Modification of Smooth Pursuit Initiation by a Nonvisual, Afferent Feedback Signal

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Purpose. To investigate the role of extraocular muscle afferent signals in the initiation and early maintenance of smooth-pursuit eye movements.

Methods. A suction scleral contact lens was used to impede the movements of the right eye while subjects tracked small targets in a step–ramp pursuit paradigm. Movements of the left eye were measured by infrared oculography. Pursuit latency, eye acceleration, and velocity were analyzed trial-by-trial and compared before, while, and after the right eye was impeded.

Results. When the right eye was impeded, initial acceleration and eye velocity were reduced. Pursuit latency was unchanged. The velocity effect had a rapid onset and offset; there was no evidence that the effects built up over a number of trials. Detailed analysis suggested that the reduction in velocity occurred approximately 40 msec after pursuit was initiated.

Conclusions. These results are consistent with the hypothesis that extraocular muscle afferent signals provide a feedback signal of the movements of the eyes that may be used to modify the initiation and early maintenance of smooth pursuit on-line. It appears that for pursuit, as with saccades, the priority in these conditions is to maintain conjugacy. (*Invest Ophthalmol Vis Sci.* 2001;42:2297–2302)

Co-ordinated movements of the eyes are essential to place and then maintain the images of objects of interest on the fovea, thereby ensuring a high level of visual acuity.[1] For this to occur accurately, the output of the oculomotor system (i.e., the movement and position of the eyes) requires constant monitoring through a combination of both visual and nonvisual feedback. There are two potential sources of nonvisual information regarding eye position: first, central monitoring of the oculomotor commands (efference copy or corollary discharge; see Bridgeman[2] and Ruskell[3] for reviews) and, second, afferent signals derived from extraocular muscle (EOM) proprioceptors.[4,5] Although the human EOMs are well endowed with intramuscular receptors, the role of afferent signals arising from these receptors remains controversial,[5,6] and it is generally accepted that efference copy is the predominant source of the nonvisual feedback.[2,3] A greater understanding of the role of EOM afferent feedback in oculomotor control would not only be of scientific interest, but also of clinical relevance, particularly because abnormal EOM proprioception has been implicated in the cause of certain oculomotor disorders, such as congenital esotropia.[7]

Recent studies have demonstrated that experimentally manipulating afferent feedback signals from the EOM in human subjects modifies static eye position[8] and both memory and visually guided saccades.[9,10] However, saccades are only one aspect of the human oculomotor repertoire. Given the rapid time course of all but the very largest saccades, there is clearly little time available for an afferent signal from the periphery to act in their control. It has therefore been difficult to establish exactly how EOM afferent signals modify them. By contrast, smooth pursuit has a much slower time course because of the lower eye velocities involved. Although it has been demonstrated that EOM afferent signals influence adaptive pursuit responses to changes in target velocity over an adapting period,[11] nothing is known about the role of nonvisual afferent signals in the initiation of smooth pursuit. Theoretically, a nonvisual feedback signal might aid pursuit performance during the initial open-loop phase of pursuit when visual feedback is not available due to delays in the visual pathway. If the initiation of smooth pursuit was modified by manipulating EOM afferent feedback, it might also be possible to establish whether effects were consistent with an on-line or parametric adaptive role for EOM afferent signals, by investigating the time at which modifications were manifest.

We therefore investigated the effect of manipulating EOM afferent signals on the initiation and early maintenance of smooth pursuit in human subjects. We used a suction contact lens to acutely increase the load under which the EOMs had to work, thus altering afferent feedback. We examined the effect of this by monitoring the movements of the other eye during step–ramp pursuit tasks.

Materials and Methods

The experimental procedures followed the tenets of the Declaration of Helsinki for research involving human subjects. Ethics committee approval and informed consent were obtained before the study began. Three adult male subjects (aged 20–37 years) participated in the experiment. Two naïve subjects (KB, JD) were tested on two occasions and one subject (PCK, one of the authors) on three occasions. Corrected visual acuities were 6/6 for each subject for each eye. Each testing session consisted of three runs of either 52 or 96 trials.

