

Effects of Learning on Smooth Pursuit During Transient Disappearance of a Visual Target

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Madelain, Laurent and Richard J. Krauzlis. Effects of learning on smooth pursuit during transient disappearance of a visual target. *J Neurophysiol* 90: 972–982, 2003; 10.1152/jn.00869.2002. Previous research has demonstrated learning in the pursuit system, but it is unclear whether these effects are the result of changes in visual or motor processing. The ability to maintain smooth pursuit during the transient disappearance of a visual target provides a way to assess pursuit properties in the absence of visual inputs. To study the long-term effects of learning on nonvisual signals for pursuit, we used an operant conditioning procedure. By providing a reinforcing auditory stimulus during periods of accurate tracking, we increased the pursuit velocity gain during target blanking from 0.59 in the baseline session to 0.89 after 8 to 10 daily sessions of training. Learning also reduced the occurrence of saccades. The learned effects generalized to untrained target velocities and persisted in the presence of a textured visual background. In a yoked-control group, the reinforcer was independent of the subjects' responses, and the velocity gain remained unchanged (from 0.6 to 0.63, respectively, before and after training). In a control group that received no reinforcer, gain increased slightly after repetition of the task (from 0.63 to 0.71, respectively, before and after training). Using a model of pursuit, we show that these effects of learning can be simulated by modifying the gain of an extra-retinal signal. Our results demonstrate that learned contingencies can increase eye velocity in the absence of visual signals and support the view that pursuit is regulated by extra-retinal signals that can undergo long-term plasticity.

INTRODUCTION

Primates use two types of voluntary eye movements to view their visual environment. Saccades are rapid movements that orient the retinal image of a target toward the high-acuity area of the retina, whereas pursuit is a continuous response that smoothly compensates for the displacement of a target. These oculomotor responses are under adaptive control to maintain accuracy through development and aging, as has been shown, for instance, for saccades (Optican and Robinson 1980; Optican et al. 1985; Raymond and Lisberger 1998), and for ocular following (Miles and Kawano 1986). Optican et al. (1985) demonstrated plasticity in the pursuit system in cases when the normal relationship between visual input and motor output was disturbed. Patients with ocular weakness in one eye greatly modified their pursuit response after prolonged monocular viewing with the weak eye. The movements of the normal eye showed adaptive changes resulting in increases of the pursuit velocity at the initiation of pursuit and during sustained track-

ing. According to Optican et al. (1985), an adaptive mechanism controls the gain of the pursuit system so that the gain is high enough for good tracking but also low enough to prevent oscillations resulting from internal delays in visual feedback.

Adaptive modifications were also observed in monkeys' smooth pursuit responses using a velocity-step paradigm (Kahlon and Lisberger 1996, 2000). In these experiments, adaptation was induced by repeatedly changing the speed of the tracking target to a second velocity 100 ms after the motion onset. This produced a modification of the eye acceleration during the early phase of pursuit: the eye speed reached the second target velocity sooner after learning than it had before learning. Similar results have been observed in humans (Fukushima et al. 1996; Ogawa and Fujita 1997). These studies focused on the first 100 ms of pursuit because the early phase is an open-loop response that probes the visuo-motor transformations before there has been time for visual feedback (Lisberger and Westbrook 1985). Learning has also been demonstrated in young infants, suggesting that the development of pursuit may depend on the formation of learned contingencies (Darcheville et al. 1999).

Because in these previous studies the visual target was always visible, it remains unclear whether learning changed the visual or motor signals responsible for pursuit. It is possible to disentangle these two factors by transiently removing visual inputs during pursuit. Eckmiller and Mackeben (1978) investigated monkey smooth pursuit behavior when a moving target briefly disappeared and then reappeared. They report that monkeys are able to continue pursuit when the target disappears for up to 800 ms. Using a similar paradigm, Becker and Fuchs (1985) showed that humans maintain smooth pursuit up to 4 s after the disappearance of the target. They found that the velocity of the eye rapidly decreased about 190 ms after the target disappearance. This deceleration phase lasted for about 280 ms and then the eye velocity stabilized at approximately 40–60% of the normal pursuit velocity. To develop an eye velocity related to the velocity of the target that preceded the extinction, the subjects needed to see the motion for at least 300 ms. Becker and Fuchs (1985) referred to this phenomenon as predictive pursuit. This mechanism can also be at play during other open-loop responses such as anticipatory smooth tracking of a highly predictable target motion (Barnes and Asselman 1991; Barnes and Donelan 1999; van den Berg 1988; Wells and Barnes 1999) or the initial phase of pursuit (Kao and

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Morrow 1994). Becker and Fuchs (1985) examined the effect of practice on predictive pursuit and reported a modest change, indicating that this response could be under adaptive control.

In the present study we examined the plasticity of the pursuit system during the transient disappearance of a visual target in humans. We used a reinforcement procedure to investigate the effects of learning on smooth pursuit. Our results show that the eye velocity during target blanking increased significantly after learning. We also observed a generalization of the learned changes to target velocities other than those used during training. These results indicate that learned contingencies can induce long-term modifications of the motor output of the pursuit system in the absence of visual signals.

METHODS

Subjects

Sixteen human subjects (10 female and 6 male, 22–38 yr of age) participated in the experiment. Two of the subjects (R and L) were authors of the study, whereas the other 14 subjects were naïve as to the experimental conditions and hypotheses, and had no previous experience of ocular motor testing (except for subjects K and B). All experimental procedures were reviewed and approved by the Institutional Review Board and each subject gave informed consent. All subjects were paid a baseline amount of money for their participation and some subjects received additional money based on the reinforcement procedure, as explained below.

Stimuli were generated using a personal computer, equipped with a high-speed graphics card (Cambridge Research System VSG2/3) and VisionWorks software (Swift et al. 1997), and displayed on a video monitor (Eizo FX-E7, 120 Hz) at a viewing distance of 41 cm. To minimize measurement errors, subjects' head movements were restrained using a bite bar so that the eyes in central position were directed toward the center of the screen. Fixation and pursuit targets were white rings (luminance: 88 cd/m²), 0.3° in diameter, displayed on a uniform gray background (luminance: 33 cd/m²). Stimuli were presented in discrete trials that required the subject to fixate and pursue a target for about 2.5 s.

Experimental protocol

For each subject a complete experimental run consisted of a baseline test session, followed by 8 to 10 daily learning sessions, and finished with a postlearning test session. For the learning sessions, subjects were randomly assigned either to a reinforced group (8 subjects), a yoked-control group (4 subjects), or a control group (4 subjects) (Table 1). Each daily session was divided in four blocks of 200 trials separated by a 10-min period during which subjects were free to move.

