Modeling of Smooth Pursuit-Related Neuronal Responses in the DLPN and NRTP of the Rhesus Macaque

Seiji Ono,1 Vallabh E. Das,1,2 John R. Economides,3 and Michael J. Mustari1,2

1Division of Visual Science, Yerkes National Primate Research Center and 2Department of Neurology, Emory University, Atlanta, Georgia; and 3Beckman Vision Center, University of California, San Francisco, California

Submitted 8 June 2004; accepted in final form 13 August 2004

Ono, Seiji, Vallabh E. Das, John R. Economides, and Michael J. Mustari. Modeling of smooth pursuit-related neuronal responses in the DLPN and NRTP of the rhesus macaque. J Neurophysiol 93: 108–116, 2005. First published August 18, 2004; doi:10.1152/jn.00588.2004. The dorsolateral pontine nucleus (DLPN) and nucleus reticularis tegmenti pontis (NRTP) comprise obligatory links in the cortico-ponto-cerebellar system supporting smooth pursuit eye movements. We examined the response properties of DLPN and NRTP neurons during step-ramp smooth pursuit of a small target moving across a dark background. Our neurophysiological studies were conducted in awake, behaving juvenile macaques (Macaca mulatta). We used multiple linear-regression modeling to estimate the relative sensitivities of neurons to eye parameters (position, velocity, and acceleration) and retinal-error parameters (position, velocity, and acceleration). We found that a large proportion of pursuit-related DLPN neurons primarily code eye-velocity information, whereas a large proportion of NRTP neurons primarily code eye-acceleration information. We calculated the relative decrease in variance found when using a six-component model that included both eye- and retinal-error parameters compared with three-component models that include either eye or retinal error. These comparisons show that a majority of DLPN (14/20) and NRTP (17/19) neurons have larger contributions from eye compared with retinal-error parameters (P < 0.001, paired t-test). Even though eye-motion parameters provide the strongest contributions in a given model, a significant contribution from retinal error was often present (i.e., >20% reduction in variance in 6-component model compared with 3-component models). Thus our results indicate that the DLPN plays a larger role in maintaining steady-state smooth pursuit eye velocity, whereas NRTP contributes to both the initiation and maintenance of smooth pursuit.

INTRODUCTION

The dorsolateral pontine nucleus (DLPN) and the nucleus reticularis tegmenti pontis (NRTP) are major components of the cortico-ponto-cerebellar pathway (Distler et al. 2002; Glickstein et al. 1994; May and Andersen 1986), which plays an essential role in smooth pursuit and gaze control (Mustari et al. 1988; Ono et al. 2004; Suzuki and Keller 1984; Suzuki et al. 2003; Thier et al. 1988). The DLPN receives visual inputs from the extrastriate cortex (Distler et al. 2002; Glickstein et al. 1980, 1994; May and Andersen 1986) and sends mossy fiber projections to the contralateral ventral paraflocculus and dorsal paraflocculus (Glickstein et al. 1994; Nagao et al. 1997) and vermal lobules VI and VII (Brodal 1979, 1982; Langer et al. 1985). The NRTP is known to receive inputs from the frontal eye fields (FEF) and supplementary eye fields (SFE) (Brodal 1980a; Giolli et al. 2001; Huerta et al. 1986; Kunzle and Akert 1977; Shook et al. 1990) and sends mossy fiber projection to the vermal lobules VI and VII (Brodal 1980b, 1982). Previous lesion and electrical stimulation studies established the DLPN and rostral region of the nucleus reticularis tegmenti pontis (rNRTP) as being primarily involved in smooth pursuit eye movements (May et al. 1988; Ono et al. 2003; Suzuki et al. 1999; Yamada et al. 1996). Further evidence for postulating an expanded role of DLPN and NRTP in eye movements comes from single-unit studies (Mustari et al. 1988; Ono et al. 2004; Suzuki and Keller 1984; Suzuki et al. 2003; Thier et al. 1988). These single-unit recording studies show that different DLPN and NRTP neurons could be classified as preferentially sensitive to smooth pursuit eye velocity, position, or acceleration.

