Comparing Extraocular Motoneuron Discharges During Head-Restrained Saccades and Head-Unrestrained Gaze Shifts

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Cullen, Kathleen E., Henrietta L. Galiana, and Pierre A. Sylvestre. Comparing extraocular motoneuron discharges during head-restrained saccades and head-unrestrained gaze shifts. *J. Neurophysiol.* 83: 630–637, 2000. Burst neurons (BNs) in the paramedian pontine reticular formation provide the primary input to the extraocular motoneurons (MNs) during head-restrained saccades and combined eye-head gaze shifts. Prior studies have shown that BNs carry eye movement–related signals during saccades and carry head as well as eye movement–related signals during gaze shifts. Therefore MNs receive signals related to head motion during gaze shifts, yet they solely drive eye motion. Here we addressed whether the relationship between MN firing rates and eye movements is influenced by the additional premotor signals present during gaze shifts. Neurons in the abducens nucleus of monkeys were first studied during saccades made with the head stationary. We then recorded from the same neurons during voluntary combined eye-head gaze shifts. We conclude that the activity of MNs, in contrast to that of BNs, is related to eye motion by the same dynamic relationship during head-restrained saccades and head-unrestrained gaze shifts. In addition, we show that a standard metric-based analysis [i.e., counting the number of spikes (NOS) in a burst] yields misleading results when applied to the same data set. We argue that this latter approach fails because it does not properly consider the system's dynamics or the strong interactions between eye and head motion.

INTRODUCTION

To generate saccadic eye movements, motoneurons (MNs) are required to provide signals to the extraocular muscles to overcome the restraining forces of the orbital tissues. The schema shown in Fig. 1*A* illustrates the classic model for saccade generation. There are two main features to this circuit: first, the output of the oculomotor burst neurons (BNs) of the paramedian pontine reticular formation drives the MNs during saccades. Second, the output of the BNs is also sent to the neural integrator (NI), which in turn provides the MNs with the tonic signal that holds the eye steady in its new post-saccadic position. In the most prominent version of this model, an eye position signal (E) and an eye velocity signal ($\dot{E}$) are carried to the MNs by the NI and BNs, respectively. Because the primary drive to MNs during saccades is from BNs, the integrated firing rate of a BN [i.e., the number of spikes (NOS) generated during the saccade-related burst] should be well related to the integral of the accompanying saccadic eye velocity profile (i.e., the amplitude of the saccade). Indeed, a number of studies have reported a strong relationship between BNs-NOS and saccade amplitude in head-restrained animals, where saccade size and duration are relatively small (Cullen and Guitton 1997a; Scudder et al. 1988; Strassman et al. 1986a,b). In this special case, the NOS generated by MNs is similarly related to saccade amplitude (Sylvestre and Cullen 1999).

Under natural conditions, where the head is not restrained, a combination of rapid eye and head movements [i.e., a gaze shift, where gaze (G) = eye-in-head (E) + head-in-space (H)] is frequently used to redirect the visual axis in space (humans: André-Deshays et al. 1988; Barnes 1979; Guitton and Volle 1987; Laurutis and Robinson 1986; Pélisson et al. 1988; Zangemeister and Stark 1982a,b; and monkeys: Bizzi et al. 1971; Crawford et al. 1999; Dichgans et al. 1973; Morasso et al. 1973; Tomlinson 1990; Tomlinson and Bahra 1986a,b). Here, the size and duration of gaze shifts can be much larger than during head-restrained saccades. Recent studies of BN discharge dynamics have demonstrated that most BNs carry head as well as eye movement–related signals during gaze shifts (Cullen and Guitton 1997b). However, BNs provide a primary input to the extraocular MNs during head-restrained saccades (reviewed in Moschovakis et al. 1996), and combined eye-head gaze shifts (Cullen and Guitton 1997a,b; Roy and Cullen 1998). Thus during gaze shifts, MNs receive a signal that is related to head as well as eye motion, but ultimately drive the extraocular muscles of the eyes alone.

It is therefore logical to ask whether an analysis of MNs would reveal that these neurons' discharges during gaze shifts are best correlated with eye motion (as predicted by their projections) or with gaze motion (as predicted by their input). On the one hand, because MNs ultimately drive the extraocular muscles of the eyes alone, it might be expected that they should encode only eye movement-related signals during gaze shifts, and that the input/output relationship between extraocular motoneuron activity and eye motion should be comparable with that observed during saccades. If this is the case, then the head movement–related signal carried to the abducens nucleus by BNs must be subtracted out at the level of the MNs by the inputs of other premotor cells. On the other hand, it is also possible that the input/output relationship between extraocular motoneuron activity and eye motion is altered during gaze shifts. For example, during gaze shifts, agonist and antagonist MN pools might carry comparable head movement–related signals, which are later subtracted out via agonist/antagonist muscle interactions in the orbit. In a preliminary report, Phillips and colleagues (1996) presented data from a single abducens nucleus neuron that showed qualitatively similar burst-tonic and pause activity for saccades and gaze shifts in the ipsilateral (ON) and contralateral (OFF) directions, respectively. More recently, they performed a metric (i.e., NOS-based)

