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Discharge of Monkey Nucleus Reticularis Tegmenti Pontis Neurons Changes During Saccade Adaptation

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Abstract

Saccade accuracy is maintained by adaptive mechanisms that continually modify saccade amplitude to reduce dysmetria. Previous studies suggest that adaptation occurs upstream of the caudal fastigial nucleus (CFN), the output of the oculomotor cerebellar vermis but downstream from the superior colliculus (SC). The nucleus reticularis tegmenti pontis (NRTP) is a major source of afferents to both the oculomotor vermis and the CFN and in turn receives direct input from the SC. Here we examine the activity of NRTP neurons in four rhesus monkeys during behaviorally induced changes in saccade amplitude to assess whether their discharge might reveal adaptation mechanisms that mediate changes in saccade amplitude. During *amplitude decrease adaptation* (average, 22%), the gradual reduction of saccade amplitude was accompanied by an *increase* in the number of spikes in the burst of 19/34 neurons (56%) and *no change* for 15 neurons (44%). For the neurons that increased their discharge, the additional spikes were added at the beginning of the saccadic burst and adaptation also delayed the peak-firing rate in some neurons. Moreover, after amplitude reduction, the movement fields changed shape in all 15 open field neurons tested. Our data show that saccadic amplitude reduction affects the number of spikes in the burst of more than half of NRTP neurons tested, primarily by increasing burst duration not frequency. Therefore adaptive changes in saccade amplitude are reflected already at a major input to the oculomotor cerebellum.

INTRODUCTION

Saccades are quick eye movements that accurately point the fovea at objects of interest. To maintain this accuracy, the saccadic system must compensate for any dysmetria caused by growth, injury, or aging. For example, although the saccades of normal elderly adults become slower, their accuracy is maintained quite well (Munoz et al. 1998; Warabi et al. 1984). Saccadic amplitude adaptation also occurs in subjects who experience weakening of the extraocular muscles of one eye. If such patients view targets with their paretic eye, conjugate saccades of the normal eye are slightly hypermetric. When the paretic eye is occluded, saccades of the normal eye become accurate within a few days whereas saccades of the paretic eye become hypometric (Kommerell et al. 1976). Similar results were observed in a patient with a medial rectus paresis (Abel et al. 1978) and in monkeys whose horizontal recti of one eye were weakened surgically (Optican and Robinson 1980; Scudder and McGee 2003; Snow et al. 1985). Thus, the saccadic system is capable of continuous adaptive control under a wide variety of conditions that produce inaccurate saccades.

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The adaptation mechanism can be engaged behaviorally by deceiving the saccadic system into thinking its saccades are inaccurate. In this behavioral paradigm (McLaughlin 1967), a saccade is detected and the target is displaced either forward or backward as the saccade is launched so the eye appears to under- or overshoot, respectively. After monkeys undergo about 1,000 to 1,500 trials, saccade amplitude is either increased or reduced, respectively, so that most adapted saccades land near the final target. These changes resemble those produced in primates by muscle weakening because they are gradual, are specific to the saccades that are adapted, and persist when an adapted animal is placed in the dark for 20 h (Robinson et al. 2002; Scudder et al. 1998).

Saccadic amplitude adaptation produced either by muscle weakening or the McLaughlin paradigm has been used to localize the neural structures that mediate saccade plasticity (for review, see Hopp and Fuchs 2004). Initial experiments have focused on structures at the level of the brain stem. The brain stem command for saccades originates in the superior colliculus (SC; see Scudder et al. 2002 for recent review). The signal from the SC reaches the motoneurons that produce the horizontal saccades considered here by two routes. The most direct SC projection is to the brain stem burst generator (BG), a group of neurons that produce the burst of spikes that are fed to motoneurons to generate the saccade. A less-direct route from the SC reaches the BG by a parallel pathway that includes first the nucleus reticularis tegmenti pontis (NRTP) and then the midline oculomotor region of the cerebellum, which consists of the oculomotor vermis and the caudal fastigial nucleus (CFN) to which the vermis projects. This midline oculomotor cerebellum has long been implicated in controlling saccade accuracy because lesions there cause saccades to become dysmetric (Optican and Robinson 1980; Ritchie 1976; Robinson et al. 1993; Vilis and Hore 1981).

Lesions of the oculomotor cerebellum also impair saccade adaptation driven either by the McLaughlin paradigm (Barash et al. 1999; Robinson et al. 2002; Takagi et al. 1998) or muscle weakness (Optican and Robinson 1980). Furthermore, neurons in the CFN change the timing and firing rates of their saccade-related bursts in association with behavioral decreases in saccade amplitude (Inaba et al. 2003; Scudder and McGee 2003). The CFN, in turn, projects to the BG where its input helps shape the burst sent to ocular motoneurons to produce saccades of different amplitudes (Scudder and McGee 2000). CFN signals are necessary for saccade adaptation because humans (Straube et al. 2001) and monkeys (Robinson et al. 2002) with lesions of this region fail to adapt. However, if muscimol inactivation of the monkey CFN is allowed to dissipate, an underlying adaptation *is* revealed, suggesting that plasticity had occurred upstream but could not be expressed through the disabled CFN (Robinson et al. 2002). Therefore, the CFN is influenced by an adapted upstream command signal whose source currently is unknown.