Recently, using sinusoidal visual and vestibular stimuli, we have shown that a large proportion of DLPN and NRTP smooth-pursuit neurons encode gaze movements with a small contribution from retinal error (Ono et al. 2004). However, the predictability and steady-state nature of sinusoidal stimuli tends to obscure relative contributions of motion parameters during the different stages of tracking (for example: smooth-pursuit initiation vs. smooth-pursuit maintenance). Two issues that remained unresolved due to the steady-state nature of sinusoidal testing was whether contribution of retinal error was masked and whether DLPN and NRTP neurons evinced relatively different sensitivity to position, velocity, and acceleration components of the stimulus. Therefore in this study, we further examined the role of the DLPN and NRTP during step-ramp smooth pursuit by applying a modeling procedure employing multiple linear-regression. The main aims of this study were to establish whether the smooth pursuit-related neurons in DLPN and NRTP show significant sensitivity to eye and retinal-error motion parameters during step-ramp tracking and to identify relative contributions of parameters of motion (position, velocity, and acceleration) toward the unit response.

METHODS

Surgical procedures

A detailed description of our surgical procedures can be found in earlier publications (Mustari et al. 1988, 1997, 2001). Behavioral and single-unit data were collected from two normal juvenile rhesus monkeys (Macaca mulatta) weighing 4–5 kg. Surgical procedures,
carried out under aseptic conditions using isoflurane anesthesia (1.25–2.5%), were used to stereotaxically implant a stainless steel head-stabilization post (Crist Instruments) and stainless steel recording chambers. In the same surgery, a scleral search coil for measuring eye movements (Fuchs and Robinson 1966) was implanted underneath the conjunctiva of one eye using the technique of Judge et al. (1980). All surgical procedures were performed in strict compliance with National Institutes of Health guidelines and the protocols were reviewed and approved by the Institutional Animal Care and Use Committee at Emory University.

Behavioral paradigms

During all experiments, monkeys were seated in a chair with the head stabilized in the horizontal stereotaxic plane. Neurons in the DLPN and rNRTP were first classified as visual or smooth-pursuit related. We tested neurons for visual sensitivity by requiring the monkey to fixate a stationary target while a large-field visual stimulus was moved in eight cardinal directions separated by 45°. Only neurons that responded during horizontal or vertical smooth pursuit of a small-diameter (0.2°) target spot moving at low frequency (0.1–0.75 Hz; ±10°) were included in this study. All neurons were tested as monkeys tracked a target that moved with a step-ramp trajectory with a constant velocity ramp (10–30°/s) over a dark background. The size of the step was adjusted so that smooth pursuit was initiated without initial saccades (Rashbass 1961). Usually the size of the step was between 2 and 4°. Data collected during step-ramp testing were used for the model fitting procedure described in the following text.

Data collection

Eye movements were detected and calibrated using standard electromagnetic methods (Fuchs and Robinson 1966) using precision hardware (CNC Electronics, Seattle, WA). Motion of the laser spot was controlled by a two-axis mirror galvanometer (General Scanning, Watertown MA). Stimulus motion was controlled with custom Labview software and National Instruments hardware (Austin, TX). Eye- and target-position feedback signals were processed with anti-aliasing filters at 200 Hz using six-pole Bessel filters prior to digitization at 1 kHz with 16-bit precision. Velocity data were generated by digital differentiation of position data using a central difference algorithm in Matlab (Mathworks, Natick, MA). Unit activity was recorded using custom-made glass-coated tungsten electrodes or modified commercial epoxy-coated tungsten (Frederick-Haer, Brunswick, ME). The impedance of the electrodes was in the 1- to 3-MΩ range. Single-unit action potentials were detected with either a window discriminator (Alpha-Omega, Israel) and represented by a TTL pulse that was generated by 10.220.33.6 on May 26, 2017 http://jn.physiology.org/ Downloaded from

Modeling responses in rhesus macaque DLPN and NRTP

The data were collected from 10 monkeys that performed the smooth pursuit task described above. The monkeys were trained to perform the task for 20–30 min each day. The task was divided into two phases: the null phase, in which the monkey was required to track a moving target, and the stimulus phase, in which the monkey was required to track a static target. The monkeys were rewarded with food for correct performance. The data were collected at the conclusion of each training session.