Test sessions

Modifications induced by the learning sessions were monitored using test sessions before and after the learning sessions. In the first three blocks of trials of the test session the target movement was predictable (constant velocity trials). The basic target motion was similar to the step-ramp target motion described by Rashbass (1961) (Fig. 1A). A fixation target appeared at an eccentricity of 11.2° from the straight-ahead position for a random period of 500–750 ms. The fixation target was then extinguished and a tracking target appeared at an eccentricity of 14° from the straight-ahead position and moved toward and through the fixation point for 2 s at 14°/s. Rightward and leftward pursuit trials were alternated. In 80% of the constant velocity trials, the pursuit target disappeared for a certain period of time (target-off periods) before reappearing for the remainder of the trial as

TABLE 1. Distribution of subjects according to test sessions and groups

Baseline and Postlearning Sessions	Constant Velocity Trials Only	Constant Velocity Trials Background Trials Randomized Velocity Trials
Reinforced group	L (10) R (8) S (8) A (9)	J (9) M (10) T (9) V (10)
Yoked control group		N (10) C (9) E (8) D (9)
Control group		H (9) I (10) K (10) Y (8)

Number of learning sessions in parentheses.

if a physical object had occluded it. During that time subjects were not in complete darkness because the uniform gray background remained unchanged. The target-off period could assume durations of 250, 500, 750, or 1,000 ms and occurred in a balanced, pseudorandom order. The duration of the initial target-on period was randomized to minimize predictability, lasting 590, 875, or 1,160 ms for the 250-ms disappearance periods; 607, 750, or 892 ms for the 500-ms disappearance periods; 625 ms for the 750-ms disappearance periods; and 500 ms for the 1,000-ms disappearance periods.

During the baseline and postlearning sessions the fourth block of each session differed from the previous blocks. In the first part of the block we introduced a textured background to distinguish between pursuit and optokinetic responses (background trials, 60 trials). The target motion was the same as that for the constant velocity trials but two checkerboards made of bright and dark squares (size of individual squares $\sim 0.55^\circ \times 0.55^\circ$) covering $19.58^\circ \times 2.74^\circ$ and separated by 1.1° were used to test the influence of structured visual backgrounds. The target disappeared in 50% of the trials for 1,000 ms and the duration of the initial target-on period was 500 ms. In the remaining trials the target was displayed during the entire trial. In the second part of the block we randomized the target speeds (10, 14, or 20°/s) to test whether learning transferred to untrained target velocities (randomized velocity trials, 160 trials). The step-ramp parameters were adjusted for each velocity so that the target would always cross the fixation point 200 ms after motion onset. The duration of the initial target-on period was 500 ms and the duration of the target-off period was 1,000 ms. Four subjects (L, R, S, and A) were tested only in the constant velocity situation and did not experience the background and randomized velocity trials as indicated in Table 1.

Learning sessions: reinforced group

A procedure was designed to induce learning that reduced the occurrence of saccades and maintained the eye velocity during pursuit within a range of velocities. This procedure consisted of the real-time delivery of a reinforcer based on the tracking performance of the subject estimated using the real-time eye velocity computation and saccade detection. The output from the eye tracker was calibrated on-line at the beginning of each block by recording the raw digital values as subjects fixated 7 known locations. The values at each location were used to generate a smooth function for converting raw eye tracker values to the calibrated horizontal eye position. An on-line eye velocity signal was obtained by differentiating the calibrated position signal over 40 ms and filtered by applying a moving average over 80 ms. A second, instantaneous, velocity signal was obtained by differentiating the calibrated position signal over 8 ms. Within a

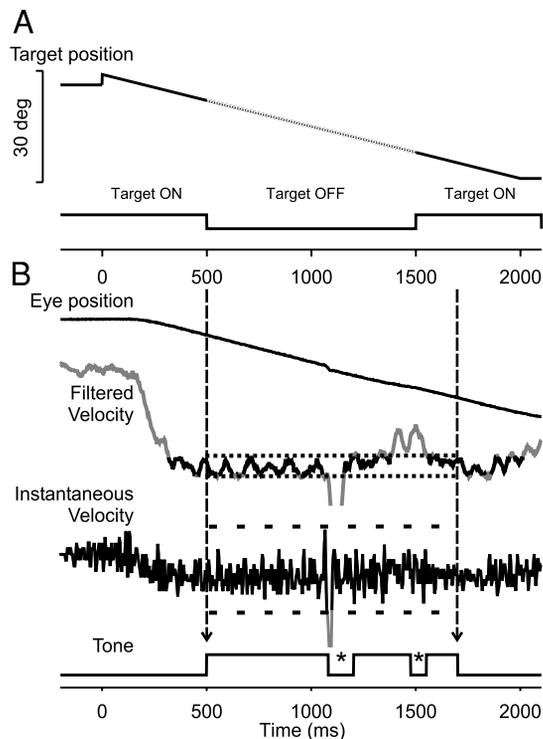


FIG. 1. *A*: schematic diagram showing time course of stimulus event. After fixation period the target moved in step-ramp fashion. After varying target ON period (thick line), the target was turned OFF (dotted line) and then reappeared for remainder of trial. *B*: criteria for reinforcement of smooth pursuit. Two vertical arrows (dashed line) show temporal window of 1,200 ms starting 500 ms after onset of pursuit target, during which we applied criteria to deliver auditory tone (see text for explanations). Based on eye position (*top trace*) a filtered velocity signal (*second trace*) was computed by differentiating eye position over 40 ms and applying a moving average over 80-ms window. *Black trace*: velocities within range of velocities (-12.6 to -15.4 %, represented by two horizontal lines with widely spaced dashes) used for delivering auditory tone (*bottom trace*). *Gray trace*: velocities outside criteria. An instantaneous velocity signal (*third trace from top*) was computed by differentiating eye position signal over 8 ms. *Horizontal traces* (short dashed line): amplitude criteria used to detect saccades (in gray). Auditory tone (*bottom trace*) was turned on if filtered velocity signal fell within predetermined range of velocities. It was turned off for 100 ms if a saccade was detected (first *) or if filtered velocity signal fell out of predetermined velocity range for more than 100 ms (second *).

temporal window of 1,200 ms starting 500 ms after the onset of the pursuit target, saccades were identified on-line by applying a fixed set of amplitude criteria values to the instantaneous velocity signal (Fig. 1*B*). A contingent auditory tone (300 Hz) was delivered through the personal computer tone generator for 100 ms as long as movements were free of saccades and the filtered velocity signal remained within a set of amplitude criteria. The upper and lower limit of the criteria applied to the filtered velocity signal were 15.4 and 12.6 deg/s, respectively. These values corresponded to eye velocity gains (i.e., the ratio of eye velocity to target velocity), ranging from 1.1 to 0.9. If a saccade was detected, the auditory tone was turned off for 100 ms. Such a procedure ensured the temporal contiguity between the auditory stimulus and the behavioral response. If the total duration of the auditory tone exceeded 80% of the 1,200-ms temporal window the trial was successful and a pair of tones (600 Hz) were delivered at the end of the trial. When 7 out of 10 consecutive trials were successful a message was displayed on the video monitor, indicating that the subject won 25 cents. The money earned by the subject was given at the end of each session.

To train subjects to maintain accurate tracking in the absence of a visual target we controlled the stimulus parameters so that the dura-

tion of the target-off periods progressively increased by steps of approximately 35 ms (4 to 5 vertical refresh periods of the video monitor) according to the subjects' performance, reaching a maximum of 1 s. The reinforcement criteria remained fixed. We took advantage of the fact that there was a cumulative change in the subjects' responses so that the level of performance achieved at the end of each daily session increased. This allowed us to adjust the reinforcement or the stimulus parameter to induce learning across sessions according to the evoked modifications of the subject's response. Figure 2 shows the time course of the learning sessions for subject T. It can be seen that the duration of the target-off periods at the beginning of each session (filled circles) was adjusted with respect to the level achieved at the end of the previous session (unfilled circles).

Our procedure required subjects to maintain an eye velocity gain ranging from 0.9 to 1.1 but smooth pursuit in naïve subjects often showed idiosyncratic differences. To reduce the intersubject variability, the first blocks of the first reinforcement sessions were designed to shape the subjects' steady-state tracking. In these trials the pursuit target was always displayed and the velocity criteria were progressively constrained according to the modification of the subjects' behavior to maintain the proportion of reinforced trials at approximately 70%.