The subjects viewed a computer monitor with the left eye from a distance of 57 cm. The right eye was either occluded but free to move or impeded and occluded by a suction contact lens and holder (described later). Head movement was prevented using a chin rest and adjustable cheek pads, with particular care taken to ensure that the head did not move during either the placement or removal of the suction contact lens. In runs of either 52 or 96 step–ramp pursuit tasks,[12] subjects were presented with a central fixation target (generated by a Visual Stimulus Generator; Cambridge Research Systems, Rochester, UK), which appeared in the center of the monitor for a random period of 0.5 to 1.5 sec. This was replaced by the smooth-pursuit target, which appeared randomly 5° to the right or left of fixation and then moved back through the center of the display at a speed of 14 deg/sec. This task configuration was chosen because it

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ensured that in most trials the beginning of smooth pursuit was not obscured by the occurrence of an early saccadic eye movement (see Figs. 1, 4), and the pursuit responses of normal subjects had been thoroughly investigated using these parameters previously.[13–15] Horizontal movements of the left eye were recorded with an infrared corneal reflection device (IRIS; Skalar Medical, Delft, The Netherlands; spatial resolution of 0.1°), which was calibrated at the beginning of each testing session. Eye position signals were digitized at 1 kHz with 12-bit precision using a data aquisition interface (CED μ1401; Cambridge Electronic Design, Ltd., Cambridge, UK). The eye position and a time marker of the appearance of the pursuit target were displayed on the computer screen; data from 100 msec before to 500 msec after the appearance of the target were stored on disc for analysis off-line.

In the first and third runs of trials, the right eye was occluded but free to move. In the second run the occluder was removed, and two drops of local anesthetic (Proxymetacaine Minims; Chauvin, Essex, UK) were instilled into the right eye before insertion of a suction scleral contact lens.[10,16] The lens had a central stalk that fitted into a custom-built holder, and this prevented movement of the lens, which in turn impeded, but did not prevent, movement of the right eye. The lens was placed while the subject's head remained stabilized, with care taken not to dislodge the eye tracker or move the head during placement. Once in place, the pressure beneath the lens was reduced by approximately 70 mm Hg, and pursuit targets were again presented to the left eye. Recording began within 90 seconds of lens insertion. We limited use of the lens to approximately 5 minutes in any testing session and on completion of the experiment the intraocular pressure and the corneal surface were examined. In a separate series of control experiments, local anesthetic was instilled into the right eye and pursuit data collected without the lens in place and with the right eye occluded.

Data were analyzed using an analysis program that displayed the recorded eye position, the calculated eye velocity, and the time at which the pursuit target appeared. For each record in which target appearance was preceded by steady fixation, the initial acceleration and latency of the smooth pursuit response were calculated from traces of eye velocity (see Fig. 1). To objectively establish the time of initiation of smooth pursuit and calculate latency, a regression technique was used.[15] Briefly, two least-squares linear regression functions were fitted to traces of eye velocity over a 50-msec period, the first from 25 msec before to 25 msec after the target appeared, and the second during the acceleration phase of the pursuit response. The slope of this second line was used to estimate initial acceleration. The intercept between these two regression lines was taken as the time of initiation of smooth pursuit.

Smooth pursuit consists of two phases: approximately the first 100 msec of pursuit is executed without the benefit of visual feedback (the open-loop period). Thereafter, pursuit can be modified by visual feedback and other nonretinal influences (closed-loop pursuit). To assess pursuit performance during both of these phases, we measured eye velocity at the end of the open-loop period 100 msec after pursuit initiation, and at 200 msec, after an appreciable amount of closed-loop pursuit. After pursuit is initiated, eye velocity often builds up to peak before declining slightly and oscillating around the target velocity. We measured the maximum slow eye velocity reached within 500 msec of pursuit initiation. Mean parameters were calculated and compared statistically with Student's *t*-test. To investigate the time evolution of the effects observed, we also examined eye velocity over the first 80 msec in more detail. For two of the subjects in which the occurrence of the first saccade was sufficiently delayed, each trial was divided into four 20-msec epochs (0–20, 20–40, 40–60, and 60–80 msec), and the mean eye velocity calculated over this segment. Data were pooled across sessions and subjects and the mean eye velocity for each epoch compared using analysis of variance and Bonferroni's multiple comparison test.