We used a model estimation procedure to identify smooth pursuit-related signals in DLPN or rNRTP during step-ramp tracking. Briefly, we attempted to reconstruct the individual response profiles of smooth pursuit-related neurons by using combinations of position, velocity, and acceleration. Similar procedures have been used with success in other parts of the oculomotor system including the cerebellum, oculomotor nuclei, the pretectal nucleus of the optic tract (NOT), and MST cortex (Das et al. 2001; Inoue et al. 2000; Shidara et al. 1993; Sylvestre and Cullen 1999). Velocity data were filtered using an 80-point finite impulse response (FIR) digital filter with a passband of 50 Hz, and acceleration data were filtered using an 80-point FIR digital filter with a passband of 30 Hz. The spike density function was also filtered at 50 Hz to reduce the variability in the unit response. Saccades were marked with a cursor on eye-velocity traces and were removed. After desaccading, the missing eye data were replaced with a linear fit connecting the pre- and post-saccadic regions of data using custom Matlab routines (Mathworks). Averaged data, taken from ≥10 trials in which the animal performed smooth pursuit, were then used to identify coefficients in the following model

\[ FR(t - \tau) = A + BE(t) + CE(t) + DE(t) \]  
\[ FR(t - \tau) = A + BR(t) + CR(t) + DR(t) \]  
\[ FR(t) = A + BE(t + \tau) + CE(t + \tau) + DE(t + \tau) \]  
\[ + BR(t + \tau) + CR(t + \tau) + DR(t + \tau) \]  

In the preceding equations, \( t \) denotes the eye position at time \( t \), \( R(t) \) denotes the retinal error position at time \( t \), and \( FR(t) \) is the estimated value of the unit spike density function at time \( t \). Coefficients in the models are defined by terms \( A, B, C, D, E, F, \) and \( G \). Therefore model 1 attempts to relate unit response to eye-motion parameters, whereas model 2 attempts to relate unit response to retinal-error motion parameters and model 3 attempts to relate unit response to a combination of eye- and retinal-error motion parameters. The latency value of the unit response with respect to pursuit (eye) onset and retinal...
error onset is represented by the “τ₁” and “τ₂” terms, respectively. τ₂ was calculated from the data as the latency between onset of target motion and the onset of unit response. While it appeared safe to assume that the initial part of the unit response was due to retinal error motion and the onset of unit response. This led to a certain ambiguity in calculating τ₁ directly from the experimental data. We therefore calculated a set of coefficients (A–G) and estimated coefficients of determination (CD) for a series of τ₂ latencies in steps of 5 or 10 ms (Fig. 2Bi). In our final model, we used coefficients that yielded a maximum CD for a specific eye latency value (Fig. 2Bi, · · · ).

Retinal error parameters were calculated as the difference between target- and eye-motion parameters. Because NRTP and DLN units are generally unresponsive to large velocities, the impulse in target velocity due to differentiation of the step in target position was removed in software prior to presenting the data to the modeling algorithm. Further, target acceleration was assumed as 0°/s² because differentiation of a step in target velocity results in zero steady-state target acceleration.

We calculated the relative decrease in variance of the six-component model (model 3) compared with the three-component model for eye (model 1) or retinal error (model 2) using the following indices

\[
\text{Formula 1} = \frac{\text{Residual}_{\text{model 1}} - \text{Residual}_{\text{model 3}}}{\text{Residual}_{\text{model 1}}}
\]

\[
\text{Formula 2} = \frac{\text{Residual}_{\text{model 2}} - \text{Residual}_{\text{model 3}}}{\text{Residual}_{\text{model 2}}}
\]

Therefore formula 1 indicates the relative decrease in variance of the model 3 compared with the eye model, while, formula 2 indicates the relative decrease in variance of the model 3 compared with the retinal-error model.

