Vision Res. Vol. 24, No. 9, pp. 1003–1009, 1984
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0042-6989/84 $3.00 + 0.00

CHARACTERISTICS OF SMOOTH EYE MOVEMENTS WITH STABILIZED TARGETS

W. B. CUSHMAN, J. F. TANGNEY, R. M. STEINMAN* and J. L. FERGUSON
Department of Psychology, University of Maryland, College Park, MD 20742, U.S.A.

(*Received* 18 *January* 1984)

Abstract—Eye movements of two subjects were recorded with a Double Purkinje Image Tracker while they pursued horizontal triangle or ramp stimuli (1, 2, 4 or 8°/sec, p—p 8°). Subjects then attempted to imitate their smooth pursuit eye movement patterns with an electronically-stabilized target or with an afterimage. Next, they attempted to reset the velocity of the stimulus to their memory of the velocity they had previously pursued. The smooth pursuit eye movements of both subjects were very similar. Their attempts to imitate this pattern of eye movements with a stabilized target were only partially successful and subject to large, qualitative individual differences. These differences did not arise from faulty memories of the nature of the pursuit stimuli. Similar results were obtained on the vertical meridian, with a lighted background, and with the stabilized target in eccentric retinal positions. We conclude that stabilization techniques are of dubious value in elucidating properties of the human smooth pursuit subsystem.

INTRODUCTION

It has been known at least since Helmholtz (1962) that an afterimage will be seen to move as the eye moves. Any target stabilized with respect to the retina displays similar properties. This easily made observation has been used in the study of visual perception, particularly position constancy (e.g. Mack and Bachant, 1969) and also to make inferences about mechanisms underlying smooth pursuit (e.g. Yasui and Young, 1976). It has been claimed that, "smooth eye movements indistinguishable from normal pursuit movements can be made in the absence of a moving visual stimulus if an after-image is tracked." (Heywood, 1972). We became suspicious about this claim during the course of attempts at afterimage tracking undertaken for essentially frivolous reasons. It is fun to generate afterimages and then try to move them about in various ways. We noticed that we could not obtain any reasonable consensus either about what we perceived or the degree to which we could manipulate the pattern of stabilized target motion and, by implication, therefore, the ways in which we could move our eyes. This led us to examine, with a high resolution eye movement monitor, our capacity to make voluntary smooth eye movements with stabilized targets. We found our capacities to be quite idiosyncratic—sufficiently so as to leave us skeptical about the significance of eye movement observations obtained with stabilized targets.

METHODS

Eye movement recording

Horizontal and vertical rotations of the right eye were monitored with a generation III SRI Double Purkinje Image Tracker (Cornsweet and Crane, 1973). Head movements were restricted by a dental bite-board and the left eye was occluded. Analog tracker output was low-pass filtered at 50 Hz and digitized by a 12-bit A to D converter which sampled eye position at 100 Hz. Digitized samples were stored for subsequent analyses. Tracker noise-level was estimated by recording from an artificial eye with intensities of the first and fourth Purkinje images adjusted so as to match the first and fourth Purkinje image light-levels observed with our subject's eyes. Noise-level, after filtering and digitization when expressed as a standard deviation, corresponded to about 0.7′ in the 16° field within which eye movements were recorded.

Fixation stimuli and retinal stabilization techniques

The fixation stimulus, 24′ dia, was either a defocused point on a display monitor (*Tektronix* 604, P4 phosphor) or an afterimage of the same size produced by a flash gun reflected from a beam splitter which placed the afterimage at the same optical position as the point target on the display monitor. The visual field was entirely dark with the exception of a slight glow of the monitor CRT produced by scatter from the relatively intense fixation stimulus which was set to be 2 log units above light-adapted absolute foveal threshold. This bright target was used because it remained visible even when stabilized as would be expected from Kelly's (1982) observations. The fixation stimulus was moved with the eye by bringing the tracker analog output signals, before filtering, to a precision summer, offset and gain control and then to the respective horizontal and vertical inputs of the display monitor. Filtering, other than that present in the tracker circuits which have a bandwidth of about 0–200 Hz, was not used in the stabilizing circuitry. Noise under this condition was estimated by digitizing at 420 Hz signals from the artificial eye matched in reflectances to our living

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*To whom correspondence and reprint requests should be addressed.

eyes. Noise, expressed as a standard deviation, in the stabilizing circuit corresponded to about 1.1′.