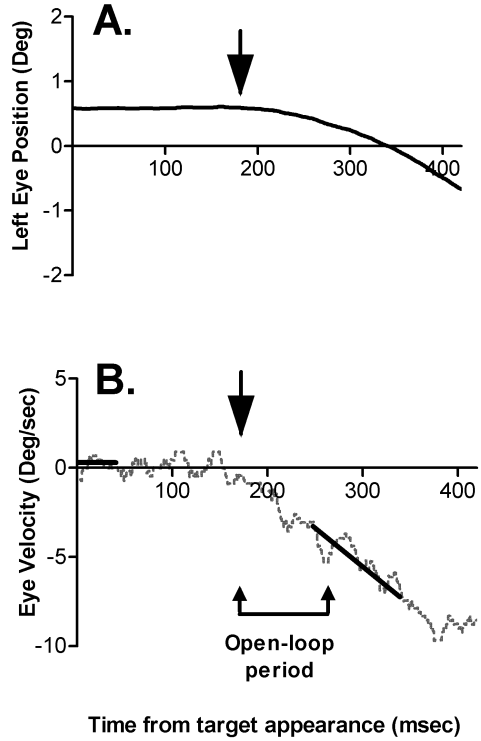

Figure 1. Example of response to a target that appeared 5° to the right and moved at 14 deg/sec back through the center of the display. Downward represents movement to left. Eye (**A**) position and (**B**) velocity. Linear regressions (*solid lines*) were fitted to velocity traces, 25 msec before to 25 msec after the target appeared, and during the acceleration phase of the response. The slope of the second line was used to estimate initial acceleration. The intercept between the regression lines was taken as the time of smooth-pursuit initiation (*large arrows*). *Small upward arrows*: first 100-msec response, open-loop.

Results

All subjects were able to execute smooth pursuit eye movements with reasonable accuracy. When the suction contact lens was placed on the right eye, they reported no discomfort and had no difficulty in visualizing the target with the left eye. None of the subjects reported any difficulty in following the target with the lens in place. In addition, no obvious difference in fixation or the quality of pursuit was noted when compared with the control trials. A degree of slippage under the lens was apparent, but a definite restriction of movement was also observed.

The mean initial acceleration of the left eye decreased significantly in all three subjects when the right eye was impeded by the suction contact lens (Fig. 2A). Because both the pattern and magnitude of effect were very similar in all three subjects, only pooled data are illustrated. For pursuit movements made in response to targets moving from right to left, the mean pooled acceleration decreased by 20% from 80 ± 22 to 64 ± 18 deg/sec^2 (mean ± SD). This reduction was statistically significant ($t = 5.6$, $P < 0.001$). For pursuit movements made in response to targets moving from left to right, the mean pooled acceleration decreased by 17% from 82 ± 19 to 68 ± 16 deg/sec^2 ($t = 4.81$, $P < 0.001$).

As might be expected, given the results on eye acceleration, eye velocity during smooth pursuit initiation decreased in all subjects when the right eye was impeded. The peak open-loop velocity, measured 100 msec after the initiation of pursuit, was reduced in all subjects (Fig. 2B). For example, in subject PCK

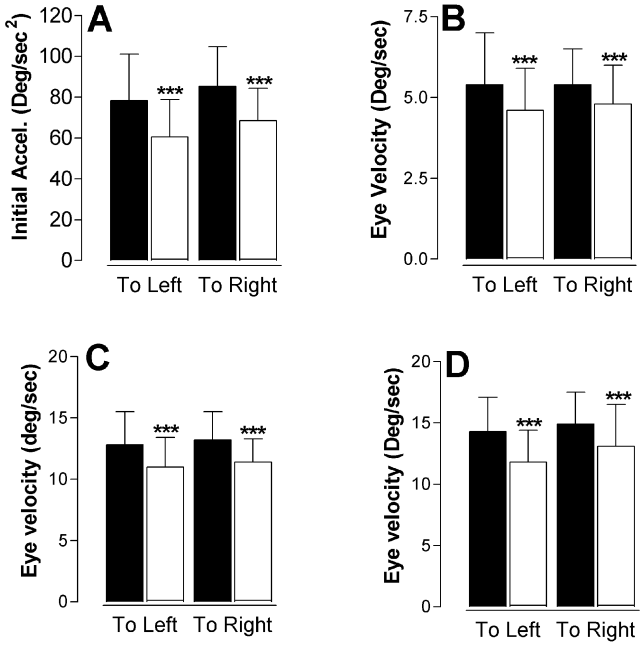

FIGURE 2. A comparison of left eye parameters before (*black bars*) and while (*open bars*) the right eye was impeded. Data pooled across subjects and sessions. Error bars, SD. ***Statistically significant differences between column pairs ($P < 0.001$). Effect on (**A**) initial acceleration, (**B**) eye velocity 100 msec after pursuit initiation (maximum open-loop velocity), (**C**) velocity 200 msec after pursuit initiation, and (**D**) maximum slow eye velocity.