We also calculated partial \( r^2 \) values for each component (eye and retinal-error position, velocity, and acceleration) to estimate the relative contribution of eye and retinal-error position, velocity, and acceleration to the firing rate of the neuron in DLN and rNRTP. All statistical tests were executed with a significance value of 0.05 unless otherwise specified.

**Results**

Response properties of DLN neurons during step-ramp tracking

We recorded 20 smooth pursuit-related neurons in DLN during step-ramp tracking. As in previous studies, we found individual DLN neurons had preferred directions that could be horizontal, vertical, or oblique (Mustari et al. 1988; Suzuki et al. 1990; Thier et al. 1988). Figure 2 illustrates the response of a representative neuron in DLN. Unit response lags the onset of target motion by 74 ms and leads onset of eye motion by an average of 60 ms. The figure shows that the neuron is most likely a velocity sensitive and is well modulated during step-ramp tracking with a rightward (contralateral) preference. The model estimation procedure for the unit of Fig. 2A is shown in Fig. 2B, a–h. Figure 2B, a–f, illustrates the compo-
ponents that were used to make up the model, g illustrates the contribution of each term of the model toward the total fit, and h illustrates the experimentally derived unit spike-density function and the corresponding model estimated fit. The fit obtained using this six-component model had a coefficient of determination of 0.88. Examination of each component of this model (Fig. 2Bg) indicates that velocity contributes most to the unit response during step-ramp tracking, whereas contributions of position and acceleration are relatively small. Figure 2Bi shows how we selected the value to use for \( \tau_1 \). For example, if \( \tau_1 \) was derived from the observed response at −60 ms (i.e., latency between onset of unit response and onset of eye motion), the CD was less than that obtained when using a \( \tau_1 \) value of −50 ms where the CD reached a maximum (Fig. 2Bi, ····). We always used the \( \tau_1 \) associated with the highest CD to conduct our modeling of eye motion. Therefore for the example neuron in Fig. 2 the first 10 ms of the unit response was due to retinal-error motion; thereafter unit response was due to a combination of retinal-error and eye motion.

Response properties of NRTP neurons during step-ramp tracking

We recorded 19 smooth pursuit-related neurons in rNRTP during step-ramp tracking. The preferred smooth pursuit directions for rNRTP neurons were distributed around the clock as reported in previous studies (Suzuki et al. 2003) Fig. 3A illustrates the response of a representative rNRTP neuron. The figure shows that the neuron is well modulated during step-ramp tracking with a rightward (ipsilateral) preference. Unit response lags the onset of target motion by 73 ms and leads onset of eye motion by 24 ms. The model estimation procedure for the unit illustrated in Fig. 3A is shown in B. Figure 3B, a–f, illustrates the contribution of components that were used to make up the models, g illustrates the contribution of each term of the model toward the total unit response, and h illustrates the experimentally derived unit spike density function and the corresponding model estimated fit. The six-component model provided a good fit to the experimental derived data (CD = 0.87). Examination of each component of this model (Fig. 3Bg) indicates that eye-acceleration sensitivity contributes strongly to the initial part of the step-ramp tracking and eye-position sensitivity contributes more to the steady-state part of the step-ramp tracking. Figure 3Bi shows the effect of changing the value of \( \tau_1 \). If \( \tau_1 \) was calculated from the actual observed response of −24 ms, the CD obtained was less than that obtained using −14 ms where the CD reached a maximum value (Fig. 3Bi, ····).