A subjective technique was used to achieve stabilization of the retinal image of the fixation stimulus. This was done by placing a graticule over the face of the display monitor and requiring the subject to adjust target-offset to be precisely at the center of the graticule while the center of the graticule was fixated. Gain of the stabilizing circuit was then adjusted so that when the subject fixated each scale division in the 16° field, the fixation stimulus moved through the same distance as the line of sight. The afterimage, by its nature, was stabilized on the retina and moved with the eye.

In those portions of the experiment where the subject smoothly pursued an objectively moving point-target stimulus, the stabilizing circuitry was disabled and the movement of the target was controlled by a Tektronix FG-501 function generator. Voltages used to move the target were digitized and stored along with eye position samples.

Subjects

Two of the authors served as subjects. All four authors were initially screened with stabilized targets and the two (J.T. and W.C.) best able to make voluntary smooth eye movements with stabilized targets served in the experiments. R.S. did not serve as a subject because he could only make smooth eye movements in the rightward direction with a stabilized target. J.F. did not serve because, although he could make smooth movements in both directions, he had little control of their speed. J.F.'s performance was very similar to W.C.'s whose results will be reported. J.T. and W.C. had never participated in an eye movement experiment, but neither, of course, was naive with respect to the purpose of the present experiments. Neither could make voluntary smooth eye movements in total darkness nor in the absence of an objectively moving target. Both could make voluntary smooth eye movements only with a stabilized fixation stimulus or when they pursued a smoothly moving target.

Procedure

Each session began by recording eye and stimulus movement while the subject pursued a target moving at constant velocity. The first experiment began with five 16-sec smooth pursuit trials recorded with a horizontal triangle-wave stimulus. The signal generator producing target motion was then switched off, the stabilizing circuitry was switched on, and the subject attempted to make the same pattern of eye movements with the stabilized target that had been made during the previous block of pursuit trials. The transition between smooth pursuit and the attempt to imitate the pursuit eye movement pattern with a stabilized target was accomplished within 1 or 2 sec. Five 16-sec pursuit-imitation trials were run. Next, an afterimage was made at the preferred foveal fixation locus and the subject recorded 5 trials once again attempting to imitate the eye movement pattern that had been made during the initial smooth pursuit trials. Afterimage pursuit-imitation typically began 10 or 20 sec after completion of the block of electronically-stabilized trials. Afterimages were refreshed by blinks or by the flash gun whenever the subject felt refreshment was necessary. Blinks were inhibited during periods of recording. Refreshment flashes were only delivered during intertrial intervals. When 5 trials had been completed, the subject rested until all traces of the afterimage had disappeared. The experimenter then reintroduced the pursuit stimulus set to a randomly selected frequency and the subject adjusted the stimulus until it resembled the stimulus originally pursued. These psychophysical settings were typically made 10–15 min after the subject had last seen the pursuit stimulus.

The experiment was run with 4 target velocities (1, 2, 4 and 8°/sec). Peak-to-peak amplitude was 8°. In the initial experimental condition, the objectively moving target was continually in motion and the subject started each trial when he felt that he was tracking well. In the subsequent conditions the subject started each trial with the stabilized targets when he felt that his pursuit-imitation was as good as it could be.