Learning sessions: yoked-control group

To test the effect of the reinforcement contingencies a yoking procedure was designed to deliver the reinforcers independently of the subject responses. For the learning sessions each subject from the yoked-control group was paired with one subject from the reinforced group. For each trial, the yoked subject received the same visual stimuli and the same duration of auditory stimulus (300 Hz tone) as his/her paired subject, regardless of behavior. Similarly, the trial was signaled successful if the paired trial was successful, and the total amount of money was given at the end of each session. Thus the yoked-subject learning sessions were identical to those for the paired reinforced subject, except for the noncontingent presentation of the reinforcers.

Learning sessions: control group

To compare the changes of smooth pursuit resulting from the reinforcement procedure to those evoked by an intensive practice of the task we carried out an experimental condition in which trials were

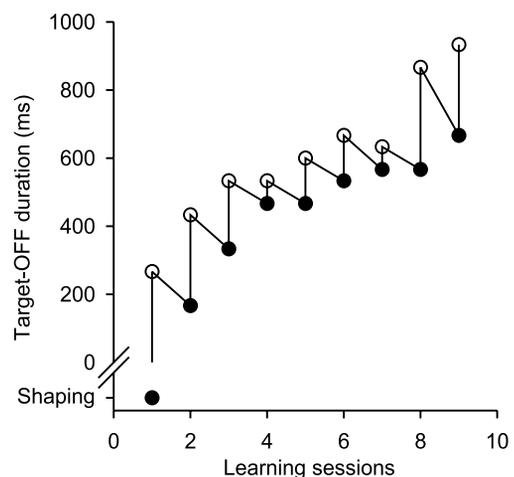


FIG. 2. Example of time course of learning sessions for subject T. Filled circles: target-OFF duration at beginning of each daily session. Empty circles: target-OFF duration at end of each daily session. First session starts with "shaping trials" during which target was always visible and reinforcement criteria were progressively adjusted to reduce variability in pursuit response.

similar to the prelearning and postlearning test sessions constant velocity trials. Subjects from the control group performed daily sessions of 800 constant velocity trials.

For all subjects, the typical instruction was: "Follow the target the best you can and try to carry on when the target is masked." For the reinforced and yoked-control group we explained that subjects would win some money during the experimental sessions. Because the auditory tones played different roles in the experiment for different groups of subjects, we did not mention the auditory tones or their role in the experiment. This permitted us to keep the instructions uniform across the different groups of subjects and to avoid the biases in performance that might otherwise have resulted. Not surprisingly, subjects from the reinforced group noted early in the experiment that the tone was contingent with their response. These spontaneous reports occurred in the first sessions, but we provided no feedback until a debriefing at the conclusion of the experiments.

Data acquisition and analysis

Presentation of stimuli, and the acquisition, display, and storage of data were controlled by a personal computer using the Tempo software package (Reflective Computing). The visual display computer received from and returned trigger signals to the Tempo computer at the onset of each new stimulus, allowing us to synchronize data collection to stimulus presentation with 1-ms resolution. Real-time computations for the on-line calibration, velocity analysis, and saccade detection were performed using the Tempo package.

Eye movements were measured with an infrared video-based eye tracking system (ISCAN, RK-726), which reported the horizontal and vertical positions of the pupil with 12-bit resolution using a proprietary algorithm that computes the centroid of the pupil at 240 Hz. Before each block, we calibrated the output from the eye tracker by recording the raw digital values as subjects fixated 19 known locations three times in a pseudorandom sequence. The mean values during 500-ms fixation intervals at each location were used to generate a smooth function (using cubic spline interpolation) for converting raw eye tracker values to horizontal eye position. We focused our analysis on the horizontal component of eye movements because the stimuli were moving exclusively along the horizontal meridian to minimize measurement errors.

All eye movement data, and events related to the onset of stimuli, were stored on disk during the experiment, and later transferred to a FreeBSD Linux-based system for subsequent off-line analysis, independent from the previously described on-line computations. An interactive analysis program was used to filter, display, and make measurements from the data. To generate smooth traces free of high-frequency noise, we applied a low-pass filter (-3 dB at 25 Hz) to the calibrated horizontal eye position signals. Horizontal eye velocities were obtained by applying a finite impulse response (FIR) filter (-3 dB at 54 Hz) to the filtered eye position signals. Signals encoding eye acceleration were then obtained by applying the same FIR filter to the signals encoding velocity. We detected the occurrence of saccades by applying a set of amplitude criteria to the eye velocity and eye acceleration signals, as described previously (Krauzlis and Miles 1996a). This algorithm permitted us to detect saccades with amplitudes as small as approximately 0.3° . To prevent any contamination of our measurements of smooth eye movements by saccades, we excluded from analysis an additional 5 ms before and after each detected saccade and replaced the corresponding values with NaNs. Saccade-free eye position, velocity, and acceleration signals were then exported to Matlab for further analysis. To assess pursuit in the absence of visual feedback we focused our analysis on the 750- and 1,000-ms target-off trials, discarding trials in which the target disappeared for less than 750 ms.

The onset of pursuit was estimated from traces of eye velocity on individual trials using a variant (Adler et al. 2002) of an algorithm described previously (Krauzlis and Miles 1996a). In this previous

technique, the variance associated with a "baseline" interval was used to detect the beginning of a "response" interval. A linear regression of the response interval as a function of time was used to determine when the response intersected the baseline—this point in time was defined as the latency of pursuit. The extrapolation used in this method makes the latency estimates sensitive to noise in the response interval. We therefore constrained the response interval to immediately follow, and be continuous with, the baseline interval, forming a "hinge" (i.e., the intersection point between the baseline and the linear regression). The baseline interval had a duration of 100 ms and the response interval had a duration of 100 ms and we tested possible placements of the "hinge" ranging from ± 40 ms from an initial subjective estimate of pursuit latency. For each of these hinge placements, the slope of the response interval was determined by linear regression and we measured the mean squared error between the data and the model (baseline plus response intervals). The hinge placement that provided the best fit was defined as the latency of pursuit and the slope of the linear regression of the eye velocity for a 100 ms "response" interval after a 100-ms "baseline" interval was defined as the acceleration of pursuit initiation. We excluded from the acceleration analysis trials with a latency shorter than 80 ms as well as trials in which a saccade occurred within 100 ms after pursuit onset.

RESULTS

Learned changes in eye velocities in the absence of visual signals

For trials with no target-off period, subjects tracked the target with a slow continuous movement interrupted by small catch-up saccades. After the onset of smooth pursuit, eye velocity reached a value close to the target velocity (velocity gain ~ 1) and remained approximately constant for the duration of the trial (Fig. 3A). For the baseline trials, if the target suddenly disappeared during pursuit, the velocity decreased after a latency of approximately 200 ms and stabilized at a new level for the time the target remained invisible (Fig. 3B). During the target-off period, pursuit was interrupted by several saccades. As described by Becker and Fuchs (1985), we observed several different profiles of velocity after the abrupt deceleration: a plateau with small variations of velocity, a slow reacceleration instead of a plateau period, or a constant decay of the velocity.