Figure 4 illustrates an rNRTP neuron with strong acceleration sensitivity. The figure shows that the neuron is well modulated during initial part of step-ramp tracking with a rightward (ipsilateral) preference (Fig. 4A). Unit response lags the onset of target motion by 64 ms and leads onset of eye motion by 32 ms. Our model estimation procedure for this unit is shown in Fig. 4B. The fit obtained using this six-component model had a coefficient of determination of 0.84. Examination of Fig. 4Bg indicates that the eye-acceleration component contributes most to the unit response during step-ramp tracking.
FIG. 4. Response of a representative rNRTP neuron with acceleration sensitivity during step-ramp tracking. Data are aligned on target motion onset. See Fig. 2 for description of panels. The equation for the best fit in h is FR(t) = 2.96 + 26.3E(t - 27) - 6.41E(t - 27) + 1.16E(t - 27) + 9.01R(t + 64) + 1.40R(t + 64) - 0.01R(t + 64).

Comparison of model testing between DLPN and NRTP

The six-component model provided a good fit to the experimental-derived data in DLPN (CD = 0.86 ± 0.11; n = 20) and rNRTP (CD = 0.83 ± 0.08; n = 19). We also calculated the relative decrease in variance of the six-component model (model 3) compared with the three-component model for eye (model 1) or retinal error (model 2). This served as a method to estimate the relative contribution of eye- and retinal-error parameters to the neurons. Figure 5 plots this data for DLPN and rNRTP. The comparison of this values between eye and retinal error parameters (Fig. 5A) indicates that a large proportion of DLPN neurons (14/20) have larger contributions from eye motion (0.65 ± 0.24; n = 14) compared with retinal error motion (0.25 ± 0.21; n = 14) parameters (P < 0.001, paired t-test). The same type of comparison between eye and retinal error for rNRTP neurons is shown in Fig. 5B. We found that most of rNRTP neurons (17/19) in our sample had larger contributions from eye motion (0.48 ± 0.16; n = 17) compared with retinal error motion (0.23 ± 0.14; n = 17) parameter (P < 0.001, paired t-test). However, even though eye-motion parameters provide the strongest contributions in a given model, a significant contribution from retinal-error motion is shown in Fig. 5. A and B (dotted lines; >20% reduction in variance in 6-component model compared with 3-component models).

To show the differential sensitivity of DLPN and rNRTP neurons to individual components, we plotted the distribution of partial $r^2$ values for eye- and retinal-error position, velocity, and acceleration. Figure 6 illustrates the distribution of partial $r^2$ values for each parameter in each DLPN neuron. The majority of DLPN neurons have the largest contributions from eye velocity compared with eye position or eye acceleration (Fig. 6, A–C). Median partial $r^2$ values in DLPN for eye velocity (0.12, n = 20) are larger than eye position (0.08, n = 20) or eye acceleration (0.02, n = 20; P < 0.05, 1-way ANOVA on ranks). Similar comparisons of partial $r^2$ values for retinal-error position, velocity, and acceleration are shown in Fig. 6, D–F. The contribution of retinal error acceleration (median value = 0.02) is smaller than retinal error position (median value = 0.09) or velocity (median value = 0.10; P < 0.05, 1-way ANOVA on ranks). In contrast, the distribution of partial $r^2$ values for rNRTP neurons indicates that eye acceleration makes the largest contribution compared with eye position or eye velocity (Fig. 7, B and C). Median partial $r^2$ values for rNRTP indicate that eye acceleration (0.22, n = 19) makes a larger contribution than eye position (0.11, n = 19) or velocity (0.07, n = 19; P < 0.01, 1-way ANOVA on ranks). Similar comparisons of partial $r^2$ values for retinal error position (median value = 0.03), velocity (median value = 0.07), and acceleration (median value = 0.04) indicate that rNRTP neurons have small contributions from these parameters (Fig. 7, D–F).

