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TRACKING EYE MOVEMENTS WITH AND WITHOUT SACCADIC CORRECTION

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RECENTLY, the importance of drifts or saccades in the maintenance of eye position has been shown to depend on the mode of viewing adopted by the subject. FIORENTINI and ERCOLES (1966) and STEINMAN, CUNITZ, TIMBERLAKE and HERMAN (1967) reported that subjects could, voluntarily, suppress saccades during maintained fixation without increasing the variability of the eye about its mean fixation position. These observations led us to ask whether different modes of viewing could, also, influence the way in which subjects track a moving target. Both saccades and smooth pursuits (drifts in the direction of target motion) are common during tracking (WESTHEIMER, 1954) and we felt that the prevalence of one or the other movement might depend on instructional variables commonly neglected in eye tracking experiments. Specifically, when a subject is asked to pursue a moving target, he can try to match velocity with the target *or* he can concentrate on maintaining minimum fixation error. The former might permit the accumulation of large tracking errors before eye position is corrected by saccades. The latter would encourage frequent saccadic position corrections, particularly, if smooth pursuits are not keeping the line of regard on the moving target. We studied these alternatives by explicitly trying to make *or* to inhibit saccadic position corrections during tracking, concentrating either on staying right on-target *or* matching target velocity.

This paper describes (1) the degree to which two experienced subjects adopted alternative tracking strategies (2) tracking error when saccades were or were not frequent during smooth pursuit and (3) the extent to which the eye matched velocity with unpredictable constant velocity target motions.

METHOD

A contact lens optical lever technique was used to record horizontal eye movements on 35 mm infrared film moving at 1 cm/sec in a modified Grass model C4H camera. The technique, described elsewhere (STEINMAN, 1965), records small rotations of the eye free from contamination by translations of the head. Eye position was measured to about 10 sec arc and time to about 5 msec. Measurement error, calculated from remeasures of 10 per cent of the recordings, was 1·49 min arc/sec.

*S*s saw a sharply focused green point (P-20 phosphor) in an otherwise dark room. The point (1·00 log unit above absolute foveal threshold) was provided by a Tektronix (Model 503) oscilloscope 1·0 m from the right eye. At the beginning of each trial *S* either "fixated" or "held" on a point centered on the scope-face. At some randomly chosen time, 3·0–9·1 sec after *S* initiated the trial, the point moved 3 deg arc at a constant velocity (60, 120, 240, 480 or 900 min arc/sec) to the right or left. The direction of target motion was selected randomly. After movement, the point stayed at the 3 deg arc position for 4·1 sec. Trials were recorded in blocks of 20 for each velocity. Instructions were alternated within blocks.

On "fixation" trials, *S*s tried to stay right on-target by making frequent saccadic corrections. On "hold" trials *S*s tried to suppress saccades, keeping their eyes in position when the target was stationary and matching velocity with it when it moved. Both subjects, *AS*, a graduate student, and *RS*, the second author, had extensive previous experience "fixating" and "holding" on stationary targets.

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RESULTS

1. *Effect of instruction on saccade rate*

Both *S*s were able to adopt and maintain each instruction. Table 1 presents mean saccade rates before, during and after target movement as well as the overall rate for the 5 velocities under each instruction. Note that in every case the saccade rate while "fixating" was markedly higher than the rate while "holding". The differences in overall rates were statistically reliable (*RS*, $t=8{\cdot}68$, $df=4$, $p<0{\cdot}001$; AS, $t=14{\cdot}13$, $df=4$, $p<0{\cdot}001$). Figure 1 shows a highly saccadic and saccade-free trial under each instruction for *RS* while he tracked a target moving at 60 min arc/sec.