For the postlearning trials, the residual velocity was considerably improved for the subjects from the reinforced group. Figure 3C shows an example of the smooth pursuit response during disappearance of the target. On this trial, eye velocity did not decrease during the target-off period but remained approximately constant for the entire trial. The response was smoother and saccades accounted for a smaller part of the total displacement.

Figure 4 illustrates averages of the eye velocity evoked in the baseline and postlearning sessions for one subject from each group. Superposition of the velocity profiles provides a direct estimate of the effect of the reinforcement procedure on the response during the target-off period. In subject M (reinforced group), the velocity increased in the postlearning session (Fig. 4A). Approximately 130 ms after the disappearance of the target, the two traces exhibit a similar decrease in eye velocity. However, the traces begin to diverge 170 ms after the disappearance of the target. In the baseline trials velocity gain continuously decreased for 240 ms, then stabilized to approximately 9 deg/s. In contrast, during the postlearning trials, the

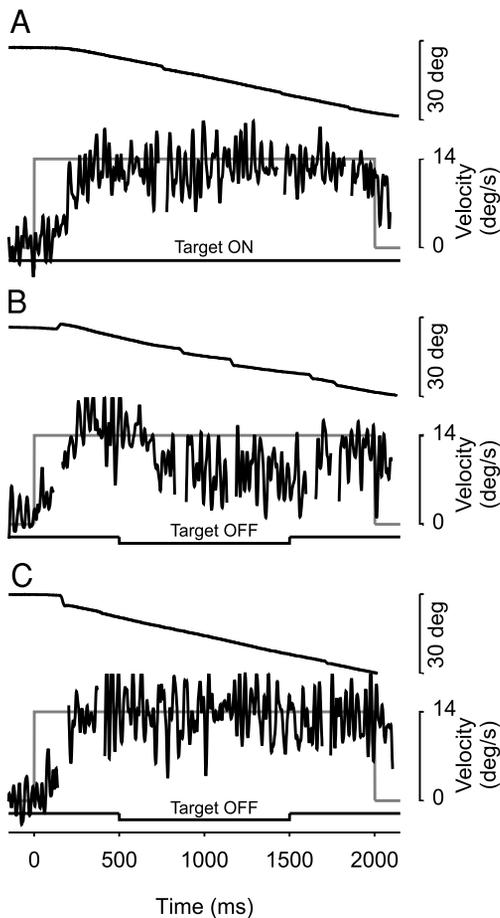


FIG. 3. Example of constant velocity single trials (subject T). *A*, top to bottom: eye position, eye velocity (black), and target velocity (gray) as function of time aligned with respect to target motion onset. Bottom solid line: presence of visual target (no target-OFF period). *B*: baseline constant velocity trial with 1-s target-OFF period. Eye velocity decreased during target-OFF period and the eye reaccelerated when target reappeared. *C*: after learning, eye velocity remained approximately constant during the 1-s target-OFF period.

velocity reaccelerated 200 ms after the beginning of the target-off period and stabilized around 13 deg/s. In subject K (control group), training had a similar but reduced effect leading to an increase in eye velocity (Fig. 4*B*). The superposition of the velocities for the baseline and for the postlearning trials reveals that the initial deceleration phase following the beginning of the target-off period ends sooner for the postlearning trials, but the overall profiles of velocities are very similar. Velocity profiles did not significantly improve between the baseline trials and the postlearning trials in subject E (yoked-control group): the eye velocity did not increase in the postlearning session (Fig. 4*C*).

Statistical analysis of the effects of learning

To quantify the effects of learning on eye velocity we followed the approach validated by Becker and Fuchs (1985) and, for each trial, computed the average eye velocity over a 40-ms interval 700 ms after the disappearance of the target. Figure 5*A* plots the average postlearning velocity as a function of the average baseline velocity for each subject. Points above the diagonal indicate that the postlearning velocity was greater than the baseline value.

For each subject we performed a comparison between the baseline and the postlearning velocity (rank sum test, $P < 0.025$, 1-tailed). We found that the velocity was improved by the reinforcement procedure for all subjects in the reinforced group (circles). Moreover, in that group all subjects except one (subject S) exhibited a postlearning velocity higher than 11.2 deg/s (i.e., a velocity gain higher than 0.8; mean \pm SD = 12.42 ± 1.80). A low residual velocity for the baseline trials could explain the apparent exception of subject S. However, for that subject, the residual velocity increased considerably, from 2.66 to 8.52 deg/s, corresponding to a change in velocity gain from 0.19 to 0.61. In the two control groups we found that the residual velocity increased significantly between the baseline and the postlearning in 4 of the 8 subjects, 3 subjects from the control group (triangles) and one from the yoked-control group (squares). However, the postlearning velocities remained relatively low in these two groups and only one subject in the control group (subject H) and one in the yoked-control group (subject C) exhibited a postlearning velocity higher than 11.2 deg/s.

We also compared the effects of learning between the groups. To ascertain that the groups were comparable we first performed an analysis of variance (ANOVA) on Ranks on the baseline velocities and found no statistical differences among the three groups. A 2-way repeated-measures ANOVA (Test sessions \times Groups) on eye velocities revealed a significant interaction between the session and the group factors ($P < 0.001$) (Fig. 5*B*). We performed a multiple comparison procedure

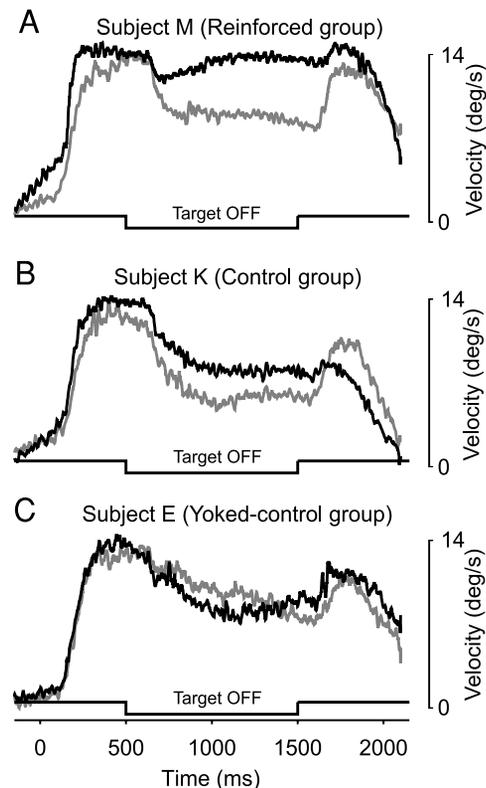


FIG. 4. Examples of average eye velocity evoked in baseline (gray traces) and postlearning (black traces) sessions for constant velocity trials as function of time (aligned on target motion onset). Bottom solid horizontal lines: target-OFF period. *A*: superimposed eye velocities for reinforced subject (subject M). *B*: superimposed eye velocities for control subject (subject K). *C*: superimposed eye velocities for yoked-control subject (subject E).