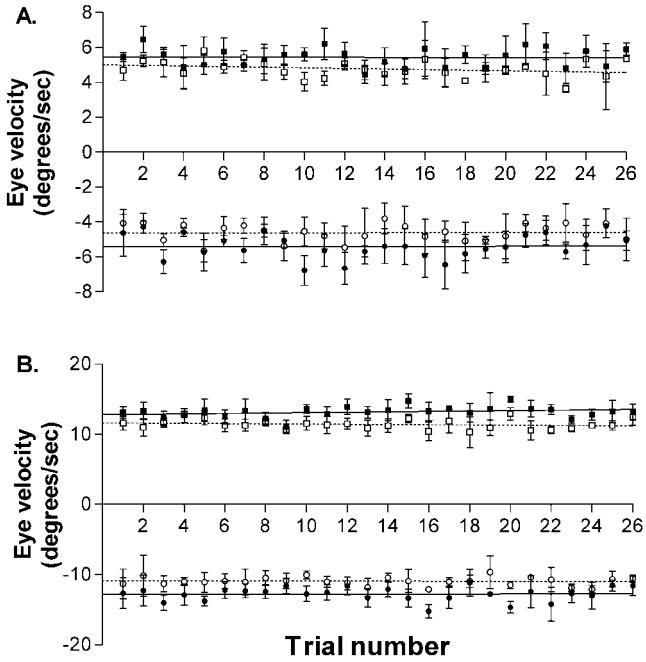

FIGURE 3. Trial-by-trial pooled mean (±SEM) left eye velocity before (*filled symbols*) and while (*open symbols*) the right eye was impeded. Lines are linear regression lines calculated from the data. Positive values: target moved from left to right. Negative values: target moved from right to left. Eye velocity (**A**) 100 msec after initiation of pursuit and (**B**) 200 msec after initiation of pursuit. Velocity was reduced from the first trial and there was little indication that the reduction built up during the run.

this reduction was from 5.1 ± 1.4 to 4.2 ± 1.1 deg/sec ($t = 3.49$; $P < 0.001$) for targets moving from right to left, and from 5.5 ± 1.2 to 4.7 ± 1.1 deg/sec for targets moving from left to right ($t = 3.63$; $P < 0.001$). For the pooled data, velocity at this point was reduced by 15% from 5.4 ± 1.6 to 4.6 ± 1.3 deg/sec ($t = 3.52$; $P < 0.001$) and by 11% from 5.4 ± 1.1 to 4.8 ± 1.2 deg/sec ($t = 3.6$; $P < 0.001$) in response to targets moving from right to left and from left to right, respectively (Fig. 2B). At 200 msec after the initiation of pursuit (i.e., well into the closed-loop phase), reductions in velocity were still observed when the right eye was impeded. For example, in subject PCK this reduction was from 12.8 ± 2.9 to 10.4 ± 2.2 deg/sec ($t = 4.66$; $P < 0.001$) for targets moving from right to left and from 13.4 ± 2.4 to 11.2 ± 2.0 deg/sec ($t = 5.16$; $P < 0.0001$) for targets moving from left to right. For the pooled data, the mean velocity was reduced by 14% from 12.8 ± 2.7 to 11 ± 2.4 deg/sec ($t = 4.72$; $P < 0.001$) and by 14% from 13.2 ± 2.3 to 11.4 ± 1.9 deg/sec ($t = 5.22$; $P < 0.001$) in response to targets moving from right to left and from left to right, respectively (Fig. 2C).

Peak velocity (the maximum slow eye velocity reached within 500 msec of the initiation of pursuit) was also reduced in all subjects when the right eye was impeded. For the pooled data, the mean velocity was reduced by 17% from 14.3 ± 2.8 to 11.8 ± 2.6 deg/sec ($t = 9.1$; $P < 0.001$) and by 12% from 14.9 ± 2.6 to 13.1 ± 3.4 deg/sec ($t = 5.87$; $P < 0.001$) in response to targets moving from right to left and from left to right, respectively (Fig. 2D).

These reductions in pursuit velocity were observed from the first trial when the right eye was impeded. Figure 3 shows trial-by-trial mean velocities (data pooled across subjects and sessions) for velocity at both 100 msec and 200 msec after the initiation of pursuit. Individual data are similar. Linear regressions of velocity on trial number for both the pooled and individual data showed no significant difference in the slope from zero, and no significant difference in the slope between the eye-free and eye-impeded conditions. Thus, there was no evidence for a build-up in the effect.