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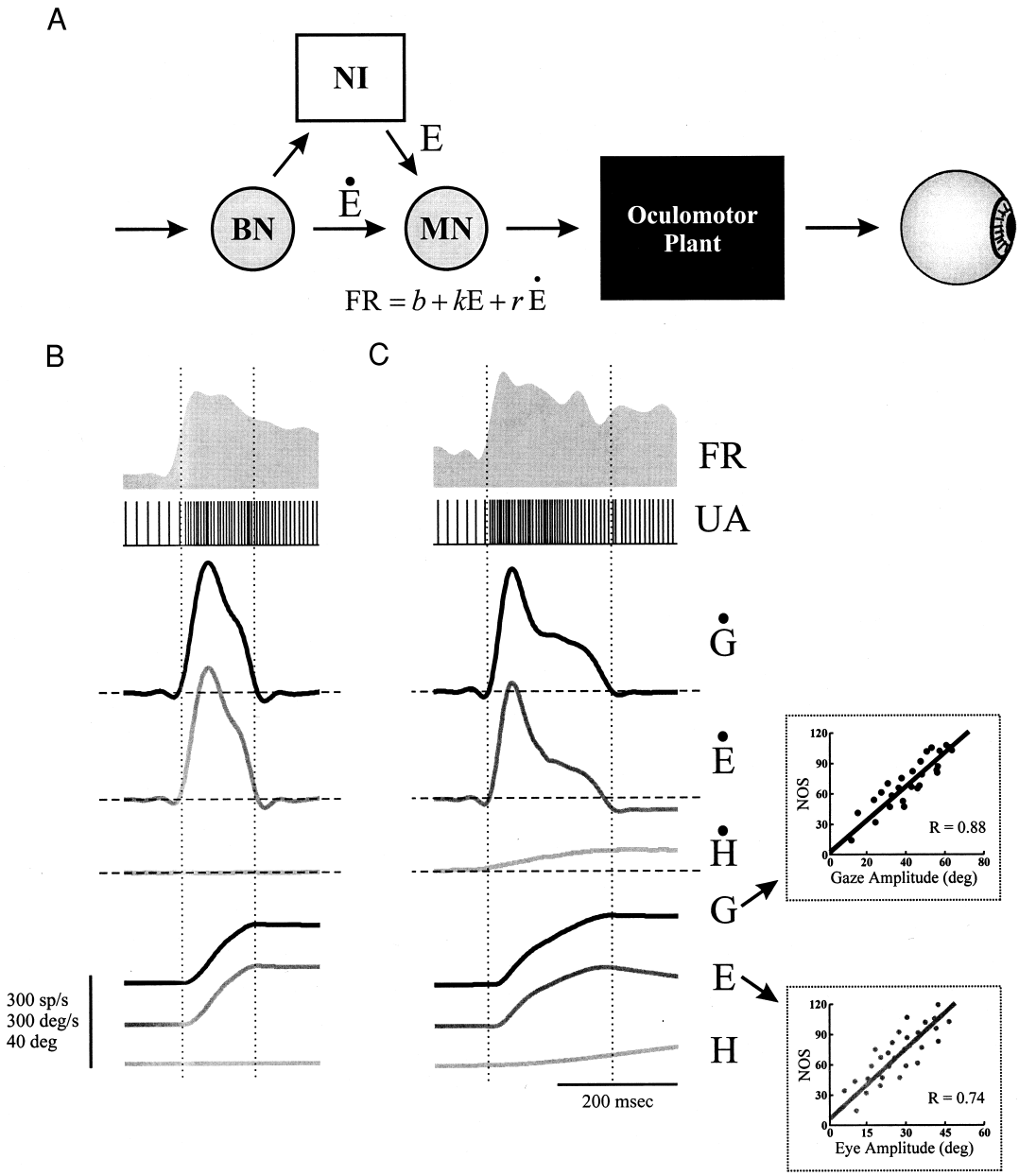

FIG. 1. *A*: the classic model for saccade generation by the brain stem. The equation describes the signal (FR) that would be encoded by the motoneurons (MNs) according to this schema (*b* is a bias term that represents the MNs resting discharge when looking straight ahead; *k* and *r* are constants). *B* and *C*: the discharge behavior of a typical neuron in the abducens nucleus (ABN; *unit B90__3*) during a horizontal saccade in the head-restrained condition (*B*), and during a combined eye-head gaze shift (*C*). Gaze position (G) = position of the visual-axis-in-space = eye-in-head position (E) + head-in-space position (H). Vertical dotted lines indicate the onset and offset of the saccade (*B*) and gaze shift (*C*), and the horizontal broken lines indicate zero velocities. FR, spike density; UA, unit activity; Ġ, Ė, Ḣ, gaze, eye, and head velocities, respectively. *Insets* in *C* illustrate the relationships for our example neuron between the number of spikes in a burst (NOS) and *1*) the amplitude of the gaze shift (*top*) and *2*) the amplitude of the ocular component of the gaze shift (*bottom*). Accompanying eye, head, and gaze, position and velocity trajectories have been shifted in time by t_d.

analysis of abducens nucleus neuron (ABN) ON direction discharges during gaze shifts (Ling et al. 1999a,b). However, the question of whether neuronal activity and eye motion are related by the same dynamic relationship during head-restrained saccades and head-unrestrained gaze shifts has remained unanswered.