2. *Tracking error*

Tracking during the 5 "hold" trials with the lowest and the 5 "fixate" trials with the highest overall saccade rates were examined in detail. *Tracking errors* (differences between eye and target positions) were estimated from successive 0·1 sec measures of eye position

TABLE 1. MEAN SACCADE RATES (saccades/sec) ON A NUMBER (*n*) OF FIXATION (*Fix*) AND HOLDING (*Hold*) TRIALS DURING *pre-movement* AND *post-movement* PERIODS FOR 5 TARGET VELOCITIES (min arc/sec)

Subject RS

	Hold					*Fix*				
Velocity		Pre	Move	Post	Overall		Pre	Move	Post	Overall
60′	Mean *n*=64	1·19	0·42	0·69	0·77	Mean *n*=44	2·06	0·87	1·40	1·44
120′	Mean *n*=41	1·34	0·62	0·81	0·92	Mean *n*=28	2·04	1·28	1·76	1·69
240′	Mean *n*=35	1·21	1·05	0·79	1·02	Mean *n*=52	2·18	1·97	1·77	1·97
480′	Mean *n*=75	1·83	0·58	0·68	1·03	Mean *n*=45	2·06	2·56	1·66	2·09
900′	Mean *n*=26	1·00	0·20	0·71	0·64	Mean *n*=26	1·58	1·40	1·64	1·19
	Grand Mean *N*=241	1·40	0·52	0·72	0·90	Grand Mean *N*=195	2·03	1·68	1·64	1·78

Subject AS

	Hold					*Fix*				
Velocity		Pre	Move	Post	Overall		Pre	Move	Post	Overall
60′	Mean *n*=49	0·35	0·77	0·20	0·44	Mean *n*=54	1·49	1·51	1·29	1·45
120′	Mean *n*=56	0·42	1·37	0·62	0·81	Mean *n*=57	1·52	1·93	1·41	1·62
240′	Mean *n*=40	0·32	1·52	0·82	0·89	Mean *n*=42	1·65	1·93	1·81	1·80
480′	Mean *n*=33	0·18	1·05	0·88	0·70	Mean *n*=42	1·65	2·35	1·78	1·93
900′	Mean *n*=46	0·23	0·00	0·83	0·35	Mean *n*=49	1·41	0·96	1·59	1·32
	Grand Mean *N*=224	0·31	0·94	0·64	0·63	Grand Mean *N*=244	1·52	1·71	1·55	1·59

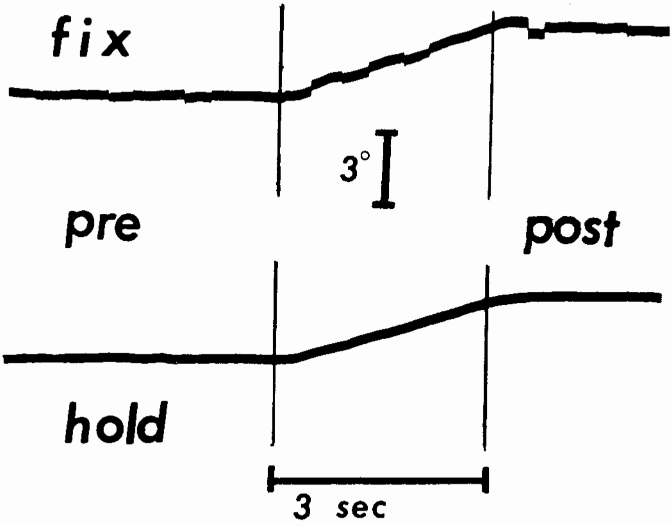

FIG. 1. Selected recordings for subject *RS* fixating (*fix*) and holding (*hold*) before (*pre*), during and after (*post*) a constant velocity (60 min arc/sec) displacement of the target. The onset of target motion is shown by a thin dark line to the left of center in the figure and the end of target motion is shown by a similar dark line to the right of center. The target moved to the right on these trials (upwards in the recorded trace).

during target motion and the first 0·5 sec following motion. Mean eye position prior to target motion was subtracted from each 0·1 sec position measure. Target positions were then subtracted from each difference in eye position to obtain 0·1 sec tracking errors. This procedure assumes that mean eye position prior to target motion coincides with the position of the centered target.

