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LETTER TO THE EDITORS

VOLUNTARY CONTROL OF SMOOTH PURSUIT VELOCITY

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RECENTLY, PUCKETT and STEINMAN (1969) reported that the frequency of saccades during tracking was under voluntary control. Their subjects adopted highly saccadic or almost saccade-free modes of tracking and changed from one to the other behaviour when asked to do so. This note shows that these subjects can also exercise voluntary control over the velocity of their smooth pursuits.

METHOD

Horizontal eye movements were recorded by a photographic contact-lens optical-lever (STEINMAN, 1965) while subjects tried to pursue constant velocity targets at specfied fractions of target velocity. The moving target (a sharply-focused green point 1·00 log unit above absolute foveal threshold) was provided by a Tektronix, Model 503, oscilloscope (P-20 phosphor) located 1·0 m from the right eye (the left eye was covered and closed).[1] Between trials with the moving target, the subject fixated a stationary red point at the right side of the scope-face. The subject initiated the trials and paced himself. When ready, he operated a relay that switched off the red point, started the recording and triggered the oscilloscope bringing the green target into view at the position previously defined by the red intertrial stimulus. The green target moved to the left as soon as it appeared and traveled through an angle of 6·0 deg arc at one of five constant velocities (34, 69, 172, 344 or 687 min arc/sec). The target disappeared when it reached the extreme position and the red intertrial stimulus came back into view on the right. The subject began the next trial whenever he felt ready, usually after 1 or 2 sec. Both subjects, *RS* and *AS* (the first and second authors) were highly experienced in the fixation of stationary and moving targets.

Records were made at two sessions each consisting of 300 trials (60 at each of the 5 target velocities). The sequence of trials at each velocity was as follows: on the first 6 trials subjects tried to match velocity with the moving target. During subsequent blocks of 12 trials, they tried to pursue at either 1/4, 1/2, 3/4 or twice the velocity of the target. During the final 6 trials, they tried, once again, to match the velocity of the target. Target velocity was then changed and another set of 60 records was made under the same sequence of instructions. Different orders of target velocities were employed at the two recording sessions. There were no obvious differences between performance at the first or second sessions, but since the task was novel, only records made at the final session were measured.

Smooth pursuit velocity was calculated for each trial from the slopes of all low velocity eye movements that were made during target motion. A variable number of paired time-position measures were made for each intersaccadic pursuit (drifts during intersaccadic

[1] The moving target was viewed in an otherwise completely dark room. The recording system employed infrared light and the scope face was kept covered when not in use so that it would not glow in the dark.

intervals). The number of pairs required to estimate the velocity of the eye was left to the discretion of the film measurers, *viz*. as few as 2 or as many as 7 pairs of measurements were made depending on the uniformity of eye velocity during a particular intersaccadic interval.[2] In records where no saccades occurred during target motion, the number of measurements was determined in a similar manner, i.e. when eye velocity appeared uniform only 2 pairs of measurements were used to estimate the slope. When the eye speeded up or slowed down noticeably in different portions of the record, a sufficient number of pairs were measured to permit a reasonable estimate of the overall slope. Slopes were fitted by the least-squares criterion and smooth pursuit velocity, on a given trial, was defined as the mean of the intersaccadic pursuit velocities calculated after each velocity had been weighted according to its duration.

RESULTS

Smooth pursuit velocities obtained under instruction to match or go more slowly than the targets are summarized in Fig. 1.

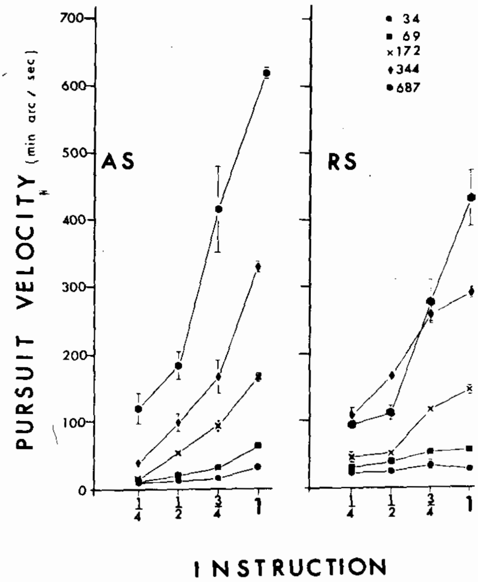

FIG. 1. Mean smooth pursuit velocities for subjects *AS* and *RS* tracking constant velocity targets under instructions to smoothly pursue at 1/4, 1/2, 3/4 or at (*1*) the velocity of the moving target. The symbols in the upper right of the figure refer to velocities (min arc/sec) of the 5 targets used in this experiment. Error bars show one standard deviation above and below the mean pursuit velocity for those cases where variability exceeded the size of the symbols used to make this graph.

[2] Three people, working in pairs, measured the recordings. A larger number of measurements were made whenever there was disagreement about how many pairs were required to estimate the slope of a given intersaccadic pursuit. Eye position could be measured to about 10 sec arc and time to about 5 msec with the optical lever and projection film reader employed.

Both subjects exercised voluntary control over the velocity of their smooth pursuits. Neither subject was very successful in producing the required fraction of the target velocity, but both succeeded in ordering smooth pursuit velocity along lines suggested by the instructions. In only one condition (*RS* tracking the slowest target) did a subject fail to make entirely appropriate adjustments in the velocity of his eye.