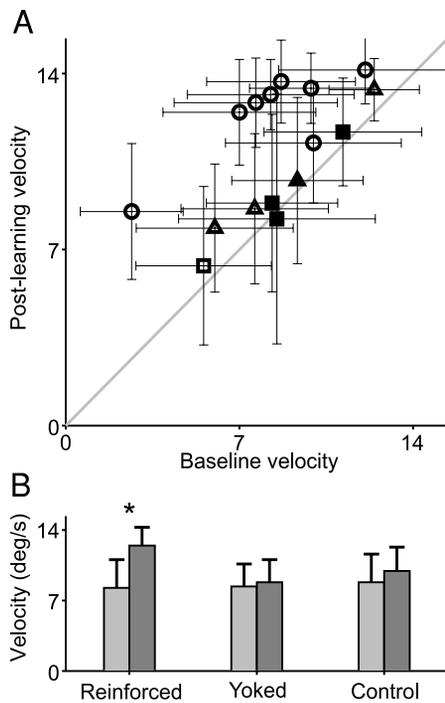


FIG. 5. Quantitative analysis of learned induced-changes in eye velocity for constant velocity trials. *A*: each point plots average postlearning eye velocity as function of average baseline velocity for one subject. Horizontal and vertical lines show corresponding SDs. Circles: subjects from reinforced group; triangles: subjects from control group; squares: subjects from yoked-control group. Empty symbols: significant change between postlearning and baseline trials (rank sum test, $P < 0.025$, 1-tailed). *B*: average eye velocity for baseline (light gray) and postlearning (dark gray) session for each group. *Significant difference between baseline and postlearning sessions.

procedure (Tukey Test), which confirmed the significant increase in eye velocity for the reinforced group [8.28 deg/s (SD = 2.77) and 12.42 deg/s (SD = 1.80), respectively, for the baseline trials and the postlearning trials, $P < 0.001$]. This corresponded to a change in velocity gain from 0.59 to 0.89. For the other two groups the effects were too small to draw conclusions. However, it can be seen that eye velocity only slightly increased in the control group [8.85 deg/s (SD = 2.75) and 9.89 deg/s (SD = 2.43), respectively, for the baseline trials and the postlearning trials, corresponding to a change in velocity gain from 0.63 to 0.71] and remained approximately constant in the yoked-control group [8.39 deg/s (SD = 2.30) and 8.77 deg/s (SD = 2.21), respectively, for the baseline trials and the postlearning trials, corresponding to a change in velocity gain from 0.60 to 0.63]. It should be noted that the intrasubject SDs of velocities were smaller for the postlearning trials than for the baseline trials in the reinforced group [3.04 (SD = 0.52) and 1.86 (SD = 0.49) on average for the baseline trials and the postlearning trials, respectively] as revealed by a paired t -test ($P = 0.005$).

We computed the frequency of saccades (number of saccades/s) for each subject during the target-off periods for the baseline and postlearning trials. For 6 of 8 subjects from the reinforced group (circles) plotting these frequencies against each other (Fig. 6A) shows a decrease in the frequency of saccades (rank sum test, $P < 0.025$, 1-tailed). A 2-way repeated-measures ANOVA (Test sessions \times Groups) and a multiple-comparison procedure (Tukey test) confirmed the

observed decrease in the frequency of saccades during target-off periods for the reinforced group [from 1.38 (SD = 0.59) to 0.45 (SD = 0.45), respectively, for the baseline and postlearning trials, $P < 0.001$]. For the two control groups the effects were too small to conclude. However, Fig. 6B shows that the frequency of saccades remained largely unchanged for the yoked-control group [from 1.42 (SD = 0.58) to 1.64 (SD = 0.59), respectively, for the baseline and postlearning trials] and for the control group [from 1.22 (SD = 0.48) to 1.27 (SD = 0.43), respectively, for the baseline and postlearning trials].

The observed effects of learning on eye movements reflect the design of the reinforcement procedure. Our procedure required subjects to maintain velocity gain within a set of fixed values (i.e., between 0.9 and 1.1) in the absence of the visual target. This increased eye velocity in the posttest trials and also reduced variability. Similarly, our procedure was designed to reduce the frequency of saccades by suppressing the auditory tone for 100 ms as soon as a saccade was detected.

Generalization of learning to untrained target velocities

To test for the effects of prediction on residual velocities we compared the average baseline eye velocity in the constant

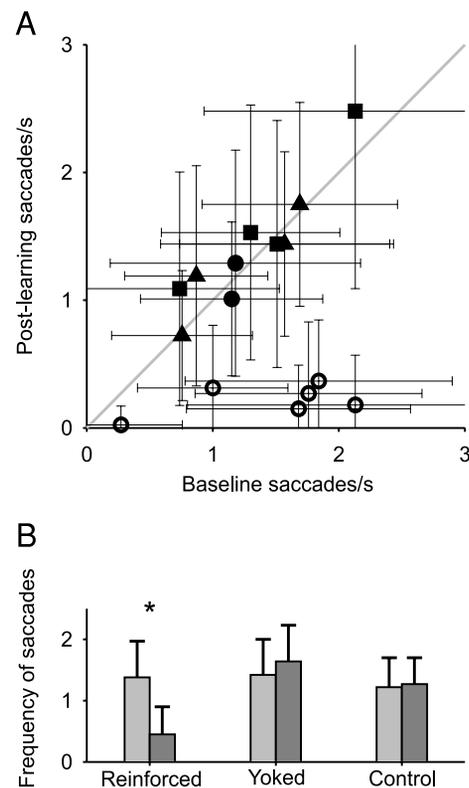


FIG. 6. Changes in frequency of saccades during target-OFF periods for constant velocity trials. *A*: each point plots average postlearning saccade frequency as function of average baseline saccade frequency for one subject. Horizontal and vertical lines show the corresponding SDs. Circles: subjects from reinforced group; triangles: subjects from control group; squares: subjects from yoked-control group. Empty symbols: significant change between postlearning and baseline trials (rank sum test, $P < 0.025$, 1-tailed). *B*: average frequency of saccades for the baseline (light gray) and postlearning (dark gray) session for each group. *Significant difference between baseline and postlearning sessions.

velocity trials and in the randomized velocity trials in subjects who experienced both conditions (Table 1), considering only the trials in which the target was moving at 14 deg/s. The eye velocity was higher when target velocity was predictable than in the randomized velocity trials [8.75 deg/s (SD = 2.20) and 6.56 deg/s (SD = 3.03), respectively, in the baseline trials, paired *t*-test, $P < 0.01$].

To facilitate comparison between the different target velocities, eye velocities were converted into velocity gains by computing the ratio of eye velocity to target velocity. Learning generalized across the untrained speeds in the subjects from the reinforced group. Figure 7 shows the individual velocity gains before and after learning in the 4 subjects from the reinforced group that were tested in the randomized velocity trials. It can be seen that the effects of learning are similar for the trained target velocity (14 deg/s) and for the untrained target velocities (10 and 20 deg/s). The eye velocity increased after learning for both the trained and untrained target velocities for subjects T, M, and V (rank sum test, $P < 0.025$, 1-tailed) but not for subject J. A high velocity for the baseline trials, leading to a ceiling effect, could explain the apparent exception of subject J. In the other two groups only one subject (subject N) exhibited a significant increase in velocity between the baseline and the postlearning trials for $V = 10$ deg/s and for $V = 20$ deg/s.