Analyses

Smooth eye movement and target velocities were calculated from a subset of the eye and target position samples recorded at 10 msec intervals. Velocities, excluding saccades, are based on position samples separated by 50 msec. Saccades were removed by a velocity criterion. The criterion velocity was determined empirically by comparing saccade counts from an analog record of each trial with the number of saccades counted by the computer algorithm. If a velocity sample exceeded the saccade criterion, it was removed along with the 50 msec velocity sample preceding and 2 samples following the 50 msec sample containing the saccade.

RESULTS

Triangle wave stimulus

During smooth pursuit both subjects approximately matched target velocity at the lower velocities (1 and 2°/sec) but undershot target velocity at the higher velocities (4 and 8°/sec). Undershooting increased as target velocity increased. These smooth pursuit characteristics are typical of normal subjects (Kowler *et al.*, 1978; Puckett and Steinman, 1969; Collewijn and Tamminga, 1984). When the target was stabilized by either the electronic or afterimage method, the eye movement pattern differed from the smooth pursuit eye movement pattern in a number of ways: (1) both subjects lost the ability to turn around abruptly, (2) systematic vertical movements often accompanied horizontal movements, and (3) one

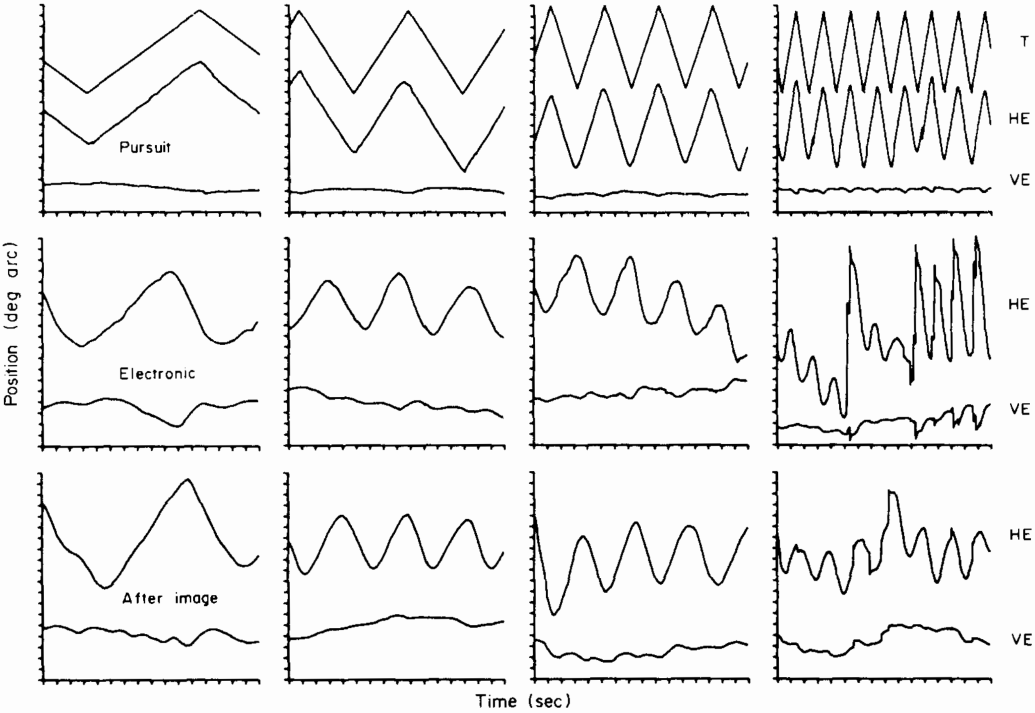

Fig. 1. Best-case analog records of subject J.T. pursuing a triangular target motion (top 4 graphs), attempting to make the same eye movement pattern with an electronically stabilized target (middle 4 graphs) and with an afterimage (bottom 4 graphs). Target velocities were: 1, 2, 4 and 8°/sec. Traces are reproduced for the target (T), the horizontal position of the eye (HE) and the vertical position of the eye (VE). The time scale shows 1 sec intervals. The position scale shows 1° distances. Upward displacements of the traces signify eye movements to the right or upward.

subject, W.C., lost the capacity to vary the frequency and amplitude characteristics of his smooth eye movements. *N.B.*: Individual differences were only observed with stabilized targets—smooth pursuit characteristics of both subjects were virtually identical.