DISCUSSION

The major goal of this study was to determine whether neurons in rNRTP and DLPN carry different signals that could support different aspects of smooth pursuit. To quantitatively estimate the signal content of rNRTP and DLPN neurons, we employed multiple, linear-regression modeling of neuronal responses during step-ramp smooth pursuit. Testing during step-ramp tracking allows us to examine the relative contributions of eye and retinal-error position, velocity, and acceleration. This is because step-ramp tracking in contrast to sinusoidal testing readily separates position, velocity, and acceleration components of target or eye. We found that most smooth pursuit-related neurons in rNRTP and DLPN have complex properties encoding both eye motion and retina-error motion. Further, examination of partial $r^2$ values for each component indicates that pursuit related DLPN neurons...
primarily code eye velocity, whereas rNRTP neurons primarily code eye acceleration.

Sensitivity to eye motion and retinal-error motion

Multiple lines of evidence suggested to us that there might be differences in smooth pursuit-related signal content of individual rNRTP and DLPN neurons and therefore net differences in the information delivered to the cerebellum from these pontine centers. First, previous single-unit recording studies described different balances in visual-, smooth-pursuit-, and eye-position-related neuronal types in NRTP and DLPN (Mustari et al. 1988; Ono et al. 2004; Suzuki and Keller 1984, 2003; Their et al. 1988). The distributions of directional preference and speed tuning in NRTP and DLPN neurons show considerable overlap. However, the NRTP appears to have a bias in the proportion of neurons with acceleration sensitivity (Suzuki et al. 2003). Second, recent anatomical studies have shown that different regions of the cerebellum project to the NRTP and DLPN (Brodal 1980a; Distler et al. 2002; Giolli et al. 2001; Glickstein et al. 1994; Huerta et al. 1986; Kunzle and Akert 1977; Shook et al. 1990). NRTP receives stronger input from the FEFs than from MT or MST cortex. In contrast, DLPN received stronger inputs from MST than MT cortex (e.g., Distler et al. 2002). Each of these cortical areas is known to contain neurons that are modulated during smooth pursuit. However, MT, MST, and FEF smooth-pursuit-related neurons appear to support different aspects of smooth pursuit (Fukushima 2003; Wurtz et al. 1990). For example, MT lesions produce retinotopic pursuit deficits while MST and FEF lesions produce directional pursuit deficits.

Differential effects of cortical lesions on smooth pursuit may relate to the progression from sensation to action thought to occur at least in part in MT, MST, and FEF cortical areas. Specifically, MT may function primarily as a necessary visual sensory area working with MST and FEF to produce a partially formed smooth-pursuit command. Previous studies (Newsome et al. 1988) established that the pursuit response of MT neurons depends on visual motion on the retina by the pursuit target, whereas the pursuit response of the dorsal-medial region of MST (MSTd) neurons included extraretinal component of unknown origin. Recent studies have shown that smooth-pursuit-related neurons in FEF, like those in MSTd, maintain their firing in the absence of a visual target during smooth pursuit (Tanaka and Fukushima 1998). The source of this extraretinal signal is a topic of considerable interest. Extraretinal (nonvisual) signals could reach cortex by corollary discharge traveling from brain stem centers through oculomotor thalamus. Alternatively, some cortical areas may construct a nonvisual signal to support smooth pursuit for brief time periods, as would be required to track a target that is briefly occluded in a complex visual environment (e.g., Churchland et al. 2003). It is likely, that different cortical areas have different balances of nonvisual signals and that both visual and smooth-pursuit-related signals travel from cortex to different regions of the cerebellum by way of different neurons in NRTP and DLPN.