Influence of structured visual background on learned response

To test for the effects of a background on residual velocities we first compared the average baseline eye velocity in the constant velocity trials and in the background trials in subjects who experienced both conditions (Table 1). The eye velocity was not affected by the presence of the background [8.75 (SD = 2.20) and 8.09 (SD = 4.09) deg/s, respectively, in the

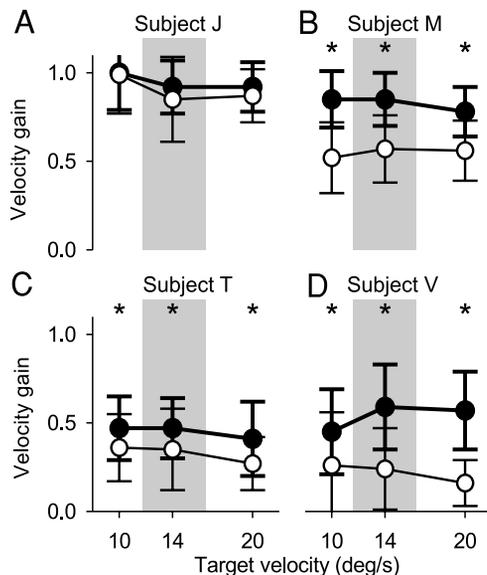


FIG. 7. Changes in velocity gain as function of target velocity for randomized velocity trials for subjects from reinforced group (A–D: subjects J, T, M, and V, respectively). Each point plots average velocity gain as function of the target velocity for one subject. Vertical lines: corresponding SDs. Empty symbols: baseline sessions; filled symbols: postlearning session. *Significant difference between baseline and postlearning sessions (see text). Gray areas indicate values for trained target velocity.

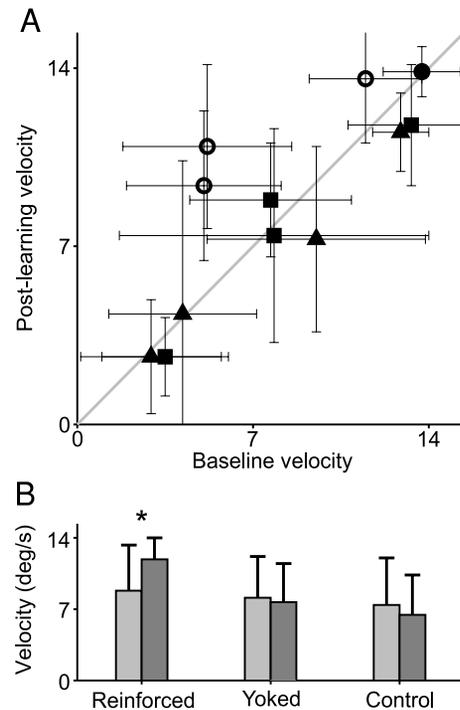


FIG. 8. Changes in eye velocity for background trials. A: each point plots average postlearning velocity as function of average baseline velocity for one subject. Horizontal and vertical lines: corresponding SDs. Circles: subjects from reinforced group; triangles: subjects from control group; squares: subjects from yoked-control group. Empty symbols: significant augmentation between postlearning and baseline trials (rank sum test, $P < 0.025$, 1-tailed). B: average velocity gain for baseline (light gray) and postlearning (dark gray) sessions for each group. *Significant difference between baseline and postlearning sessions.

absence and in the presence of a background in the baseline trials, Wilcoxon signed-rank test NS).

The presence of a textured visual background did not abolish the learned changes in velocity. Figure 8A plots the average postlearning velocity as a function of the average baseline velocity for each subject in the background trials with target-off periods. Points above the diagonal indicate that the postlearning velocity was greater than the baseline values. We found that the velocity was improved by the reinforcement procedure for all target velocities for 3 of the 4 subjects from the reinforced group (unfilled circles) (rank sum test, $P < 0.025$, 1-tailed). A high velocity for the baseline trials, leading to a ceiling effect, could explain the apparent exception of subject J (filled circle). In the other two groups no subject exhibited a significant increase in velocity between the baseline and the postlearning trials.

A 2-way repeated-measures ANOVA (Test sessions \times Groups) on velocities revealed a significant interaction between the two factors ($P = 0.017$). Multiple comparisons (Tukey Test) confirmed the significant increase in eye velocity for the reinforced group between the baseline and postlearning trials [8.85 deg/s (SD = 4.42) and 11.95 deg/s (SD = 2.17), respectively, for the baseline trials and the postlearning trials, $P = 0.005$]. In the other two groups the effects were too small to draw statistical conclusions. However, it can be seen that the eye velocities remained largely unchanged [8.07 deg/s (SD = 4.04) and 7.68 deg/s (SD = 3.77), respectively, in the baseline and postlearning trials for the yoked-control group;

and 7.35 deg/s (SD =4.66) and 6.46 deg/s (SD =3.85), respectively, in the baseline and postlearning trials for the control group] (Fig. 8B). These results show the persistence of the learned changes in the presence of the background for the reinforced group.

Effects of learning on pursuit of a visible target

In addition to the effects on pursuit during blanking we also observed modifications of eye velocity when the target was present. Three subjects from the reinforced group exhibited a significantly higher eye velocity in the postlearning session than in the baseline session in trials with no target-off periods. Eye velocities were computed by taking the average eye velocity over a 40-ms interval 1,200 ms after motion onset. Velocity increased (rank sum test, $P < 0.025$, 1-tailed) from 12.43, 8.94, and 12.30 deg/s in the baseline session to 13.97, 13.64, and 14.01 deg/s in the postlearning session, respectively, for subjects L, S, and T, from the reinforced group. Part of our procedure was designed to induce learning in steady-state tracking in the presence of a visual target by shaping the response in subject with a low baseline eye velocity. In the control group subjects H and K exhibited a similar increase (13.45 and 11.23 deg/s in the baseline and 14.02 and 13.16 deg/s in the postlearning, respectively, for subjects H and K). This effect was not present in subjects from the yoked-control group.

We also observed modifications at the initiation of pursuit in the reinforced group [from 115.7 (SD =36) to 137.2 (SD =37) deg/s², respectively, before and after training]. Figure 9 plots the average acceleration during pursuit initiation in the postlearning session as a function of the average acceleration in the baseline for each subject from the reinforced group. Points above the diagonal indicate that the postlearning acceleration gain was greater than the baseline value. Acceleration significantly increased in 6 subjects (L, S, A, J, T, and V) and decreased in one subject (subject R) in the postlearning session (rank sum test, $P < 0.05$, 2-tailed).

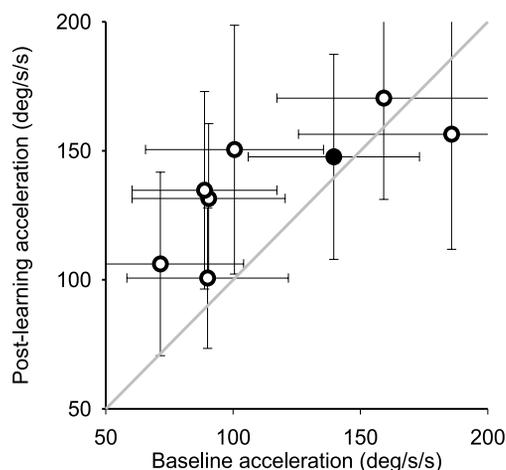


FIG. 9. Changes in acceleration at initiation of pursuit. Each point plots average postlearning acceleration for the first 100 ms of pursuit as function of average baseline acceleration for one subject from reinforced group. Horizontal and vertical lines: corresponding SDs. Empty symbols: significant difference in acceleration at initiation of pursuit between postlearning and baseline trials (rank sum test, $P < 0.05$, 2-tailed).