Having found that impeding the right eye led to significant reductions in left eye velocity as early as 100 msec after pursuit initiation, we attempted to establish with more precision the time point at which reductions in velocity first became apparent. In two of the subjects (PCK and JD) the first saccade occurred relatively late in their responses to target motions (Fig. 4). This made it possible to analyze the

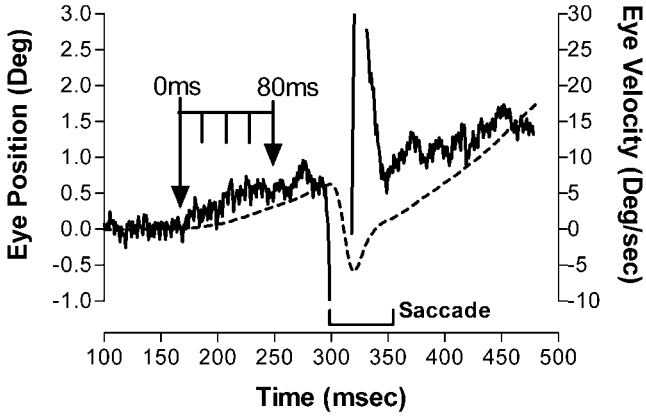

FIGURE 4. Eye position (*dashed line*) and eye velocity (*solid line*) during a single trial, showing the four 20-msec epochs over which eye velocity was averaged. For this trial, pursuit latency was 157 msec and the saccade latency was 299 msec. Initial eye acceleration was 64 deg/sec^2. Eye velocity averaged over the four epochs was: 1.38 deg/sec, 2.42 deg/sec, 4.55 deg/sec, and 4.78 deg/sec.

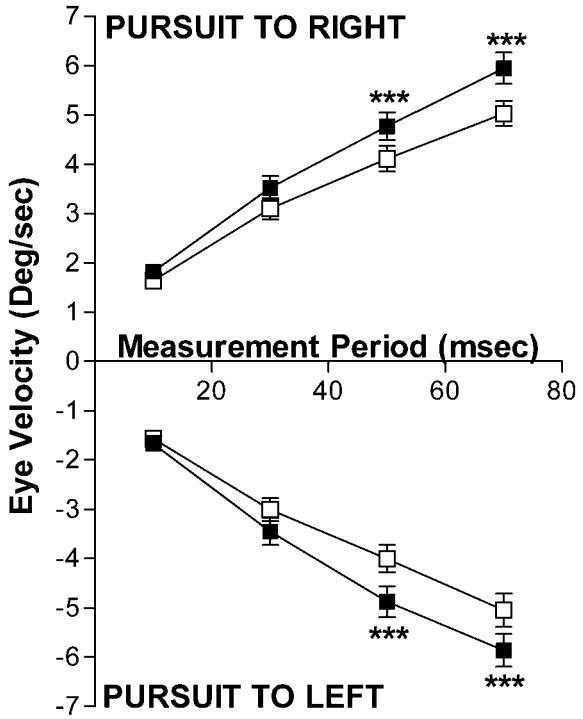

FIGURE 5. Mean (± SEM) left eye velocity over 20-msec epochs during the first 80 msec of the pursuit response before (*filled symbols*) and while (*open symbols*) the right eye was impeded. Center point of epoch is plotted. Positive values: target moved from left to right. Negative values: target moved from right to left. ***Significant differences between epochs ($P < 0.001$).

first 80 msec of the pursuit response by averaging eye velocity over four 20-msec epochs from the initiation of pursuit without having to either "desaccade" records or reject large numbers of trials. Unsurprisingly, there was a statistically significant difference overall in the means for both leftward (F: 129.4, $df = 7,1323$; $P < 0.0001$) and rightward (F: 157.2, $df = 7,1416$; $P < 0.0001$) pursuit when compared by ANOVA. Using Bonferroni's multiple comparison test to compare mean eye velocity in impeded and free conditions, we found that there was no statistically significant difference in mean velocity in the first (0–20 msec) or second (20–40 msec) epochs for either leftward or rightward pursuit ($P > 0.05$; Fig. 5). However, eye velocity was significantly reduced when the right eye was impeded in both the third (40–60 msec) and fourth (60–80 msec) epochs for both rightward (third: $t = 3.8$, $P < 0.001$; fourth: $t = 5.3$, $P < 0.001$) and leftward (third: $t = 4.5$ $P < 0.001$; fourth: $t = 4.2$, $P < 0.001$) pursuit. Thus, the difference in velocity between the two conditions became significant at approximately 40 msec.

