW and RS), always tracked gratings moving as slowly as 5′/sec. The drift direction (when they were asked to track) was always in the direction of grating motion and their eye velocity was always at least 80% of the velocity of the grating. However, when they were asked to use slow control to stay in place on a visible stationary point, both subjects still drifted in the direction of the moving grating, but their average eye velocity was much lower—only about 20% of the velocity of the grating. So, even when the background moves as slowly as ordinary fixation drifts, smooth pursuit and slow control can be elected voluntarily.

Our findings raise questions about the mechanisms that underlie smooth pursuit and slow control. When a subject opts to track, rather than to stay in place with smooth eye movements, is he activating an oculomotor subsystem specifically designed to follow moving targets which is different from the subsystem that he uses when he wishes to stay in place? This seems unlikely because both kinds of performance can be handled by the smooth pursuit subsystem, providing that the subject can select the stimulus (either stationary or moving) that he wishes to use as input to his oculomotor system. This idea, that there is a single low velocity eye position control subsystem that is used for the smooth pursuit of moving targets and also for slow control when the fixation stimulus is stationary, was suggested by Nachmias (1961) when he discovered that there was a corrective component in the pattern of drifts observed during maintained fixation of a stationary target. More recently, Robinson (1971) has modeled a system with these properties. It allows the eye to smoothly track moving targets and at the same time stay in place when the target is stationary.

Our results are consistent with such a model. Separate slow control and smooth pursuit subsystems are not required to explain the strong influence of the moving grating when the subject chooses to track and the negligible influence of the same grating when he chooses to keep his line of sight on the stationary target. We found that the option to pursue or to stay in place is only available when appropriate stationary and moving stimuli are present which suggests that the simplest explanation of our results is that the subject's voluntary control of his low velocity eye movements is limited to the selection of the stimulus that he will use as input rather than to the activation of separate tracking or stabilizing subsystems.

A striking feature of our results is the degree to which such selection can be accomplished. Practically none of the signal produced by the feature of the visual field that is not attended (either moving or stationary) shows up in oculomotor performance. It would be of considerable interest to know where this efficient selective filter is and how it is constructed.

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