Tracking errors of subject *RS*, our better *S*, are shown in Fig. 2. *RS* tracked accurately when he "fixated" the slowest target (circles in Graph *A*). His constant error was only −1·7 min arc and his variability about the zero error axis was small (S.D.=6·8 min arc); not much larger than when he "fixated" (S.D.=4·4 min arc) or "held" (S.D.=2·5 min arc) on the stationary centered target during pre-movement periods. *AS* also "fixated" (S.D.=3·5 min arc) and "held" (S.D.=2·4 min arc) very well in the pre-movement periods, but he did not track as well. His smallest constant error was −11·1 min arc (with the slowest target). Tracking error was larger when targets moved faster, particularly when saccades were not used to correct position errors (triangles in Fig. 2). Neither *S* smoothly pursued the fastest target (900 min arc/sec). They "fixated" or "held" at the center and made one or more high velocity movement to the displaced target position where they maintained one or the other instruction. At the lower target velocities, shown in Fig. 2, tracking errors were reduced by saccades and smooth pursuits during the movement period (connected points) and the ½ sec following motion. Completely smooth tracking is shown in the "hold" functions (triangles) since there were no saccades, whatsoever, during any phases of the extreme trials plotted for this *S*. These curves, then, show saccade-free smooth pursuit.

Two things stand out: (1) very large fixation errors built up as the target moved and (2) these errors persisted for several sec after the target came to rest. Note, for example, the triangle plotted at the extreme right of Graph *D* which shows mean eye position during