When the contact lens was removed, the parameters of smooth pursuit returned to their original values. We observed no statistically significant difference in smooth-pursuit latency when comparing trials in which the right eye was free and those in which it was impeded. To check that the effects we observed were not caused by the use of local anesthetic, we performed a control experiment that was identical in all respects with the main experiment, with the exception that no suction lens was placed on the right eye. There was no difference in any of the pursuit parameters measured when comparing the first (preanesthetic) with the second (postanesthetic) run.

DISCUSSION

We have previously shown that impeding the movement of one eye modifies the saccades of the contralateral eye. Specifically, saccade amplitude is reduced, whereas the main sequence relationships are unaltered.[10] However, saccades are only one element in the human oculomotor repertoire. We have now investigated another important class of human eye movements—smooth pursuit—which serves a different function than saccades and has a distinct neurobiological substrate.

Our results show that impeding the movement of one eye while the subject executes smooth pursuit with the contralateral eye leads to small but consistent alterations in the initiation and early maintenance of pursuit. Both the initial acceleration and the peak open-loop velocity in the free eye were reduced by a statistically significant amount. These parameters provide a measure of the performance of the pursuit system in the absence of either retinal (visual) feedback or internal representations of target trajectory. We found no evidence that the effects built up over time or initial trials; they were present from the first trial in which the eye was impeded. Given that latency was unaffected, it seems unlikely that subjects had any difficulty seeing target motion and extracting useful information from it. Had impeding one eye altered motion thresholds, then we would have expected pursuit latency to be increased. Gross problems seeing motion would have lead to large reductions in pursuit gain with a marked increase in the number of catch-up saccades. Although we examined only the first 300 to 400 msec of pursuit, we would still have expected to see marked qualitative as well as quantitative changes in pursuit in these circumstances. We saw nothing of the sort.

One objection may be that the relatively predictable step–ramp trajectories used in these experiments might allow subjects to compensate for difficulties in perceiving motion, complicating the interpretation of our findings. However, we know from previous experiments[13,14] that there is sufficient temporal uncertainty (by displaying the fixation target for a variable period) and spatial uncertainty (by having targets appear randomly to right and left) to prevent significant prediction and anticipation in the pursuit tasks used in the study. And indeed, over the first few trials of each run, there was no evidence of a systematic decrease in pursuit latency, which would be expected if prediction or anticipation were a feature of these responses.

The velocity 200 msec after pursuit initiation and peak velocity were also reduced when the contralateral eye was impeded. From approximately 100 msec after pursuit is initiated, retinal feedback is available to indicate the accuracy of the pursuit response. This information could, in theory, be used to provide a retinal error signal, indicating that velocity in the free eye was inadequate, thereby allowing a compensatory response to be initiated. We saw no indication of such compensation. There was a reduction in eye velocity of 14% at 200 msec and of 17% and 12% in peak velocity for targets moving to left and right, respectively. However, a number of factors must be borne in mind. With a target velocity of 14 deg/sec the observed reductions in peak eye velocity imply a retinal slip velocity of 1.68 deg/sec and 2.4 deg/sec over, at most, a few tens of milliseconds. It may be that retinal errors of this magnitude are not sufficient to trigger alterations in pursuit. If they had persisted—that is, if we had exposed subjects to longer trajectories of target motion or used higher target velocities—we presume the most likely effect would have been the occurrence of saccades to correct the growing position error. Alternatively, if we had exposed subjects to larger trial numbers we may have observed adaptation of the pursuit system.[17]

van Donkelaar et al.[11] used a suction contact lens system to hold one eye in the primary position during a pursuit visual

adaptation paradigm and demonstrated a modification in the normal adaptive processes. They concluded that nonretinal afferent signals, probably originating in the EOMs, provide information concerning eye and target motion that is necessary for the normal operation of the pursuit system. Although their approach was clearly different from ours, their results appear to be complementary. However, our results also indicate that in addition to providing information used for parametric adaptation of pursuit responses on the time scale of minutes or hours, the nonvisual afferent signal induced by impeding the eye may alter oculomotor responses on-line. We found no evidence that there was any build-up in the velocity reductions we observed; rather, they appeared to be present from the first trial. The detailed velocity analysis we conducted of the first 80 msec of pursuit suggested that within individual trials, effects were manifest within approximately 40 msec of the initiation of smooth pursuit. This is compatible with an afferent signal exerting an effect centrally, and bringing about a reduction in eye velocity. It also implies that both the receptors and the control system are sensitive to small changes in performance. If the effects we observed beginning at 40 msec are based on online detection, then this must occur over the first 10 to 20 msec of each trial. The difference between intended eye position or velocity and actual eye position or velocity is clearly rather small, at least in absolute terms, over this part of the response.