In the present study, we addressed this question by recording from the same ABNs during both saccades and gaze shifts. Neuronal discharges were analyzed using two different approaches. First, a metric analysis method (i.e., counting the NOS) was used to determine whether the discharges of neurons in the abducens nucleus were better related to eye or gaze movement (i.e., eye or gaze amplitude). This analysis approach has been commonly used by oculomotor researchers to study brain stem mechanisms of saccade generation (see reviews from Fuchs et al. 1985; Hepp et al. 1989; Moschovakis et al. 1996). Second, a dynamic analysis method was also applied to the same neural discharges during saccades and gaze shifts, by

postulating a simple first-order model (FR = $b + k\mathrm{E} + r\dot{\mathrm{E}}$, Fig. 1*A*), or alternatively a second-order model that included an exponentially decaying (or "slide") term (FR = $b + k\mathrm{E} + r\dot{\mathrm{E}} + u\ddot{\mathrm{E}} - c\dot{\mathrm{F}}\mathrm{R}$) that has been shown to provide more accurate descriptions of ABN activity during saccades (Sylvestre and Cullen 1999). These models were used to describe motoneuronal firing rates with respect to eye (E), gaze (G), or E and head (H) motion during saccades and gaze shifts. We conclude that the same dynamic eye movement–based models can be used to describe motoneuronal discharges during head-restrained saccades and combined eye-head gaze shifts. In addition, we found that a classic NOS-based analysis can lead to the erroneous conclusion that ABN discharges, and by extension premotor neuron discharges, are better correlated with gaze than with eye motion. We demonstrate that this apparent correlation is physiologically meaningless and is due to *1*) the dynamics of the system being improperly considered, and *2*) the correlation of eye and head motion during gaze shifts.

METHODS

Two monkeys (*Macaca mulatta*) were prepared for chronic extracellular recordings. The surgical techniques have been previously described (Sylvestre and Cullen 1999). All experimental protocols were approved by the McGill University Animal Care Committee and complied with the guidelines of the Canadian Council on Animal Care. During the experiments, the trained monkey was seated in a primate chair that was fixed to the suprastructure of a vestibular turntable. Head-restrained saccades and head-unrestrained gaze shifts were elicited by stepping a laser target between horizontal positions (±35° range) in predictable and random trials. In addition, large amplitude gaze shifts (up to 75°) were obtained using a "barrier" paradigm in which a food target appeared unexpectedly on either side of an opaque screen facing the monkey (Cullen and Guitton 1997a). Smooth pursuit eye movements were elicited by sinusoidal target motion (40°/s peak velocity, 0.5 Hz). Behavioral paradigms, target and turntable motion, and data storage were controlled by a QNX-based real-time data acquisition system (REX) (Hayes et al. 1982). Gaze and head position signals, target position, vestibular turntable velocity, and unit activity were recorded on DAT tape for later playback and analysis. Off-line, the position signals were low-pass filtered at 250 Hz (8-pole Bessel filter) and sampled at 1,000 Hz. The sampled gaze and head position signals were digitally filtered at 125 Hz, and eye position was calculated as the difference between gaze and head position. Position signals were digitally differentiated to obtain velocity signals.

Extracellular single-unit activity was recorded using enamel-insulated tungsten microelectrodes (7–10 MΩ impedance, Frederick Haer) as has been described elsewhere (Sylvestre and Cullen 1999). The abducens nucleus was identified based on its stereotypical discharge patterns during eye movement and whole-body rotation paradigms (Robinson 1970). The location of each neuron, in the present study, was confirmed using three-dimensional reconstructions of electrode tracts; units that were located in regions >0.5 mm from the estimated center of the abducens nucleus were not included. Each neuron's eye position threshold was plotted versus its eye velocity sensitivity during sinusoidal smooth pursuit. We then compared our data to that of Fuchs et al. (1988) and concluded that our sample contained ~70% MNs (see also Broussard et al. 1995; Sylvestre and Cullen 1999).