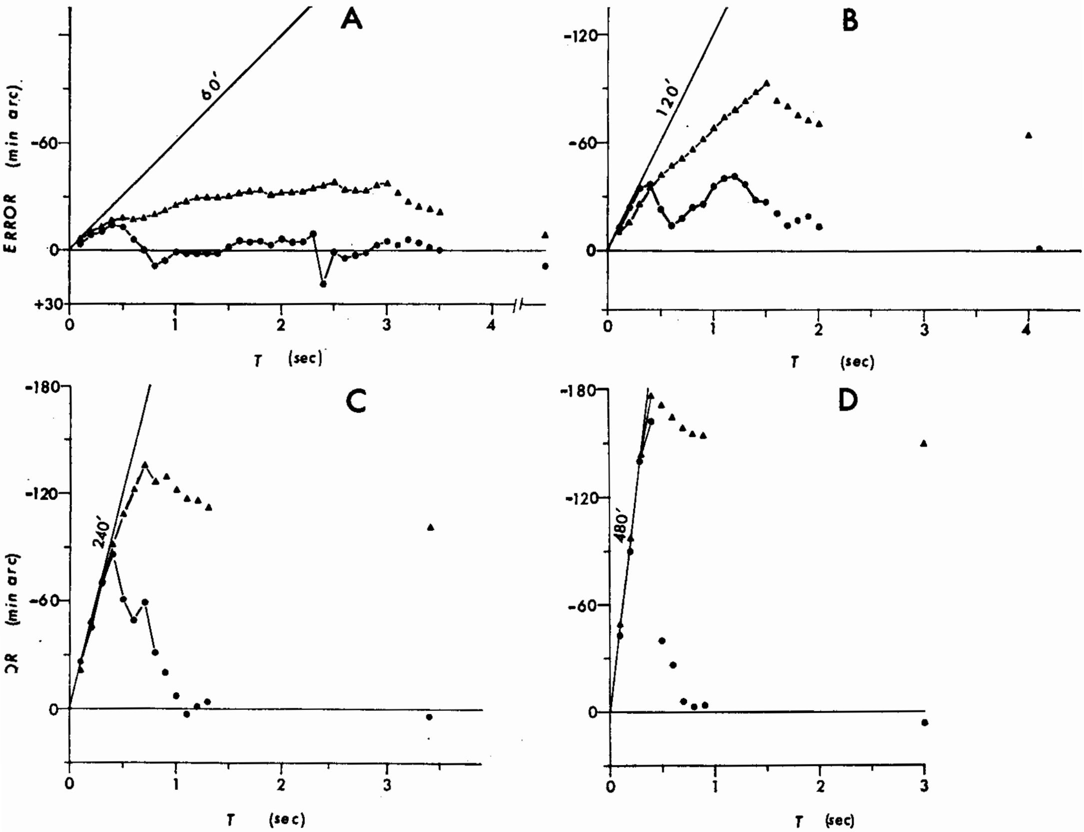

FIG. 2. Tracking error (*error*) of subject *RS* while he "fixated" (filled circles) or "held" (triangles) on targets moving 60, 120, 240 or 480 min arc/sec. Zero on the ordinate represents the pre-movement mean position. Negative errors, given in minutes of arc, show that the eye was behind the target and positive errors show that it was ahead. Zero on the abscissa is the onset of target motion. Each data point is a mean error based on 5 "fixate" trials with the highest overall saccade rates and 5 "hold" trials during which there were no saccades whatsoever. Mean errors are plotted for successive 0·1 sec intervals during target motion (connected points) and during the half-second immediately following target motion (unconnected points). The mean tracking errors plotted under the "hold" instruction are reasonably representative of smooth pursuit on each of the 5 trials that were averaged to make these graphs, i.e. mean S.D. of each data point = 5·7 min arc (S.E. = 3·1 min arc). The mean error during the final 3 sec of the trials is plotted at the midpoint of the post-movement temporal interval. Each diagonal line (labeled with the velocity of the target) represents the absolute deviation of the target from its starting position.

the final 3 sec of the stationary post-movement period. *RS* is "holding" about 150 min arc away from the target position. Eye position was maintained for several seconds even though the target was far from the foveal "center of best vision". The standard deviation during the post-movement periods of the "hold" trials shown in Graph *D* was only 5·3 min arc. The target was completely outside of the fovea but *S* held his eye in position very well.

3. *Velocity matching*

*S*s did not match velocity with the targets. This can be seen in Fig. 2 (triangles) where velocity matching during target motion would produce smooth tracking functions parallel to the abscissa. Failure to match velocity with the target led to accumulation of large tracking errors (described above). Similar failures were found in intersaccadic drift measures made for the extreme trials sampled under the "fixate" instruction (circles). Almost all intersaccadic drifts were pursuits, i.e. they were in the direction of target motions, but the closest either *S* came to matching velocity was 87 per cent (*AS* "fixating" the slowest target). Intersaccadic velocity matching was much poorer for *RS* with this target (68 per cent) and still worse for both *S*s when targets moved faster than 60 min arc/sec.

We were disappointed in the performance of the low velocity pursuit system on trials that had the lowest and highest saccade rates and decided to sample smooth pursuits under conditions most favorable for velocity matching. We measured pursuit velocity during the last ½ sec of the slowest target motions (60 and 120 min arc/sec). *S*s, during this period of these trials, had at least 1 sec or as much as 2·5 sec to attain target velocity following the unpredictable onset and direction of motion. Our only restriction was that the last ½ sec did not contain saccades. This restriction was imposed so that smooth pursuit could be examined free from saccadic velocity contamination (ROBINSON, 1965). Results of this analysis are shown in Table 2.