DISCUSSION

Effects of learning on pursuit in the absence of a visual target

The plasticity of pursuit during tracking of a visual target has been revealed by a number of studies in humans (Fukushima et al. 1996; Ogawa and Fujita 1997; Optican et al. 1985; Takagi et al. 2000, 2001) as well as in monkeys (Kahlon and Lisberger 1996, 2000). We have shown that the smooth pursuit response in the absence of visual feedback may also be affected by learned contingencies: after learning, subjects were able to maintain high velocities without visual feedback. The velocity gains were close to values typically observed during steady-state tracking with an average of 0.89 for the reinforced group. We also found that the learned enhancement in eye velocity persisted in the presence of a textured visual background. The selectivity of the pursuit system could account for transfer of these learned changes to the presence of a fixed textured background, whereas for the optokinetic system the retinal slip of the image of the background would likely have canceled the eye movement. Although we cannot rule out that learning also took place in the optokinetic system, these results suggest that the learning critical for the tracking we observed took place primarily in the pursuit system. That learning generalized over untrained target velocities indicates a change of a multiplicative gain in the pursuit system. Learning did not simply increase eye velocity by a fixed amount because the learned increases in eye velocity were scaled with the target velocity. This also implies that the changes we observed were not due to a cognitive prediction of one target speed. Pursuit initiation and the steady state component were also affected by learning. The ability to induce changes in the pursuit response in the absence of a visual target suggests that the gain of the pursuit system is regulated by nonvisual signals and that these nonvisual signals can undergo plastic changes.

Short-term versus long-term adaptation

Studies of adaptation in the pursuit system usually focus on short-term modifications (Fukushima et al. 1996; Kahlon and Lisberger 1996, 2000; Ogawa and Fujita 1997; Takagi et al. 2000, 2001). Kahlon and Lisberger (1996) tested the retention of learning in monkeys in a pursuit adaptation experiment. They performed two postlearning tests: one immediately after the learning trials and a second one after the monkey had sat in darkness for 30 min with his head fixed. The results show that learned changes in the initiation of pursuit were similar in the first and second postlearning tests. However, they also report overnight recovery when the monkeys were allowed natural viewing conditions, indicating that the learning they observed involved short-term adaptation of the pursuit system.

By contrast, our learning procedure involved long-term modifications of the pursuit system, allowing us to progressively increase the duration of the target-off periods in the reinforced group: there was a cumulative change in the subjects' responses so that the level of performance achieved at the end of each daily session increased. Moreover, the postlearning session was systematically performed 24 h after the last learning session. By allowing overnight recovery of the short-term effects we were able to demonstrate long-term modifications of the pursuit system. We know of only one experiment on

humans that attempted to quantify long-term adaptation in the pursuit system by measuring pursuit before and after a week of monocular viewing (Optican et al. 1985). We believe that we were able to observe these long-term modifications because we used a reinforcement procedure instead of a simple repetition of the task.

Effects of the reinforcement contingencies

Our procedure allowed us to directly test the effects of the reinforcement contingencies. The data from the yoked-control group, in which the distribution of the reinforcer was independent of the subjects' response, indicate that the temporal contiguity between the reinforcer and the eye movement is critical: when the distribution of the reinforcer was not contingent on the response, the smooth pursuit velocity gain during target disappearance was not significantly modified (from 0.60 to 0.63, respectively, before and after training). In contrast, when the reinforcer was immediately contingent on the subjects' response (reinforced group), the velocity gain significantly increased after learning (from 0.59 to 0.89, respectively, before and after training). Repetition also induces learning because some subjects from the control group slightly improved their response after practice, as revealed by the increase in velocity gain (from 0.63 to 0.71, respectively, before and after training). We know of only one study using a similar procedure in young infants (Darcheville et al. 1999). Using an auditory reinforcer contingent on smooth eye movements this experiment showed learning-induced increases in the proportion of slow movements elicited by a moving target in infants aged from 1 to 7 days. When the presence of the auditory stimulus was independent from the infants' eye movements the proportion of slow movements remained unchanged. This observation is similar to the lack of effect we report here in the yoked-control group. Together these results provide evidence that smooth pursuit, even in the absence of visual target, is an operant behavior, that is, a response that is, at least partly, under the control of its consequences.

Our experimental procedure mimics the reinforcement process occurring in everyday practice. In natural situations, moving targets often disappear temporarily behind occluding objects. The ability to maintain tracking while the target is occluded might be necessary for the eye to acquire the target faster and improve tracking when the target reappears, allowing an optimization of the visual perception of the target. It may be assumed that this optimization acts as a reinforcer and that tracking during the transient disappearance of a target is a learned response. In our experimental situation a similar process is at play, given that the systematic relationship between the reinforcer and the response results in a significant increase in the velocity gains. It has been proposed that the function of adaptive control in the pursuit system is to minimize error signals (i.e., the retinal slip) (Optican et al. 1985). Our results suggest that, in addition, learning can occur to maximize the presence of a reinforcer.

Pursuit in the absence of a visual target requires prediction

The present observations confirm earlier results (Becker and Fuchs 1985) showing that smooth pursuit continues during transient disappearance of a visual target. These previous au-

thors reported that eye movements after the disappearance of the target exhibit two main characteristics: 1) eye velocity starts to decelerate within 0.2 s after the disappearance of the target, and 2) after the deceleration phase that lasts for about 300 ms, the eye velocity remains approximately at a constant value until the visual target reappears. It should be noted that the values for the baseline constant velocity trials observed in our procedure are similar to those reported by Becker and Fuchs (1985), with an average of 0.60. A low velocity gain (0.19) was observed in one subject (subject S), whereas it was higher than 0.8 in 3 subjects (subjects C, J, and H). Becker and Fuchs (1985) found that training had only a modest effect on the observed pattern, but their protocol was not designed specifically to study the effects of learning.

Becker and Fuchs (1985) argue that pursuit in the absence of a visual target is the result of a predictive mechanism. As pointed out by the authors the residual eye velocity observed during the transient disappearance of the visual target most likely results from a combination of expected velocity, based on previous trials, and extrapolated velocity, based on the actual target velocity. Two effects reported here support this assumption. First, in the constant velocity trials, when the target motion is highly predictable, the eye velocity gain is higher than that in the randomized velocity trials, suggesting that the eye velocity is influenced by predictive mechanisms using previous experience. Second, in the randomized velocity trials the velocity gain is scaled to the actual target velocity, indicating that the pursuit system is able to continue the ongoing pursuit movement based on extrapolated velocity. Prediction has been demonstrated in the pursuit system: it has been shown, for instance, that anticipatory smooth pursuit can be made before the onset of a motion signal (Barnes and Donelan 1999; Kao and Morrow 1994; Kowler et al. 1984). These anticipatory movements are scaled to the expected target velocity and are therefore predictive of the target's motion. That similar pursuit prediction may be observed at various stages of pursuit suggests that the ability to use predictive mechanisms to maintain pursuit in the absence of visual feedback is a fundamental property of the pursuit system, not a specific effect of our experimental procedure.

Simulation of learning

That learned contingencies may modify the output of the pursuit system in the absence of visual feedback suggests that learning can affect the processing of nonvisual signals for pursuit. Krauzlis and Miles (1996b) proposed a model of the smooth pursuit system in which the gain is under the continuous control of such nonvisual signals (Fig. 10). In their model the visual input results from the subtraction of the eye velocity from the target velocity. After a fixed delay two parallel pathways process this visual signal. The "image acceleration" pathway computes the first derivative of the signal and applies a nonlinear scaling. The outputs from the parallel pathways are then summed with a copy of the eye velocity ("positive efferent copy feedback"). The resulting signal is modulated by a second input signal ("gain") in a multiplicative junction. This multiplicative junction affects equally the gain of the visual inputs and the gain of the positive efferent feedbacks.