The spike train of each ABN was determined using a windowing circuit (BAK) that was manually set to generate a pulse coincident with the rising phase of each action potential. The neural discharge was represented using a spike density function in which a Gaussian function (5 ms standard deviation) was convolved with the spike train (Cullen et al. 1996). Saccade and gaze shift onsets and offsets were defined using a ±20°/s gaze velocity criteria. Neuronal lead times relative to movement onset were determined by *1*) measuring the latency between the occurrence of the first spike in the burst and the onset of gaze motion and *2*) using a first-order model (see *Eq. 1* in RESULTS) to optimize the lead time, t_d, simultaneously with the other model parameters (Sylvestre and Cullen 1999). The number of spikes in a burst (NOS) was defined as the number of spikes that a neuron produced in the time interval between movement onset and offset (Henn and Cohen 1973) and was computed after shifting the firing rate by t_d. (Note that the NOS measurements did not differ significantly if the 1st spike estimate of lead time was used.) A NOS value corrected for the position sensitivity of ABNs ($\mathrm{NOS_C}$) was also computed for each saccade/gaze shift following the method used by Delgado-Garcia et al. (1986a,b) in their analysis of ABNs: first, the tonic firing rate immediately preceding movement onset was subtracted from the firing rate, and second, the remaining firing rate was integrated. For each unit, optimal model fits (see *Eqs. 1* and *2* in RESULTS) were also obtained from an ensemble of ≈20 ipsilaterally directed saccades or gaze shifts using least-square algorithms (Cullen et al. 1996). A dynamic model's ability to estimate neuronal discharges was assessed by calculating the variance-accounted-for (VAF = {1 − [var (*mf* − *fr*)/var (*fr*)]}, where *mf* represents the modeled firing rate and *fr* represents the actual firing rate). Statistical significance was determined using a paired Student's *t*-test.

RESULTS

Ten neurons were sufficiently well isolated during head-restrained saccades, head-restrained smooth pursuit, and head-unrestrained gaze shifts, to allow the quantitative analysis included in this report. Figure 1*B* illustrates the discharge of an example ABN (*unit B90__3*) during a head-restrained saccade. This neuron was typical in that the first spike in its burst led ipsilateral saccades by 4 ± 1 ms [mean value pooled over all units ($\mathrm{Mean_p}$): 4.2 ± 0.8 ms, mean ± SD] when the head was restrained. For each ABN, the total number of spikes (NOS) generated during the saccadic burst was proportional to the amplitude of the saccadic eye movement ($\mathrm{Mean_p}$: slope = 1.1 ± 0.5, intercept = 3.0 ± 2.5, R = 0.85 ± 0.08).

Once a neuron was fully characterized during head-restrained paradigms, the monkey's head was slowly and carefully released to allow full freedom of head motion. During this critical transition, the unit's activity and waveform were monitored on an oscilloscope to ensure that the cell remained undamaged and well isolated. Figure 1*C* illustrates the discharge of our example neuron during a voluntarily generated gaze shift. This neuron was typical in that the onset of its burst led ipsilateral gaze shifts by 6 ± 3 ms ($\mathrm{Mean_p}$: 5.0 ± 1.3 ms). For ABNs, the NOS was better correlated with the amplitude of the gaze shift ($\mathrm{Mean_p}$: R = 0.75 ± 0.18) than with the amplitude of the eye movement component ($\mathrm{Mean_p}$: R = 0.65 ± 0.22). Indeed, the NOS was better related to gaze than to eye motion for most (80%) of the neurons in this study. This result is illustrated for our example neuron in Fig. 1*C* (*insets*). Correcting the NOS for the tonic discharge of ABNs ($\mathrm{NOS_C}$; see METHODS) did not significantly alter these conclusions (70% of units were better correlated with gaze motion). Given that ABNs control the motion of the eye, this finding is, at first glance, rather surprising. However, it is important to note that both the NOS-based and $\mathrm{NOS_C}$-based analyses did *not* properly consider the dynamics of the input-output relationship between ABN firing rates and eye motion; inherent to both approaches is the assumption that a neuron's firing rate (FR) is

solely proportional to eye velocity ($\dot{E}$) during saccades and gaze shifts (i.e., FR $\propto \dot{E}$, and by extension $\int$ FR $\propto \int \dot{E}$, thus NOS $\propto \Delta E$), which is not the case. This is an important point that we shall now consider in detail.

We first addressed the question of whether *dynamic* eye-based models that accurately describe ABN activity during head-restrained saccades could be used to predict head-unrestrained discharges of ABNs during gaze shifts. Stated differently, if the dynamic relationship between neuronal activity and eye movement is constant, it should be possible to use the same eye movement–based model to describe the discharges of ABNs during saccades and combined eye-head gaze shifts. To test this prediction, we utilized two dynamic models based on either a simple first-order approximation of eye plant dynamics

$$FR(t) = b + kE(t - t_d) + r\dot{E}(t - t_d) \quad (1)$$

or a more accurate second-order formulation of eye plant dynamics that included a term proportional to the derivative of firing rate

$$FR(t) = b + kE(t - t_d) + r\dot{E}(t - t_d) + u\ddot{E}(t - t_d) - c\dot{FR}(t) \quad (2)$$