Voluntary control of smooth pursuit velocity was possible only when subjects tried to pursue more slowly than the target moved. When asked to go twice as fast as the target, they did go faster but always made saccades to get ahead and held in place when they reached what they thought was the position of maximum target displacement.[3] We confined our measurements, under the "twice" instruction, to smooth movements made prior to the time the eye reached the 6 deg arc limit of target displacement and found that pursuits were equal to, or, more frequently, slower than the velocity of the moving target. *RS*'s overall mean smooth pursuit was only 43 per cent (S.D. = 28·9 per cent) of target velocity. *AS*'s smooth pursuits were faster: 82 per cent (S.D. = 12·1 per cent) of target velocity. Neither subject, however, showed any sign of being able to make smooth pursuits that were appreciably faster than the targets moved. This was true even when the targets moved very slowly and the instruction to go twice as fast required smooth pursuits that could be easily made when faster targets were tracked.

Examples of voluntary control, obtained under optimal conditions, are shown in Fig. 2 where 6 consecutive eye movement records are reproduced. Conditions were altered in

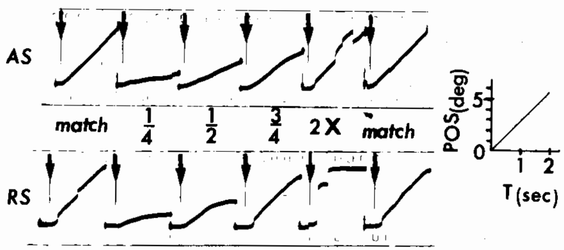

FIG. 2. Horizontal eye movement recordings of subject *AS* and *RS* tracking a horizontal constant velocity target moving at 172 min arc/sec to the left (upwards) through an angle of 6 degrees. The record for each subject shows 6 consecutive trials run under the following sequence of instructions: on the first trial (shown at the left of the figure) subjects tried to match velocity with the target, on the subsequent 4 trials they tried to pursue at 1/4, 1/2, 3/4 or twice (*2X*) the velocity of the target. This sequence was followed by a final attempt to match the velocity of the eye to the velocity of the target. The arrows point to a faint dark line that marked the time of appearance of the moving target on the film.

two ways to make these records. First, a delay was introduced between the start of each recording and the appearance of the moving target (192 msec for *AS* and 308 msec for *RS*). This delay encouraged subjects to run trials one right after the other since they could saccade to the starting position, start the next trial and still have a little time to get set to pursue at the required fraction. Second, and probably more important for optimal performance, subjects ran only a single trial under each instruction permitting them to adjust smooth pursuit velocity relative to performance on an immediately preceding trial. This

[3] Their memory for this position was quite good, i.e. the overall mean error (difference between eye position during the last ¼ of each trial and the 6 deg limit) was 25 min arc (S.D. = 31·5) for subject *RS* and 16 min arc (S.D. = 28·4) for subject *AS*.

strategy was not possible in the main experiment where 12 trials were recorded under a single instruction before the next fraction was requested, a procedure that forced heavy reliance on relatively long term memory of prior performance.

Neither subject, generally, matched eye to target velocity when he explicitly tried to do so. Their mean smooth pursuit velocities were less than the velocities of all 5 targets. This finding can easily be seen in Fig. 1 where *RS*'s smooth pursuits under the "match" instruction (*1*) were noticeably less than target velocities. *RS*'s overall mean smooth pursuit velocity when he tried to match was only 80 per cent (S.D. = 7·9 per cent) of target velocity. *AS* did somewhat better, i.e. 92 per cent (S.D. = 3·2 per cent) of target velocity, but he, too, made smooth pursuits that were, on the average, slower than each of the targets.

DISCUSSION

The failure of our highly experienced eye movement subjects to match constant velocity target motions has been reported before (PUCKETT and STEINMAN, 1969). In the prior experiment, however, the onset-time and direction of motion was unpredictable and targets moved through an angle of only 3 degrees of arc. In the present experiment subjects knew precisely when and in which direction the target would move through an angle of 6 degrees: these procedural changes would be expected to facilitate accurate smooth pursuits. Performance in the present experiment was somewhat better, but still fell short of expectations based on reports of other investigators who concluded that the eye "accurately" matched velocity with unpredictable targets moving at the same velocities we used in the present and earlier work (WESTHEIMER, 1954; RASHBASS, 1961; and ROBINSON, 1965).

When we found, in our prior work, that velocity "undershooting" rather than "matching" was a general characteristic of smooth pursuit, we proposed that the stimulus for smooth pursuit may arise from residual movements of the target image on the retina. Such image motions would be produced by mismatches between low velocity eye movements and constant velocity motions of the target. In other words, we proposed that the rate of error might serve as the stimulus for smooth pursuit velocity. Our present findings offer additional support for this suggestion, *viz.* we found that (1) relatively large predictable constant velocity target motions were not, on the average, matched by smooth pursuits and (2) subjects could pursue with low velocity eye movements that allowed the targets to get ahead of their lines of regard at different, voluntarily selected, rates. The first finding implies that the rates of fixation error (differences between target image position and the preferred foveal fixation locus) is available to subjects when they track constant velocity target motions. The second finding shows that subjects can use this error signal (the change in error) *selectively* to make smooth pursuits that are slower than the movements of the target. These findings raise the following problems: (1) why is the operation of the low velocity control system confined to smooth pursuits below target velocity and (2) under what conditions, if any, does the velocity of the eye accurately match the velocity of constant velocity target motions?

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