TABLE 2. MEAN LAST 0·5 sec PURSUIT VELOCITIES (min arc/sec) (*V*) ON A NUMBER (*N*) OF FIXATION (*Fix*) AND HOLDING (*Hold*) TRIALS IN RESPONSE TO 60 *and* 120 min arc/sec TARGET MOVEMENTS. STANDARD DEVIATIONS (*S.D.*) AND VELOCITY-MATCHING (%) ARE ALSO SHOWN

Subject *RS*	*Hold*				*Fix*			
	V	*N*	S.D.	%	*V*	*N*	S.D.	%
60′	49·6	64	8·77	82·7	52·2	36	9·00	87·0
120′	73·4	38	19·29	61·2	81·5	24	15·65	67·9
Subject *AS*								
	V	*N*	S.D.	%	*V*	*N*	S.D.	%
60′	42·1	45	14·32	70·2	50·8	40	9·90	84·7
120′	52·8	41	40·19	44·0	70·7	29	44·67	58·9

Both *S*s pursued more slowly than the target moved even after they had been given considerable time to see the direction and speed with which it was moving. The differences between target and eye velocity shown in Table 2 were statistically significant, i.e. the *least* reliable difference occurred when *AS* "held" on the 120 min arc/sec target ($t=3{\cdot}78$, $df=28$, $p<0{\cdot}001$, two-tailed). As would be expected from ROBINSON's (1965) analysis, smooth pursuits were slightly more brisk under the "fixate" instruction which led, on the average, to about twice as many saccades in the pre- and early movement periods. Frequency distributions of velocities were approximately normal and the large standard deviations reported in Table 2 show that there were occasional trials when pursuit velocity closely approximated target velocity and even trials when velocity over-shooting occurred. On the average, however, both *S*s' smooth pursuits were much slower than the constant velocity motions of the target. This "poor" performance persisted throughout the several weeks required to make our recordings. There was no difference between smooth pursuit velocity recorded on the first or last days of our experiment.

DISCUSSION

1. *Effect of instruction on saccade frequency*

*S*s can adopt a highly saccadic or almost saccade-free mode of viewing, maintain it throughout a period of target motion and for several seconds afterward despite the fact that the target is unexpectedly set into motion in an unpredictable direction. This finding extends the conditions under which *S*s can suppress microsaccades. We also found that large fixation errors need not *elicit* saccadic corrections and that eye position can be maintained (S.D. = 5·3 min arc), without saccades, when the target falls as much as 2½ deg arc from the foveal "center of best vision".

2. *Failure to match velocity*

Our *S*s' smooth pursuits did not match constant velocity target motions under conditions where velocities, predictability and extent of movement were selected to favor such performance. We modeled our experiment after an often-cited study by RASHBASS (1961) where "precise match of eye velocity to target velocity" was reported when targets moved, unpredictably, through a distance of 3 deg arc at velocities from 48 to 600 min arc/sec. The failure of our *S*s to match velocity under the same conditions was evident in (1) tracking error functions derived from recordings with the lowest and highest saccade rates (2) intersaccadic pursuit velocities on these extreme trials and (3) intersaccadic pursuit velocities during the final ½ sec of more than 300 trials with slowly moving targets (60 and 120 min arc/sec).

We can not account for the difference between Rashbass' and our results. Some plausible explanations are as follows:

(a) *Large individual variations* in eye movement patterns are common (emphasized in NACHMIAS, 1959; FIORENTINI and ERCOLES, 1966; and STEINMAN, 1965; and apparent in DITCHBURN and FOLEY-FISHER'S, 1967, compilation of the performance characteristics of most contact lens *S*s). We can not reject the possibility that *AS* and *RS* are poor *S*s, but their weakness is confined to smooth pursuit since these *S*s are known to maintain eye position very well with a variety of stationary targets (STEINMAN, 1965; STEINMAN *et al.*, 1967; STEINMAN and CUNITZ, 1968; and CUNITZ and STEINMAN, in press). Rashbass' *S*s are described as young and emmetropic as were WESTHEIMER'S (1954) who were also reported to "generally, but by no means always," match target velocity. Perhaps relatively inexperienced *S*s are more adept at velocity matching.