These results are illustrated qualitatively in Figs 1 and 2 where analog records showing the *best* performance of each subject are reproduced. Quantitative features are summarized in Figs 3 and 4 which are based on measurements averaged over all the trials recorded. Note that W.C.'s pursuit-imitation speeds (absolute velocities) were higher with electronic stabilization than with the afterimage. W.C. reported frequent afterimage fading. We suspect that his lower afterimage pursuit-imitation speeds were due to the periodic disappearance of this type of stabilized target. The results of the psychophysical experiment, plotted in Fig. 3, show both subjects performing similarly. They tended to *overestimate* the original target speed. This result allows us to conclude that defective memory of target speed does not explain the differences observed between real smooth pursuit and attempts to imitate smooth pursuit with a stabilized target. Pursuit-imitation was slower, or unrelated to, not faster than the actual pursuit stimulus.

Figure 4 summarizes the frequency characteristics of the smooth eye movements made by both subjects under the various stimulus conditions. J.T.'s performance shows that he not only remembered when he should change direction during pursuit-imitation but also that he could change direction with the stabilized target when he wished. J.T.'s deficiencies in pursuit imitation were confined primarily to difficulty encountered in making high velocity smooth eye movements. W.C., however, also knew when he should change direction (his memory of the frequency of the pursuit stimulus was good) but he had little, if any, control over the frequency of his smooth eye movements when he tried to imitate pursuit. W.C.'s eye oscillated at from 0.45 to 1.1 Hz during pursuit-imitation. W.C.'s poor control of speed under these conditions has already been described.

So, although both subjects' smooth pursuit characteristics were virtually identical, their capacity to make pursuit-like smooth eye movements with stabilized targets were very different. J.T.'s abilities to imitate smooth pursuit might encourage an oculomotor investigator, who encounters such a relatively rare subject (one of the four we observed), to believe that a stabilized target, which is perceived as moving when the eye moves, provides a sufficient stimulus for voluntary smooth pursuit-like eye movements. We found clear differences, however, between J.T.'s voluntary smooth eye movements with the stabilized and objectively moving targets (noted above), suggesting that it would be prudent to resist the temptation to treat observations with stabilized targets as though they revealed important mech-