Sensitivity to position, velocity, and acceleration

The earlier NRTP and DLPN smooth pursuit studies mentioned in the preceding text did not include statistical modeling. Because pontine neurons often evoke multiple sensitivities, we wanted to specifically examine the potential contributions of position, velocity, and acceleration due to eye or retinal image motion while tracking a target spot. We found that DLPN and rNRTP neurons appear to receive different contributions of position, velocity, and acceleration signals. Therefore we calculated the coefficients of partial determination (partial $r^2$ values) to determine the relative importance of each term. The partial $r^2$ values for DLPN neurons show that velocity makes a larger contribution than position or acceleration. In contrast, partial $r^2$ values for rNRTP neurons show that acceleration makes a larger contribution to unit response than position or velocity. However, the other terms in our models for both DLPN and rNRTP neurons suggest that position and velocity make small but significant contributions.
to overall response during smooth pursuit. We suggest that different biases of acceleration and velocity sensitivity could be associated with different roles in initiation (rNRTP) and maintenance (DLPN) of smooth pursuit. It is important to note that we specifically chose to model smooth-pursuit-related neurons and did not model neurons that were sensitive to visual motion alone. Kawano and colleagues (1992) have conducted modeling studies of DLPN neurons that respond to large-field visual motion that produces short-latency ocular following and found them to be strongly related to retinal image motion. Similarly, neurons in the pretectal nucleus of the optic tract (NOT) are best modeled using retinal-error parameters during either ocular following (Inoue et al. 2000) or smooth pursuit (Das et al. 2001). Our results indicate that neurons in both rNRTP and DLPN carry, at least, a partially formed smooth-pursuit command to the cerebellum.

Anatomical studies show that the NRTP projects most strongly to the vermis (lobules VI and VII) and DLPN to the ventral parafloculus and flocculus (Brodal 1982; Glickstein et al. 1994; Langer et al. 1985). Lesion studies have demonstrated differential effects of lesions in different regions of oculomotor cerebellum that receive input from rNRTP and DLPN. For example, recent study (Takagi et al. 2000) has demonstrated the lesions of oculomotor vermis (lobules VI and VII) produce the most significant deficits in the open-loop rather than closed-loop portions of smooth pursuit. In contrast, Stone and Lisberger (1990) found that lesions of the flocculus had a profound effect on the closed-loop portion of smooth pursuit. When both flocculus and ventral paraflocculus were damaged, deficits in initiation and maintenance of smooth pursuit were reported (Rambold et al. 2002).

Our modeling studies and single-unit studies of Suzuki and colleagues (2003) strongly suggest that the rNRTP is a likely source of acceleration-related signals for the cerebellar vermis. These signals would be expected to have the largest impact on the initiation of smooth pursuit, where eye acceleration is required. In contrast, the DLPN is dominated by eye-velocity-related neurons that could provide the flocculus and ventral paraflocculus with signals appropriate for maintaining the closed-loop portion of smooth pursuit.
Conclusion and future studies

In conclusion, we have shown that the neurons in the rNRTP and DLPN with smooth-pursuit-related activity during step-ramp tracking are primarily encoding aspects of eye motion with secondary contributions from retinal-error motion, unlike the neurons in the NOT. These different functional roles may in part reflect different balances of cortical input to NRTP and DLPN neurons, thus allowing rNRTP and DLPN to play crucially different functional roles in the initiation, maintenance, and control of smooth eye movements. Our results support the suggestion that the rNRTP may play a larger role in the initiation, whereas DLPN contributes to maintaining steady-state eye velocity during smooth pursuit. One of the most important unresolved questions regarding NRTP, DLPN, and basilar pontine function in general is whether these areas simply relay signals to the cerebellum or whether significant processing occurs in the basilar pontine nuclei per se (see Schwarz and Thier 1999 for review). Given the multiple cortical inputs to each area, it seems likely that signal integration in the basilar pons is possible. By performing modeling studies like those reported here, we should be able to compare the properties of neurons in cortex, basilar pons, and cerebellum for evidence of signal transformation. Further studies will be required to consider the role of basilar pontine neurons not only in relatively simple position, velocity, and acceleration coding for smooth pursuit but also in more complex processing associated with, e.g., decision making and reward, that could be modulated, at least in part, in cortico-ponto-cerebellar circuits.

ACKNOWLEDGMENTS

We thank T. Brozyna for expert technical assistance.

GRANTS

This work was supported by National Institutes of Health Grants EY-06069, EY-13308, and RR-00165.