where *b, k, r, u,* and *c* are constants that were optimized for each neuron in our sample, and E, $\dot{E}$, and $\ddot{E}$ are eye position, velocity, and acceleration, respectively, and $\dot{FR}$ is the derivative of the neuron's firing rate (FR). *Equation 1* is generally accepted as a good description of motoneuron activity during saccades (Robinson 1970; Sylvestre and Cullen 1999). Indeed, *Eq. 1* provided a useful description of ABN firing rates during head-restrained saccades [$Mean_p$: variance-accounted-for for parameter optimization (VAF_{opt}) = 0.61 ± 0.16]. The fit of *Eq. 1* to the discharge of our example unit (*unit B90__3*) is shown in Fig. 2*A*. The parameter values estimated during saccades (*b, k,* and *r* in *Eq. 1; b, k, r, u,* and *c* in *Eq. 2*) were then used to predict the discharge of each neuron during head-unrestrained gaze shifts.

For our sample of neurons, eye-based model predictions (using *Eq. 1*) well approximated the neuronal discharges during gaze shifts [$Mean_p$: variance-accounted-for for model predictions (VAF_{pred}) = 0.31 ± 0.20]. This result is illustrated for example *neuron B90__3* in Fig. 2*B* (thick black line). In contrast, gaze-based models in which E and $\dot{E}$ were replaced by G and $\dot{G}$ in *Eq. 1,* respectively, provided a poor prediction of unit discharges ($Mean_p$: VAF_{pred} = −0.71 ± 0.98). This is also illustrated, for our example neuron, in Fig. 2*B* (thick gray line). Note that a negative VAF_{pred} indicates that the predicted model fit is worse than simply fitting the data with a mean value. Comparable results were obtained when a more accurate representation of ABN discharges during saccades, *Eq. 2* (Sylvestre and Cullen 1999), was utilized ($Mean_p$: VAF_{opt} head-restrained = 0.69 ± 0.16; $Mean_p$: VAF_{pred} head-unrestrained = 0.38 ± 0.18 vs. −0.07 ± 0.54, eye-based vs. gaze-based models, respectively). In addition, we found that the values estimated for the parameters of eye-based models during gaze shifts were not significantly different from those estimated during saccades ($P > 0.05$). Finally, when H and $\dot{H}$ terms were added to eye-based *Eqs. 1* and *2,* no significant improvements in VAF_{opt} were observed ($P > 0.05$), and the estimated head movement parameters were not significantly different from zero ($P > 0.05$).

In summary, although the NOS and NOS_C analyses imply a gaze sensitivity on ABN discharges during gaze shifts, ABN firing rates are well determined by eye plant dynamics alone. Furthermore, our dynamic analyses indicate that ABN discharges are related to eye motion by the same dynamic relationship during head-restrained saccades and head-unrestrained gaze shifts.

DISCUSSION

In this study, we have applied dynamic analysis techniques to ABN discharges recorded during saccades made with the head-restrained, and during combined eye-head gaze shifts. This approach provided an objective comparison between the discharges of these neurons during saccadic eye movements that *1*) were not accompanied by head motion and *2*) were accompanied by head motion. Such a comparison is important to understand how the brain stem simultaneously processes eye and head motor signals during gaze shifts. Based on the results of our analysis, we conclude that models of ABN discharges obtained during head-restrained saccades can adequately represent the discharge of these same neurons during combined eye-head gaze shifts.

Previous studies of gaze shifts have demonstrated that eye movement-based dynamic models of premotor BNs activity are parametrically altered when comparing saccades to gaze shifts (Cullen and Guitton 1997a,b). During gaze shifts, the discharge frequency of BNs was shown to be approximately proportional to the sum of $\dot{E}$ and $\dot{H}$ signals. Therefore with respect to MNs (i.e., the ABNs of the present study), the question arises as to how the BN discharge, given that it contains a signal proportional to $\dot{H}$, is transformed into the eye-only motor command that is required to properly drive eye motion. One possibility is that the agonist and antagonist MNs encode comparable $\dot{H}$-related signals that are subsequently nulled at the level of the oculomotor plant via the interaction of the agonist/antagonist muscle pair. However, the results of the present study indicate that this is not the case; the relationship between agonist ABN firing rate and eye motion does not change when the head is moving, and the head movement–related information carried by ABNs is negligible. Consequently, during combined eye-head gaze shifts, the inappropriate signals (i.e., $\dot{H}$-related) carried to the abducens nucleus by BNs must be offset by other premotor cells. We propose that projections to the abducens motor nucleus from premotor cells in the vestibular nucleus/nucleus prepositus complex contribute to offsetting the $\dot{H}$ signal.