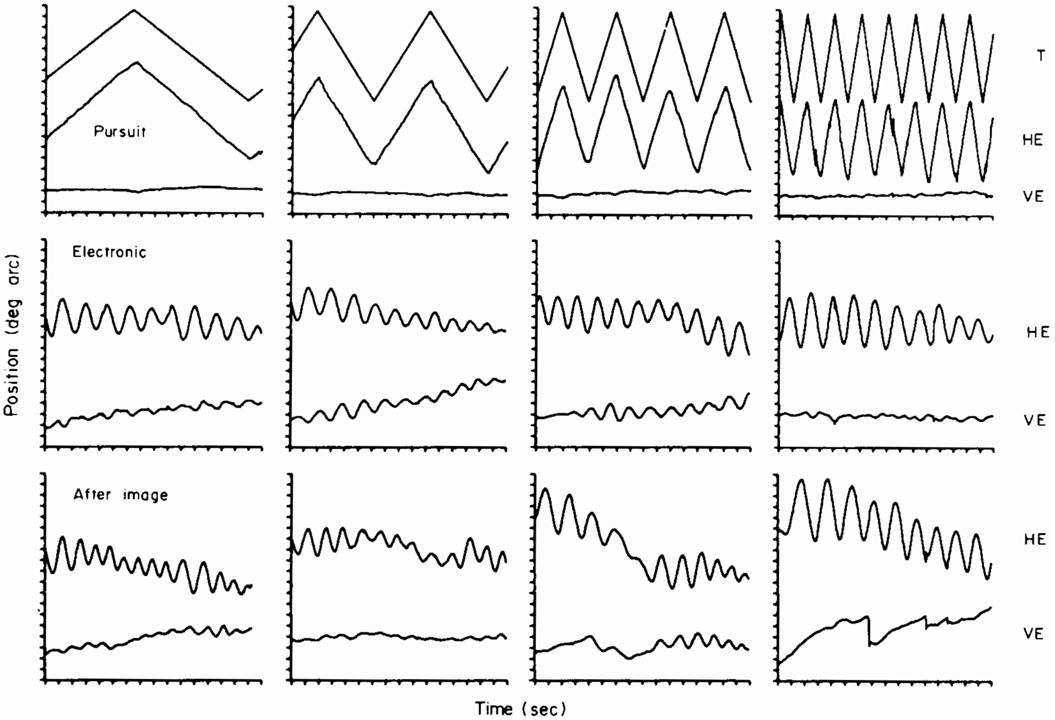

Fig. 2. Best-case analog records of subject W.C. pursuing a triangular target motion (top 4 graphs), attempting to make the same eye movement pattern with an electronically stabilized target (middle 4 graphs) and with an afterimage (bottom 4 graphs). Target velocities were: 1, 2, 4 and 8°/sec. Traces are reproduced for the target (T), the horizontal position of the eye (HE) and the vertical position of the eye (VE). The time scale shows 1 sec intervals. The position scale shows 1° distances. Upward displacements of the traces signify eye movements to the right or upward.

anisms underlying the normal operation of the smooth pursuit subsystem—a subsystem which uses primarily retinal image slip to control smooth pursuit (see Kowler and Steinman, 1979a, b, 1981; Kowler *et al.*, 1984; for examples of cognitive inputs to the smooth eye movement subsystems). Also, it is important to remember that J.T. is exceptional. If, as would be more likely, the investigator encountered subjects whose capacities resembled W.C. (two of the four subjects we observed), his likely conclusions about underlying mechanisms would be quite different. W.C. would be described as demonstrating

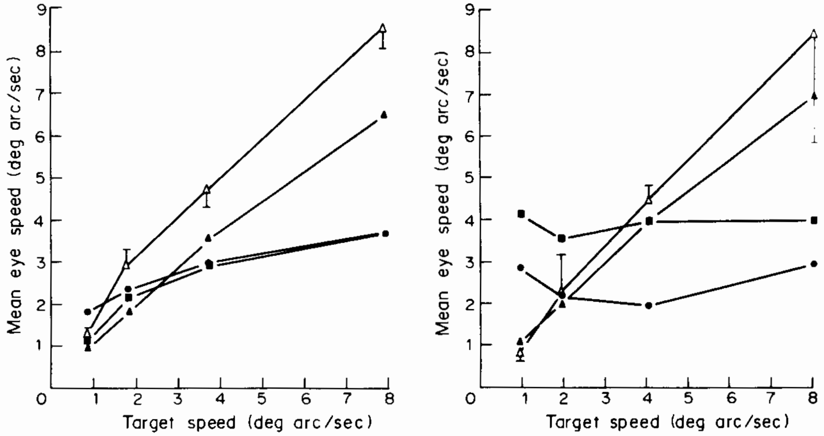

Fig. 3. Mean smooth eye movement speed as a function of target speed for subjects J.T. (left) and W.C. (right) during triangle-wave tracking and imitation. Solid triangles show smooth pursuit, solid squares show imitation with electronic stabilization, solid circles show imitation with an after image. The empty triangles show the speed to which each subject reset the pursuit stimulus after completing the imitation trials. Saccades were removed from these analyses. Error bars, were larger than the plotting symbols, show 1 SEM except in the case of the psychophysical results where semi-interquartile ranges ae shown. Each mean eye speed is based on about 2500 fifty msec sample for W.C. and about 3000 fifty msec samples for J.T.