Previous studies have concluded that the burst discharge of neurons in the SC does not change during saccade adaptation and continues to encode the desired saccade size, as estimated by the size of the target step, and not the size of the adapted saccade (e.g., Edelman and Goldberg 2002; Frens and van Opstal 1997). However, saccade adaptation might influence neurons in the NRTP, which receives direct inputs from the SC (Harting 1977; Kawamura et al. 1974; Scudder et al. 1996), and, in turn, projects directly to the oculomotor vermis (Brodal 1980; Shinnar et al. 1975; Thielert and Thier 1993; Yamada and Noda 1987) and to the CFN (Gonzalo-Ruiz and Leichnetz 1990; Noda et al. 1990). Therefore, we investigated whether activity in the NRTP is changed during saccade adaptation. As had been done previously in the SC, we asked specifically whether the burst discharge of NRTP neurons was related to actual or desired saccade size. Our data show that the discharge of more than half of the NRTP neurons changes with adaptation but that the adapted discharge is not related simply to either the desired or actual saccade size.

METHODS

General procedures

Four juvenile, male rhesus monkeys (*Macaca mulatta*, 4–5 kg, K, R, M, and A) were used in these experiments. The monkeys underwent two different surgical procedures under inhalation anesthesia and aseptic conditions. First, we implanted head-stabilization lugs and a preformed scleral search coil (Judge et al. 1980) for the electromagnetic measurement of eye movements (Collewijn 1977; Robinson 1963). After a week of recovery, the monkeys were trained to track a jumping target spot (see Soetedjo et al. 2002a for details).

After about a month of training, we implanted a stainless steel recording cylinder over a hole trephined in the posterior cranium. The cylinder was centered on the midline, tilted backward 30° from the vertical, and directed 1–3 mm anterior to stereotaxic zero to allow access to the NRTP. After a week of recovery, we recorded extracellular neuronal activity, which we observed on-line and also stored on hard drives, digital video tape backup, and optical disks (see Kaneko and Fukushima 1998 for details).

Experimental paradigms

PREADAPTATION PHASE—We identified saccade-related burst neurons while the monkey tracked a target that stepped pseudorandomly between points separated by 5° on a centered 7 × 7 square array. After we isolated a single saccade-related neuron, we estimated its response field and approximate preferred direction by observing peak firing rates on a storage oscilloscope (Soetedjo et al. 2002b). We determined the edges of the response field as those directions associated with a minimal burst in about 50% of the trials. The preferred direction was taken as the angle lying halfway between the edges. In previous recordings in the SC, this strategy allowed us to determine, on-line, a neuron's preferred direction to within 10° of the direction that was calculated by analyzing the same data quantitatively post hoc (Soetedjo et al. 2002b). For five NRTP neurons, we confirmed that preferred directions determined on-line and off-line also were within 10°. To determine the unit's preferred amplitude, we then required the monkey to make saccades to target jumps of different amplitudes along this estimated preferred direction. If the burst rate continued to increase with amplitude, the units were classified as “open field” but if the discharge reached a maximum for a “preferred” amplitude and then decreased for larger amplitudes we termed them “closed field.” We used both the unit activity played over an audio monitor and the instantaneous firing rate monitored on a memory scope to estimate the preadaptation movement field.

To characterize the movement field, we usually chose five target amplitudes that included and bracketed the adapted step amplitude. The amplitudes were selected to elicit the preadapted saccade, the predicted adapted saccade, and one or two saccades outside the anticipated adapted range. For example, the neuron in Fig. 1A did not discharge for saccades less than about 6°. Therefore, we attempted to adapt saccades of 8° down to an amplitude of 5–6° to see whether adapted saccades would be associated with a discharge even though preadapted saccades of the same size were not. Thus we included target amplitudes of 8°, the preadaptation target step, and 5°, the predicted adapted saccade. In addition, we included a target step of 10°, to elicit an approximately 8° saccade after adaptation, to allow comparison of the discharge associated with pre- and postadaptation saccades of the same amplitude. Finally, to complete the assessment of the movement field, we used larger target steps of 15 and 20°. Although we also used steps of 30 and 40° for the sake of completeness in this example, one of our first units recorded, we later limited the number of target steps to five to shorten the time necessary to assess the movement field. The set of target amplitudes chosen for each neuron was based on the preadaptation movement field. For closed movement field neurons, (Fig. 1B), we attempted to include in our set target amplitudes sizes that elicited saccades associated with the unit's

peak discharge. For a given neuron, the same set of target steps was used during the preadaptation, adaptation, and postadaptation assessment of the movement field (see below).