(b) *Our recording method* was more sensitive than Rashbass' (or Westheimer's) which could not detect eye movements smaller than 5 min arc. Perhaps, the Rashbass report of velocity matching does not describe smooth pursuit but, rather, a composite of small saccades and smooth pursuits (we noted many saccades during smooth pursuit that were smaller than 5 min arc). On the other hand our more sensitive contact lens method might be subject to slippage artifacts. We consider this unlikely because (1) lenses like ours, moulded to fit tightly at the limbus, are known to be reasonably stable (RIGGS and SCHICK, 1968) and (2) although there were occasional small baseline changes over 35 min recording sessions, baselines were stable between successive 10 to 20 sec tracking trials and our pursuit velocities are based on within-trial position measures.

There is a recent report of velocity matching with unpredictable constant velocity targets that is not open to question on the grounds of recording sensitivity (ROBINSON, 1965). In this study, however, an "embarrassing" degree of intrasubject variability in the pursuit pattern was noted and, unlike our report, the degree of velocity matching was not inferred from statistical treatment of a large sample of recordings. Also, Robinson's targets moved through an angle of 10 deg arc which afforded 3 times as much time for the eye to attain target velocity than was available in our or RASHBASS' (1961) experiments. It may be that 10 deg arc target displacements provide sufficient time for learning and prediction to operate with ramp stimuli; a possibility that Robinson explicitly desired to avoid.

(c) *Stimulus conditions* were not precisely the same in our and in Rashbass' experiment. His *S*s tracked a "blue" spot of unspecified luminance. Ours tracked a "green" spot whose luminance was set 1·00 log unit above absolute foveal threshold. Perhaps, spectral distribution and/or luminance are critical for velocity matching. We cannot reject this possibility but consider it unlikely because (1) color and luminance have little or no effect on fixation of high contrast stationary targets once luminance is set slightly above absolute foveal threshold (STEINMAN, 1965; BOYCE, 1967) and (2) large luminance effects on responses to step and sinusoidal target motions are only found near and below absolute foveal threshold (WHEELESS, JR., COHEN and BOYNTON, 1967). The luminance of Rashbass' target was not specified but it could not have been much higher than ours because oscilloscope spots, viewed in darkness, become very large and surrounded by halos when the intensity of a stationary display is increased much beyond the level employed in the present experiment.

It should be noted that the eye movement patterns reported in the present paper would not be expected if target luminance was not above absolute foveal threshold: Fixation and tracking are very different when the target is not visible foveally (STEINMAN and CUNITZ, 1968; WHEELESS, JR., *et al.*, 1967).

3. *Conclusions*

Experienced *S*s can adopt different strategies when asked to track unpredictable constant velocity target motions. They can, when explicitly instructed, (1) either make very frequent saccadic position corrections or suppress saccades, sometimes entirely, and track the target primarily with smooth pursuits and (2) maintain eye position, without saccades, when the target falls far from the normal retinal fixation locus.

Saccadic tracking leads to much smaller position errors than smooth tracking. This is not surprising since saccades are known to correct position errors. A surprising, and controversial finding, was that our *S*s did not, generally, match velocity during smooth pursuit. The mismatch was large (mean eye velocity was less than 87 per cent of target velocity and less than 68 per cent of target velocity when targets moved at 1 or 2 deg arc/sec, respectively). Even more important, the large variability in pursuit velocity on different trials with the same target shows that velocity undershooting does not simply arise from a constant lag in the smooth pursuit system.

We conclude that either our *S*s are abnormal or prior reports of good velocity matching do not describe general characteristics of the smooth pursuit of unpredictable constant velocity target motions. We prefer the second alternative because we used highly experienced eye movement *S*s, our method was sufficiently sensitive to detect all saccades that occurred during tracking and our conclusion is based on measurements of a large sample of smooth pursuits under conditions where velocity matching should be good.