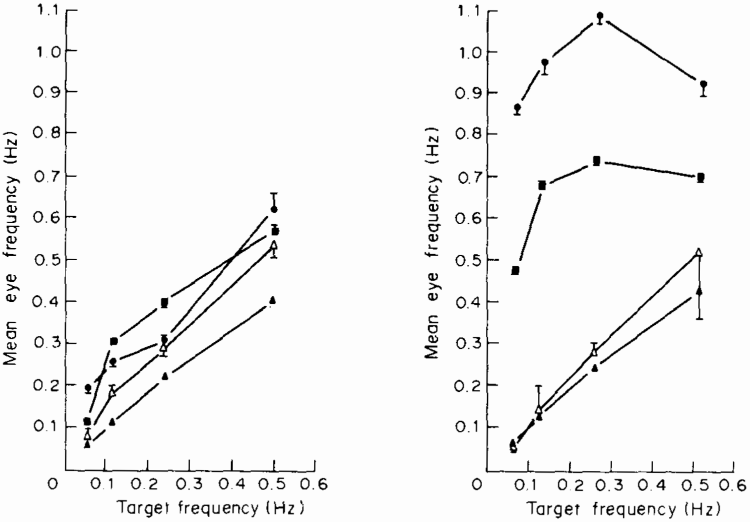

Fig. 4. Mean smooth eye movement frequency as a function of target frequency for subjects J.T. (left) and W.C. (right) during triangle-wave tracking and imitation. Solid triangles show smooth pursuit, solid squares show imitation with electronic stabilization, solid circles show imitation with an afterimage. The empty triangles show the frequency to which each subject reset the original pursuit stimulus after completing imitation trials. Saccades were removed from these analyses. Error bars, where larger than the plotting symbols, show 1 SEM except in the case of the psychophysical results where semi-interquartile ranges are shown. Each mean smooth eye movement frequency is based on about 30 half-cycles for J.T. and about 50 half-cycles for W.C.

"oscillatory nystagmus" when presented with a stabilized target because the absence of "the usual afferent signal [retinal image slip] causes the eye to become the slave of a primitive mechanism with its own characteristic rhythm" (Ten Doesschate, 1954). Both interpretations of stabilized-image-tracking are in the oculomotor literature. The story becomes even less tidy when we consider the results of our second experiment in which W.C. and J.T. were required to pursue a ramp target displacement and then imitate their eye movement pattern with a stabilized image.

Ramp stimulus

This experiment was essentially the same as the triangle-wave experiment. First, subjects were required to smoothly pursue a right- or left-going ramp and then attempt to imitate the eye movement pattern with an electronically-stabilized target or an afterimage. The experimenter gave the signal to begin each trial when he saw that the subject's eye was not drifting systematically in either direction. There were three ramp velocities (1, 2 and 4°/sec). Ramp-trials were 2 sec long. Five trials were run in each block under each stimulus condition and, once again, psychophysical measurements of remembered ramp velocity were made at the end of each of the 3 eye movement conditions.

Results were similar to those observed with the triangle wave stimulus, viz. both subjects pursued the ramp accurately and both were able to make smooth eye movements with the stabilized targets. As before, there was a qualitative difference in their capacities to make smooth movements with the stabilized target. J.T. had control of velocity. W.C. did not but he could move his eye smoothly in either direction on command. This last result shows quite clearly that W.C.'s eye movement pattern with stabilized targets is not an "oscillatory nystagmus" produced by depriving his oculomotor system of all retinal slip. The results of this experiment are summarized in Figs 5 and 6.

Additional experiments

A portion of the triangle wave experiment was repeated on the vertical meridian with the same results. The experiments were also repeated with a large afterimage and in a lighted room with the graticule in place on the display monitor. We also got the same results.