A second conclusion of this study is that a standard metric-based analysis [i.e., counting the number of spikes (NOS) in a burst] is inappropriate in the study of combined eye-head gaze shifts. This finding can be better understood by considering recent models of coordinated eye-head gaze shifts. A number of published gaze control models, with a structure similar to that shown in Fig. 3*A,* predict temporal coupling between eye and head movements during gaze shifts (Fuller et al. 1983; Galiana and Guitton 1992; Guitton and Volle 1987; Guitton et al. 1984, 1990; Laurutis and Robinson 1986; Pélisson and Prablanc 1986; Pélisson et al. 1988; Roucoux et al. 1980; Tomlinson 1990; Tomlinson and Bahra 1986a,b; see review by Guitton 1992). The *inset* of Fig. 3*A* illustrates examples of the coupling that we observed during gaze shifts. $\dot{H}$ increased with

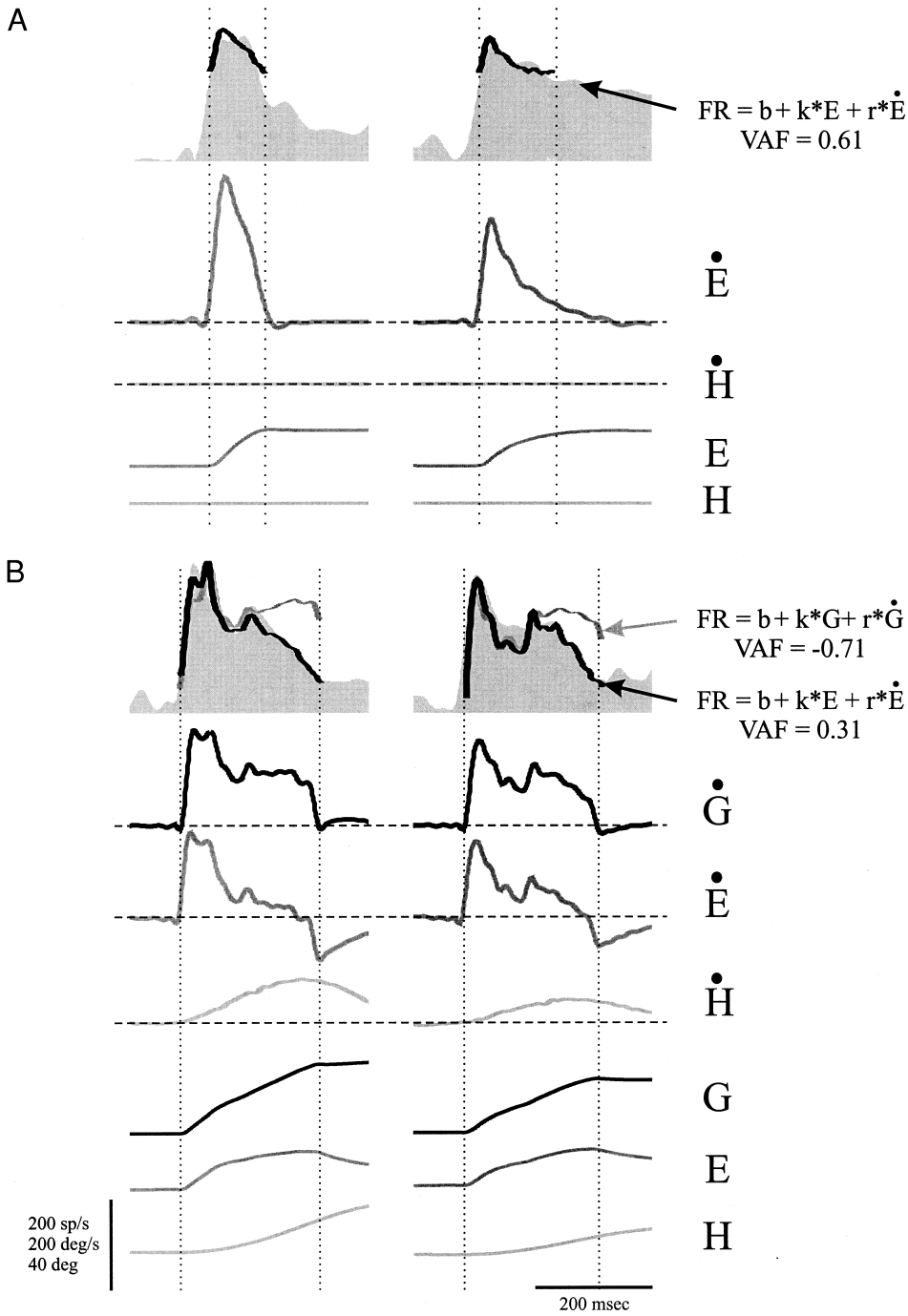

FIG. 2. Examples of model fits to an ABN's (*unit B90__3*) firing frequency profiles. *A*: a 1st-order model of oculomotor plant dynamics was effective in describing ABN discharges during head-restrained saccades. Two example horizontal saccades are shown, in which the shaded trajectories represent the actual unit firing rates, and the superimposed curves represent optimal model fits. *B*: the same 1st-order model could be utilized to adequately predict the same neuron's discharge during head-unrestrained gaze shifts. Two example horizontal gaze shifts are shown. The firing frequency calculated using the saccadic head-restrained model [$FR(t) = b + k * I(t - t_d) + r * \dot{I}(t - t_d)$] displayed in *A* are illustrated when *1*) gaze (heavy gray line) and *2*) eye (heavy black line) were utilized as the inputs (I and $\dot{I}$) to the model. The $Mean_p$ VAF_{opt} and VAF_{pred} obtained over the entire data set of saccades (*A*) and gaze shifts (*B*), respectively, are provided below each model. Abbreviations are as in Fig. 1. Accompanying eye, head and gaze, position and velocity trajectories have been shifted in time by t_d.

the eye contribution and remained high toward the end of the gaze shift despite a decrease (and sometimes an actual plateau or reversal) in ocular velocity.