Our results are compatible with the hypothesis that impeding the eye induces a nonvisual afferent signal that indicates to the oculomotor control system that one eye is moving more slowly than it should. The lens we used stands clear of the cornea, contacting the eye at the sclera, and lies under the lid margins. Because the eye carrying the lens was anesthetized in our experiments, although we cannot conclusively rule out scleral or orbital sources, the most likely sources for such a signal are EOM intramuscular receptors. Afferent signals from the EOM are known to carry information concerning eye position and velocity in a wide range of species including those that, like humans, have muscle spindles[18,19] and those that do not.[20,21] These signals are known to alter the central processing of visual, vestibular, and oculomotor information (see Weir et al.[5] for review). Why the response of the oculomotor control system should be to reduce eye velocity in the contralateral eye is unclear. It appears that for pursuit, as with saccades,[10] the priority in these conditions is to maintain conjugacy.

The exact site or sites within the central nervous system where EOM afferent feedback may influence the smooth-pursuit system is not clear. However, the unexpected finding that impeding one eye reduces the drive from the oculomotor system during pursuit strongly parallels our earlier results on saccades. In that study, we found that when one eye was impeded, the saccade amplitude in the other eye was reduced, whereas the main sequence relationships were substantially unaltered. This suggests a signal acting above the brain stem gaze centers, perhaps at the level of the superior colliculus or cerebellum, both of which receive afferent signals from the EOMs.[5,21–24] Of these two, the structure that plays a central role in the control of both saccade amplitude and smooth pursuit is the cerebellum. It is interesting to note that new models of both the saccade[25] and pursuit[26] control systems incorporate cerebellar monitoring of oculomotor performance, with the latter[26] also including a role for EOM proprioception in providing eye position and velocity information by mossy fiber input. Although this model relates to predictive targets rather than the randomized step–ramp target trajectories used in our study, it adds weight to the evidence presented herein that EOM afferent feedback contributes to the generation and control of smooth pursuit eye movements.

There is not necessarily a conflict between our results and data indicating the absence of a monosynaptic stretch reflex in one species of monkey,[27] notwithstanding the recent questioning of the applicability of this to a wider range of species.[28] Neither the results we report here nor our saccade data[10] require monosynaptic brain stem–level interactions; indeed, as argued, they suggest interactions higher up in the hierarchy of oculomotor control structures.

In addition to providing further evidence for the role of EOM afferent signals in human oculomotor control, our results have clinical implications. By impeding the movement of one eye, we have acutely increased the load under which the EOMs operate. This may be analogous to situations in which the function of the EOMs have been altered unilaterally as a result of a pathologic process—for example rectus muscle entrapment after a blow-out fracture. Our findings give some insight into the changes that might occur acutely, as the oculomotor system tries to compensate for any restriction of eye movement. In addition, strabismus surgery involves manipulating, and potentially damaging, the very areas of the EOMs that are richly endowed with sensory receptors. Although surgical procedures have been shown to affect spatial localization,[29] possibly by altering afferent feedback, what effect, if any, they have in modifying subsequent oculomotor control is not known. A better understanding of this may enable further refinements in strabismus surgery.