Next, we asked both subjects to make smooth eye movements or to keep the line of sight in place with the electronically stabilized target located at the preferred foveal fixation position (the placement used in all the prior experiments) and 8° to the right or 8° to the left of this position. We found that the smooth eye movement position control subsystem (slow control) was not sensitive to the position of the stabilized target. This result would be expected from prior research on position sensitivity of slow control (Murphy *et al.*, 1974). This result also shows, once again, that W.C. does not have an "oscillatory nystagmus." His eye did not oscillate when he was asked to keep his line of sight in place despite the absence of all retinal slip. However, when W.C. and J.T. attempted to make voluntary smooth eye movements with the targets stabilized at different retinal positions they, once again, showed qualitative differences in capacity. W.C. could only make smooth eye movements when the stabilized target was at his preferred foveal fixation position. His attempts

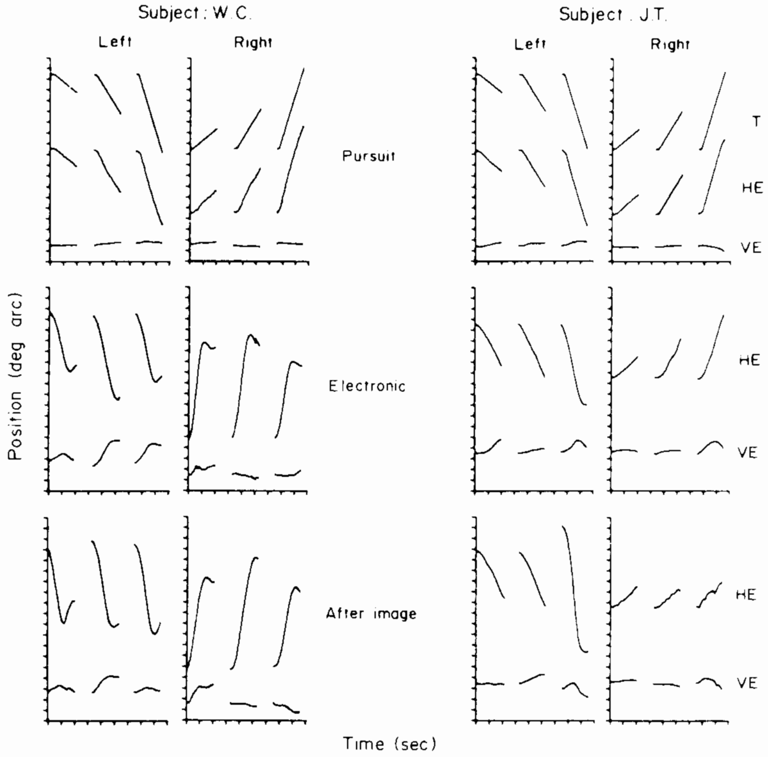

Fig. 5. Best-case analog records of subjects W.C. (left) and J.T. (right) pursuing a ramp motion to the left and to the right (top 4 graphs), attempting to make the same eye movement pattern with electronic stabilization (middle 4 graphs) and with an afterimage (bottom 4 graphs). Target velocities were 1, 2 and 4°/sec. Traces are reproduced for the target (T), the horizontal position of the eye (HE) and the vertical position of the eye (VE). The time scale shows 1 sec intervals. The position scale shows 1° distances. Upward displacements of the traces signify eye movement to the right or upward.

to make smooth eye movements with eccentric targets led to a highly saccadic eye movement pattern containing nonsystematic intersaccadic drifts. This is the same kind of pattern W.C. makes when he attempts to make smooth eye movements in total darkness. J.T., on the other hand, made the same pattern of voluntary smooth eye movements when the stabilized target was centered at fixation, was 8° to the left of fixation or 8° to the right of fixation.