By changing the gain input while maintaining all other parameters fixed we were able to simulate the essential features

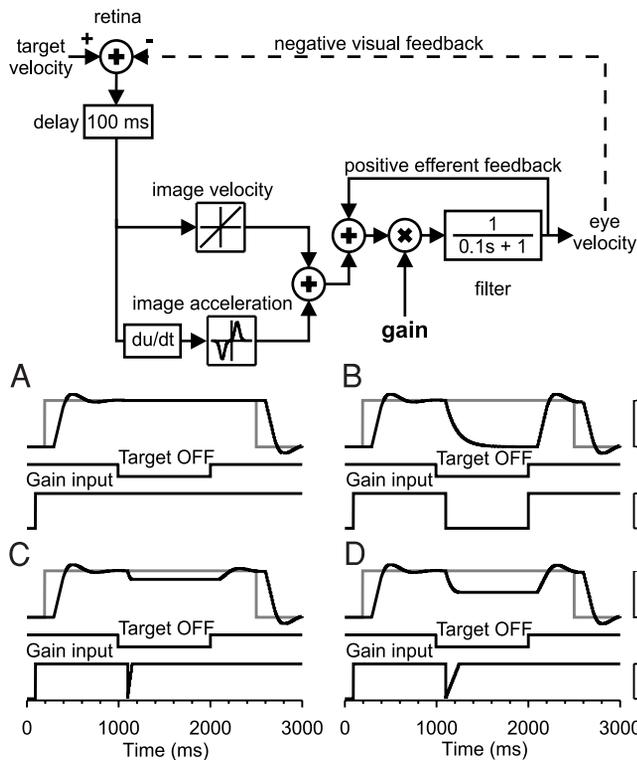


FIG. 10. Diagram of model proposed by Krauzlis and Miles (1996b) (*top*). Simulation of eye velocity profiles by varying gain input during target-OFF period (*bottom*). Inputs of model were target velocity signal (*gray trace*, here in normalized units) inactivated during target-OFF period, and a gain input (*lower black traces*). Output of model is shown by solid black line (in normalized units) superimposed to target velocity traces. *A*: gain input remains at unity. *B*: gain input signal is set to zero by target disappearance. *C* and *D*: steepness of slope of gain input is varied to simulate different velocity profiles.

of our data. Figure 10, *A–D* shows the relationship between the gain signal and the output of the pursuit system. In these examples the target-off periods started 800 ms after motion onset and lasted for 1,000 ms. When the visual feedback was suppressed, the only remaining signal in the system was the positive efferent feedback modulated by the gain signal. Therefore if the gain signal remained at unity (Fig. 10*A*), the eye velocity signal was not affected by the disappearance of the target because the positive efferent feedback was constant. On the other hand, if the gain was set to zero when the target disappeared (Fig. 10*B*), the eye velocity signal quickly dropped to zero and reaccelerated after the target-off period, when the gain signal was set back to unity. We chose to modify the profile of the gain input so that it was set to zero after the target disappearance and ramped up to 1 with a fixed slope. This is an admittedly arbitrary profile of the gain input and we chose it primarily because it was very simple and could account for the qualitative features of our data. Using this profile, eye velocity quickly decelerated but the deceleration stopped when the input gain reached unity. By changing the slope of the input gain we were able to reproduce the patterns of eye velocity observed in our subjects. If the slope of the gain input was steep (Fig. 10*C*), eye velocity stabilized at a high value. On the other hand, if the slope was less steep (Fig. 10*D*), eye velocity decreased for a longer period of time and therefore stabilized at a lower value. Similar effects could be obtained by using alternate profiles for the gain input, but an important aspect of

these simulations is that we were able to generate changes in the velocity profiles by manipulating a single-model parameter.

As the results of the simulations suggest, the learning we observed can be attributed to changes in a variable gain element for pursuit. Also note that changes in this gain input would also be expected to affect the processing of visual inputs. Thus one would predict that changes in gain would also affect eye acceleration at the initiation of pursuit, and we did in fact find this effect in the reinforced subjects (Fig. 9). The locus of such a gain controller is unknown, although studies of the pursuit-related neural structures suggest a number of possible sites responsible for the learned changes of the gain signal.

Possible sites for learning

Kahlon and Lisberger (1996) concluded from the learning they observed that pursuit adaptation occurs in a reference frame defined in both image and motor coordinates, a result compatible with our observations. Recently, Chou and Lisberger (2002) inferred that neural sites for learning should also contain cells with receptive fields large enough to account for generalization to a range of spatial locations. The learned effects we reported here suggest that potential sites responsible for learning must exhibit two properties: they must convey a mix of image and eye motion-related signals, and they must respond in the absence of motion signals.

The available physiological data suggest several possibilities. The ventral paraflocculus area of the cerebellum receives motor signals during pursuit (Fuchs et al. 1994; Lisberger et al. 1994; Suh et al. 2000) and the Purkinje cells in the paraflocculus encode eye velocity signals even during the stabilization of the target image on the fovea (Stone and Lisberger 1990) while maintaining activity during blanking of a predictable target (Suh et al. 2000). Kahlon and Lisberger (2000) showed that some studied Purkinje cells in the floccular complex exhibit learned-related changes in their simple spike responses. However, these effects do not provide evidence for cerebellar learning and could also be the result of learning that occurs upstream. Neurons in the medial superior temporal area (MST) appear to encode not only visual signals but also nonvisual signals related to the execution of pursuit movements that may derive from corollary discharge or from efference copy (Newsome et al. 1988). Electrical microstimulation in the smooth eye movement region of the frontal eye fields (FEFsem) results in smooth pursuit-like movements during fixation (Gottlieb et al. 1993) and enhancement of pursuit responses to perturbations of the target (Tanaka and Lisberger 2001) and suggesting that pursuit neurons in FEF may play a critical role in gain control for pursuit (Tanaka and Lisberger 2001, 2002). Other structures may be responsible for learning as well: some neurons in the DLPN have been shown to discharge during pursuit (Thier et al. 1988) even when the visual signals are removed (Mustari et al. 1988); the superior colliculus also exhibits extra-retinal signals during pursuit (Krauzlis 2001). Further studies are necessary to determine which of these structures are responsible for learning in the pursuit system.

Functional significance of gain control

The pursuit system has been historically described as a servo-system driven by retinal slip (Robinson et al. 1986). Because of an

inherent delay in the pursuit system, the performance depends on the values of internal gain parameters that determine the time required to acquire the visual target and the oscillations during steady-state tracking. In a servo-system, the need to control the gain is mainly for calibration purposes: the ability to adaptively modify internal parameters is required to compensate for modifications in the relationship between visual input and motor output (Optican et al. 1985). These modifications naturally occur during development and aging as a result of changes in the eye plant after eye growth or muscular weakness.

However, a number of studies indicate that the pursuit system is an actively controlled system. For instance, it has been shown that pursuit is not always driven by the raw retinal slip but can follow the perceived motion of an object (Steinbach 1976; Stone et al. 2000). Moreover, the pursuit response is modulated by attentional factors (Khurana and Kowler 1987), prediction (Barnes and Donelan 1999; Barnes et al. 2000; Wells and Barnes 1998), and, as we report here, learning induced by the reinforcing consequences of improved tracking. Therefore the functional significance of gain control in the pursuit system might extend well beyond motor calibration.

DISCLOSURES

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