References

1. Leigh RJ, Zee DS. *The Neurology of Eye Movements*. 3rd ed. New York: Oxford University Press; 1999.
2. Bridgeman B. A review of the role of efference copy in sensory and oculomotor control systems. *Ann Biomed Eng.* 1995;23:409–422.
3. Ruskell GL. Extraocular muscle proprioceptors and proprioception. *Prog Retinal Eye Res.* 1999;18:269–291.
4. Steinbach MJ. Proprioceptive knowledge of eye position. *Vision Res.* 1987;27:1737–1744.
5. Weir CR, Knox PC, Dutton GN. Does extraocular muscle proprioception influence oculomotor control? *Br J Ophthalmol.* 2000; 84:1071–1074.
6. Carpenter RHS. *Movements of the Eyes*. 2nd ed. London: Pion; 1988.
7. Corsi M, Sodi A, Salvi G, Faussone-Pellegrini MS. Morphological study of extraocular muscle proprioceptor alterations in congenital strabismus. *Ophthalmologica.* 1990;200:154–163.
8. Lennerstrand G, Tian S, Han Y. Effects of eye muscle proprioceptive activation on eye position in normal and exotropic subjects. *Graefes Arch Clin Exp Ophthalmol.* 1997;235:63–69.
9. Allin F, Velay JL, Bouquerel A. Shift in saccadic direction induced in humans by proprioceptive manipulation: a comparison between memory-guided and visually guided saccades. *Exp Brain Res.* 1996;110:473–481.
10. Knox PC, Weir CR, Murphy P. Modification of visually guided saccades by a non-visual afferent feedback signal. *Invest Ophthalmol Vis Sci.* 2000;41:2561–2565.
11. van Donkelaar P, Gauthier GM, Blouin J, Vercher JL. The role of ocular muscle proprioception during modifications in smooth pursuit output. *Vision Res.* 1997;37:769–774.
12. Rashbass C. The relationship between saccadic and smooth tracking eye movements. *J Physiol.* 1961;159:326–338.
13. Knox, PC. The effect of the gap paradigm on the latency of human smooth pursuit eye movement. *Neuroreport.* 1996;7:3027–3030.
14. Knox, PC. Stimulus predictability and the gap effect on smooth pursuit. *Neuroreport.* 1998;9:809–812.
15. O'Mullane G, Knox PC. Modification of smooth pursuit initiation by target contrast. *Vision Res.* 1999;39:3459–3464.
16. Al-Hinnawi M, Barbenel J, Al-Qurainy I, Dutton G. Quantitative mechanical assessment of the extraocular muscles. *Proc Inst Mech Eng.* 1991;205:101–108.

17. Fukushima K, Tanaka M, Suzuki Y, Fukushima J, Yoshida T. Adaptive changes in human smooth pursuit eye movement. *Neurosci Res.* 1996;25:391–398.
18. Cooper S, Daniel PM, Whitteridge D. Nerve impulses in the brainstem of the goat: short latency responses obtained by stretching the extrinsic eye muscles and the jaw muscles. *J Physiol* (*Lond*). 1953;120:471–490.
19. Cooper S, Fillenz M. Afferent discharges in response to stretch from the extraocular muscles of the cat and monkey and the innervation of these muscles. *J Physiol* (*Lond*). 1955;127:400–413.
20. Fahy FL, Donaldson IM. Signals of eye position and velocity in the first-order afferents from pigeon extraocular muscles. *Vision Res.* 1998;38:1795–1804.
21. Abrahams VC, Rose PK. Projections of extraocular, neck muscle, and retinal afferents to superior colliculus in the cat: their connections to cells of origin of tectospinal tract. *J Neurophysiol.* 1975; 38:10–18.
22. Donaldson IM, Long AC. Interactions between extraocular proprioceptive and visual signals in the superior colliculus of the cat. *J Physiol* (*Lond*). 1980;298:85–110.
23. Baker R, Precht W, Llinas R. Mossy and climbing fiber projections of extraocular muscle afferents to the cerebellum. *Brain Res.* 1972;38:440–445.
24. Kimura M, Takeda T, Maekawa K. Contribution of eye muscle proprioception to velocity-response characteristics of eye movements: involvement of the cerebellar flocculus. *Neurosci Res.* 1991;12:160–168.
25. Quaia C, Lefevre P, Optican LM. Model of the control of saccades by superior colliculus and cerebellum. *J Neurophysiol.* 1999;82: 999–1018.
26. Kettner RE, Mahamud S, Leung HC, et al. Prediction of complex two-dimensional trajectories by a cerebellar model of smooth pursuit eye movement. *J Neurophysiol.* 1997;77:2115–2130.
27. Keller EL, Robinson DA. Absence of a stretch reflex in extraocular muscles of the monkey. *J Neurophysiol.* 1971;34:908–919.
28. Mon-Williams M, Tresilian J. A framework for considering the role of afference and efference in the control and perception of ocular position. *Biol Cybern*. 1998; 79:175–189.
29. Steinbach MJ, Smith DR. Spatial localization after strabismus surgery: evidence for inflow. *Science* 1981;213:1407–1409.