It has been proposed that premotor neuron/motoneuron discharge metrics will appear more linearly related to gaze shift amplitude than to eye movement amplitude when eye and head motion are coupled (Galiana and Guitton 1992). The result of the present study, as well as other recent reports (Ling et al. 1999a,b), demonstrate that this, in fact, is the case for ABN discharges (Fig. 1*C, insets*). In Fig. 3, *B* and *C,* we further emphasize this finding by plotting the cumulative NOS in an ABN burst versus current eye and gaze amplitude, respectively, for the same neuron that was illustrated in Figs. 1 and 2 (*unit B90__3*). The neural responses for the same four example gaze shifts that were plotted in the *inset* of Fig. 3*A* are shown (gray traces). It is clear that the NOS-gaze phase plane plot trajectories are fairly linear, whereas the NOS-eye phase plane trajectories are significantly curved.

Two important conclusions can be made based on the relationships shown in Fig. 3, *B* and *C*. First, Ling and colleagues (1999b) argued that during gaze shifts, the last spikes in the burst are "consumed" by the oculomotor plant, because the eye movement is constrained by the mechanical limits of the orbit. We show that this is not the case because, during gaze shifts, the eye often plateaued or turned around well before reaching the mechanical limits of eye rotation (i.e., <30°; Fig. 3*B*).