If smooth pursuits do not, *generally*, match unpredictable constant velocity target motions, the stimulus for such pursuits may arise from residual movements of the target image on the retina. The image of a moving target is rarely stationary if eye and target velocity do not generally match. In other words, the rate of error might be the stimulus for smooth pursuit if target velocity is not accurately matched. RASHBASS (1961) considered and rejected this possibility when he reported that smooth pursuit velocity closely matched target velocity. Our measurements seem to revive this possibility.

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Abstract—A contact lens optical lever was used to record horizontal tracking eye movements made in response to unpredictable constant velocity target motions (1 to 15 deg arc/sec). *S*s were instructed either to make frequent saccadic position corrections *or* to suppress saccades and follow the target, as much as possible, with smooth pursuits. *S*s were able to adopt these different tracking strategies and tracking error, when saccades were frequent, was much smaller than error when smooth pursuits were used almost exclusively. Eye position stability when the target was stationary, before and after movements, did not require saccades either when the target was in the preferred retinal fixation locus or when it fell as much as 2½ deg arc from this position. Both *S*s failed, generally, to match the velocity of the moving target with their smooth pursuits.

Résumé—On enregistre avec un levier optique à verre de contact les mouvements de poursuite des yeux en réponse à des mouvements imprévisibles d'une cible à vitesse constante (1 à 15 deg arc/sec). On demande aux sujets soit de faire de fréquentes corrections de position par saccades, soit d'éviter les saccades et de suivre régulièrement la cible, autant que possible. Les sujets sont capables d'adopter ces stratégies différentes de poursuite, et l'erreur de poursuite était beaucoup plus petite avec de fréquentes saccades que lorsqu'on employait presque uniquement une poursuite régulière. La stabilité de position des yeux pour une cible immobile, avant et après les mouvements, ne comportait pas de saccades, soit que la cible se trouve au lieu préféré pour la fixation rétinienne, soit qu'elle tombe jusqu'à 2½ deg arc de cette position. Les deux sujets échouent en général à égaliser la vitesse de la cible mobile avec celle d'une poursuite régulière.

Zusammenfassung—Ein optischer Hebel mit Haftglass wurden benützt, um die wagrechten Folgebewegungen des Auges auf unvorhersehbare Objektbewegungen von stetiger Geschwindigkeit (1 bis 15 Grad/Sek.) zu registrieren. Die Beobachter wurden aufgefordert, entweder häufige Stellungsverbesserungen zu machen oder die Sakkaden zu unterdrücken und dem Ziel so gut wie möglich mit glatten Bewegungen zu folgen. Die Beobachter fanden dass es möglich ist, diese verschiedenen Folgestrategien vorzunehmen und die Folgefehler waren kleiner, wenn die Sakkaden öfter gemacht wurden, als wenn fast ausschliesslich glatte Bewegungen gemacht wurden. Wenn das Objekt stillstand, war die Augenstabilität vor oder nach einer Bewegung von der Fixationsrichtung, oder wenn diese bis auf 2½ Grade von der Bildrichtung abwich, unabhängig. Keinem der beiden Beobachter gelang es im allgemeinen die Geschwindigkeit des beweglichen Zieles mit glatten Folgebewegungen nachzuahmen.

Резюме — Контактная линза со специальным оптическим устройством использовалась для записи горизонтальных движений глаз при слежении за объектом, движущимся с непредсказуемой скоростью, без ускорения (диапазон от 1 до 15 град/сек.). Испытуемым предлагалось *либо* часто переводить взгляд, *либо* подавлять скачки и следить за объектом как можно более плавно. Испытуемые оказались в состоянии произвольно выбирать тактику прослеживания; ошибка — при частых саккадах — была гораздо меньшей, чем при исключительно плавном прослеживании, без скачков. Стабильность положения глаз при неподвижном объекте — до и после его движения — не требовала скачков ни в тех случаях, когда объек тпроецировался в оптимальную зону сетчатки, ни в тех — когда он отклонялся от этой зоны на 2,5°. Оба испытуемыхв общем не смогли уравнять скорость движения глаз со скоростью движения объекта при плавном прослеживании.