CONCLUSION

A variety of voluntary smooth eye movements can be made with stabilized targets. These voluntary smooth eye movements are not like smooth pursuit eye movements in a number of respects. Furthermore, there are large, qualitative individual differences in the capacity of each subject to make voluntary smooth eye movements with stabilized

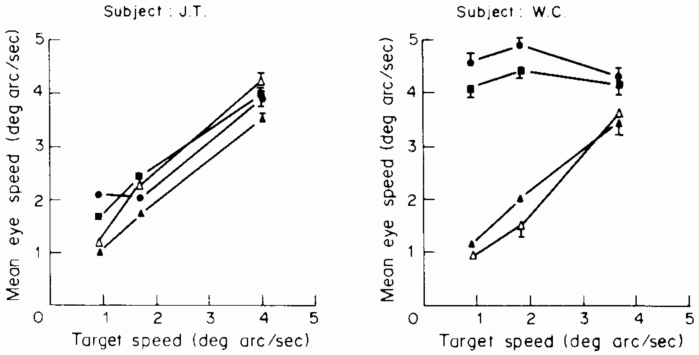

Fig. 6. Mean smooth eye movement speed as a function of target speed for subjects J.T. (left) and W.C. (right) during ramp tracking and imitation. Solid triangles show smooth pursuit, solid squares show imitation with electronic stabilization, solid circles show imitation with an afterimage. The open triangles show the speed to which each subject reset the original pursuit stimulus after completing the imitation trials. Saccades were removed from these analyses. Error bars, where larger than the plotting symbols, show 1 SEM except in the case of the psychophysical results where semi-interquartile ranges are shown. Each mean eye speed is based on about 200 fifty msec samples.

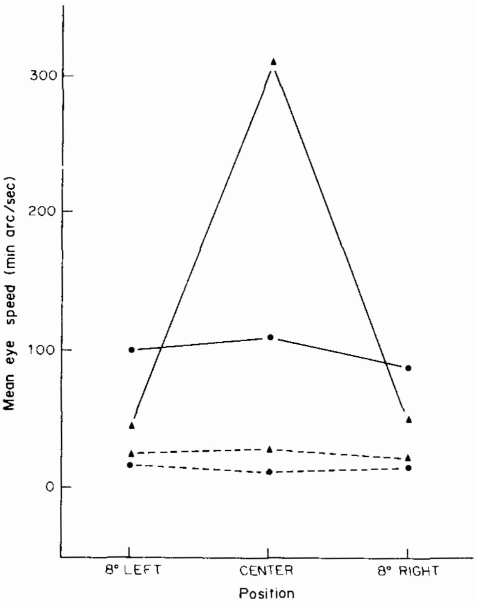

Fig. 7. Mean horizontal smooth eye movement speed made under instructions to stay in place (dashed lines) or to make smooth eye movements (solid lines) with the fixation target stabilized electronically at the line of sight (center), or 8° to the left or to the right of the line of sight. W.C. is shown by triangles, J.T. by circles. Standard errors were smaller than the plotting symbols.

targets. Our results lead us to conclude that caution is necessary when drawing interferences about human oculomotor system characteristics from experiments done with stabilized targets. This conclusion agrees with Tamminga'a (1983) recent conclusion, based on experiments with motion imposed on a stabilized target, that, "in an open loop condition pursuit eye movements primarily reflect idiosyncracies of the particular subject used in the experiment" (p. 70). We believe that data obtained with stabilization techniques should be avoided, or at least treated as exotic phenomena, in research on human oculomotor control.

Acknowledgements—We thank E. Kowler, G. Iverson and A. J. Martins for valuable suggestions. This research was supported by Grants BNS 77-16474 and BNS 80-25344 from the National Science Foundation and Grant EY04647 from the National Eye Institute to R. M. Steinman, and Grant EY01640 from the National Eye Institute to J. Z. Levinson and J. F. Tangney. Portions of this research were reported at The Oculomotor Symposium '80 at the California Institute of Technology in January, 1980, at the annual meeting of the Association for Research in Vision and Ophthalmology in Kissimee, FL, May, 1980 and at the Vision Technical Group meeting of the Optical Society of America in Sarasota, FL, April, 1980.

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