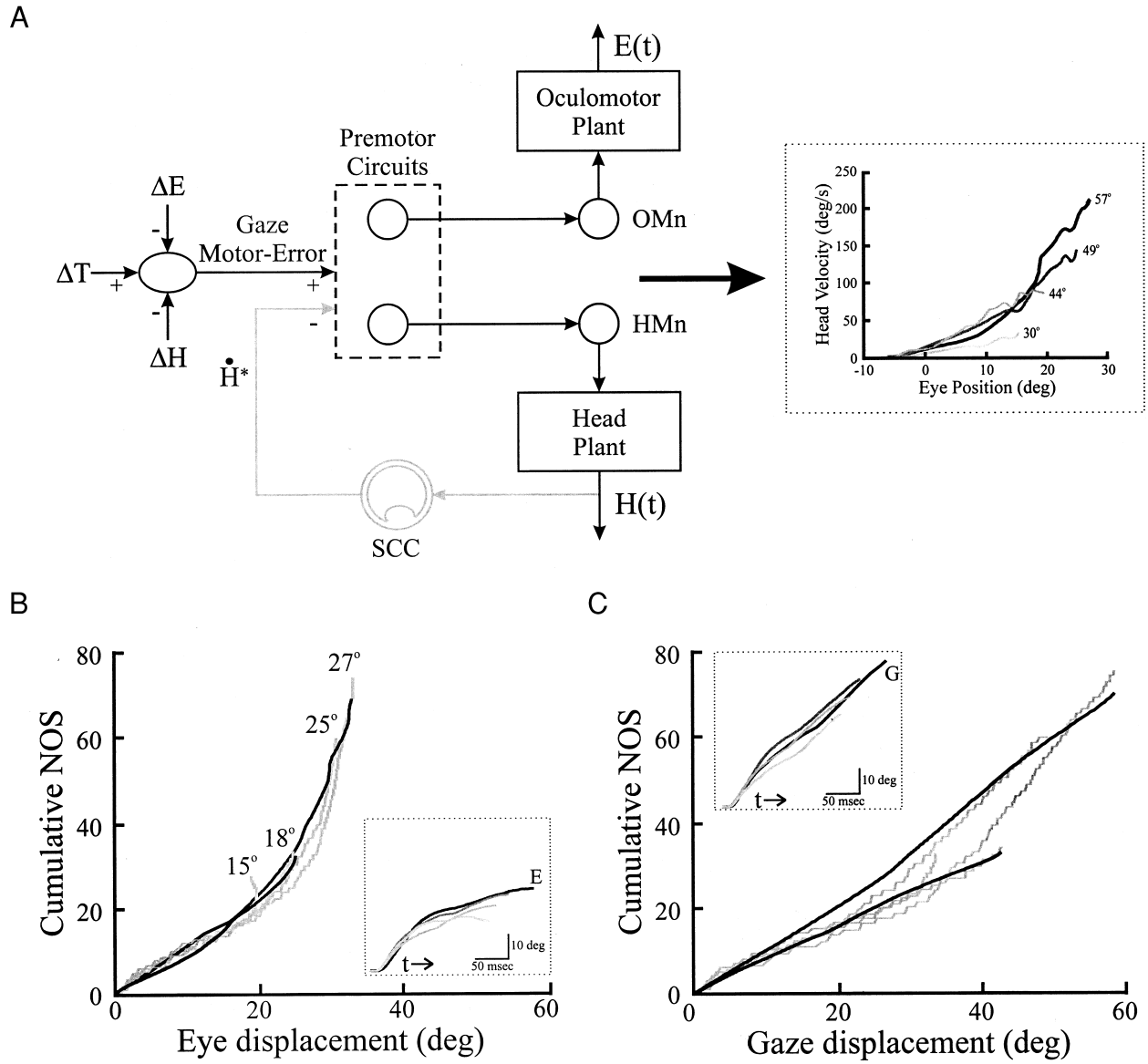

FIG. 3. *A*: the classic model for saccade generation (Jürgens et al. 1981) extended to describe the control of gaze shifts. There are 3 main features of this model. *1*) The premotor circuits are driven by a gaze error signal [desired gaze shift amplitude in space (ΔT) − change in gaze position (ΔG = ΔE + ΔH, where ΔE and ΔH represent the changes in eye-in-head and head-in-space positions that have occurred since the onset of the gaze shift, respectively)] from upstream structures. *2*) The eye and head premotor circuitries receive their input from a shared upstream controller, and therefore the eye and head trajectories are not independent. *3*) The relationship tying eye [E(*t*)] and head [H(*t*)] motion to the signals carried by the eye (OMns) and head (HMns) motoneurons is determined by the mechanical properties of the eye and head plants, respectively. In addition, the circuit contains a projection from the semicircular canals to the premotor circuitry (shown as gray lines). The gain of this pathway can be varied to reflect the status of the vestibuloocular reflex (VOR) and is not essential to the arguments that will be presented here. *Inset*: instantaneous head velocity is plotted as a function of instantaneous eye position for 4 gaze shifts of increasing amplitude but similar initial eye and head positions. Note that the eye and head trajectories are not independent. *B* and *C*: superimposed phase plane plots in which the cumulative NOS in a burst (*unit B90__3*) is plotted vs. instantaneous eye (*B*) and gaze (*C*) displacement (gray traces) for the 4 gaze shifts illustrated in the *inset* of (*A*). Note the significant curvature of the eye-based plots, where the orbital position of the eye at the end of the gaze shift is indicated for each trajectory. The *eye-based* dynamic model fit of the same neuron was integrated during 2 of these gaze shifts to obtain the cumulative NOS predicted by a 1st-order model. The predicted phase plane plot trajectories (black traces) are superimposed on the actual data. *Insets*: eye (*B*) and gaze (*C*) trajectories as a function of time recorded during the same 4 gaze shifts as shown in the *inset* of (*A*). In *B* and *C*, the eye and gaze position trajectories were shifted in time by t_d for analysis.

Second, the results in Fig. 3, *B* and *C,* can be accounted for by a first-order model of oculomotor plant dynamics. We integrated the first-order eye-based dynamic model of *unit B90__3* during two of the example gaze shifts to obtain the predicted cumulative NOS (black traces). The modeled NOS-eye and NOS-gaze phase plane plot trajectories showed trends that are comparable with the actual data. The resultant cumulative NOS yielded a nonlinear relationship with eye displacement, and paradoxically a more linear relationship with gaze displacement. There are two reasons why this occurs: *1*) the NOS and

gaze shift size are both increasing monotonically, whereas the eye in the orbit can reach plateaus and even reverse its direction during gaze shifts (compare the *insets* of Fig. 3, *B* and *C*), and *2*) ABN activity will be correlated mainly with eye velocity only for short-lived saccades where the eye plant acts as an integrator of high-frequency inputs. During larger, longer-lasting gaze shifts, eye plant dynamics begin to play a more important role: the eye plant no longer acts as a simple integrator and the NOS-eye relationship breaks down and, in fact, is no longer appropriate.

In summary, ABN activity always remains appropriately related to eye position through the dynamics of the eye plant during both head-restrained saccades and head-unrestrained gaze shifts. The apparent strong correlation between the NOS generated by ABNs and gaze metrics is therefore simply incidental to the fact that eye and head trajectories are strongly correlated and together form a monotonically increasing gaze trajectory. We conclude that, although metric-based analyses are commonly used to characterize brain stem neurons during rapid eye movements, it is crucial that the system dynamics be properly considered in the study of gaze control.

We are grateful to J. E. Roy for contributing to the data collection and for several valuable suggestions. We thank D. Guitton, M. Huterer, and A. Dubrovsky for critically reading the manuscript. We also thank M. Drossos, W. Kucharski, and A. Smith for outstanding technical assistance.

This study was supported by the Medical Research Council and by the Natural Sciences and Engineering Research Council of Canada.

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Received 24 June 1999; accepted in final form 8 September 1999.

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