To elicit target steps, we jumped the laser diode, back-projected target along the unit's optimal saccadic direction using a mirror galvanometer system. Neither starting position, timing, nor the direction of movement was predictable. Each target displacement began at the end of the previous displacement but its amplitude was constrained by the limits of our screen and the animal's oculomotor range. As mentioned, the same set of target steps was used during preadaptation, adaptation, and postadaptation phases but *only* the *single* target step being adapted (8° in our example) was followed by an adaptation step (backward 2° in our example). We collected 10–25 (usually ~ 15) trials of each step size. This strategy allowed us to document any change in the burst with saccade amplitude.

ADAPTATION PHASE—We used the McLaughlin paradigm (1967) to increase or decrease saccade size. This method has been shown to be equivalent to muscle weakening (Scudder et al. 1998) for induction of saccade amplitude adaptation. For neurons with open movement fields, we reduced saccade amplitude ($n = 31$) so that adaptation would produce a saccade that, before adaptation, was associated with a very small burst and ideally none at all (most units had an amplitude threshold for burst activation; see *RESULTS*). If thresholds were too low, we used target amplitudes that before adaptation were associated with large differences in discharge. We attempted to decrease saccade amplitude for open field neurons because amplitude increases are smaller and more difficult to induce (e.g., Straube et al. 1997) so that associated changes in firing would be more difficult to discern. If the unit had a closed field, we mostly (11/14 neurons) attempted to increase saccade amplitude. We used forward rather than backward adaptation because the preferred amplitudes of our closed movement field neurons averaged $< 8^\circ$ (see *Types of NRTP neurons* in *RESULTS*). It is difficult to reduce the amplitudes of such small saccades by adaptation (see Hopp and Fuchs 2004) and any associated changes in discharge would have been small (i.e., few spikes) and thus very difficult to detect.

To cause either saccade amplitude increases or decreases, we stepped the target forward or backward, respectively, as the monkey made a saccade toward it. The direction of the initial and the adapting target step was along the unit's preferred direction; *only one target* amplitude was adapted, based on the characteristics of the preadaptation field as discussed above. To promote a continual robust amplitude change in as few trials as possible, we increased the size of the adaptation steps incrementally. We usually began with an adaptation step size of about 30–50% of the initial target step size and then increased the size to 50% or more after about 300 adaptation trials. This strategy produced a relation between saccade amplitude and adaptation trial number that appeared more linear than exponential (Figs. 4, 5, and 7).

POSTADAPTATION PHASE—When the monkey showed a sufficient amplitude change (usually about -20% for backward adaptation and about $+15\%$ for forward adaptation) and if the unit remained well isolated, we assessed the postadaptation movement field in the preferred direction with the same target steps that were used during preadaptation. The eye movement window size was set at $\pm 3.5^\circ$ during and after the adaptation phase to accommodate the monkey's dysmetric saccades.

In one monkey (M), we tried to promote the retention of adapted amplitude changes during the postadaptation testing by blanking the target for 500–750 ms as the monkey made a saccade toward it (cf. Shafer et al. 2000). In three experiments, we compared pre- and postadaptation movement fields, obtained both with and without blanking. In all three experiments, data obtained with and without blanking produced similar movement fields. Therefore, we treated data obtained from blanked and nonblanked experiments together.

Data analysis

The relation between unit activity and both target and eye movement was determined off-line by means of homemade interactive programs as described previously (Kaneko and Fukushima 1998). Briefly, saccades were detected when eye velocity exceeded 50°/s and their onset and offset was defined as the time at which the velocity rose above and fell below 10°/s, respectively. The associated bursts were marked as the epoch when firing rate exceeded and then fell below 40 spikes/s. In a few cases (less than ~10%), artifacts (e.g., noise, blinks, etc.) caused incorrect markings, and the first author adjusted the computer markings. All accepted saccades and spikes were stored and analyzed by other homemade or commercial (Igor, WaveMetrics, Lake Oswego, OR; Matlab, The MathWorks, Natick, MA) software programs. Our homemade program determined the amplitude, duration, and peak velocity of saccades and the duration, the peak firing rate averaged over the three shortest interspike intervals, and the number of spikes in the burst. In addition, our program determined the timing of various features of the burst (such as onset, time to peak burst rate, and burst end), relative to the time of occurrence of salient features of the saccade (such as onset, peak velocity, and end). All relations between any of these and other variables were fit by linear regressions. The Student's *t*-test was used for statistical analysis with $P < 0.05$ indicating statistical significance, unless otherwise stated. Averages are presented as means and variances as SDs unless otherwise indicated.

We used these off-line determinations of burst and saccade metrics to evaluate the effects of adaptation in three ways. First, we documented whether adaptation was indeed accompanied by a change in neuronal discharge by comparing the average number of spikes after adaptation to that occurring before adaptation.

Second, we determined whether adaptation altered the unit's *movement field* by plotting the movement fields before and after adaptation. We considered changes in the movement field only along its preferred direction, which is the direction along which adaptation was produced. Because the peak firing rate can be distorted by short interspike intervals in a burst of a few spikes for small saccades, we used the number of spikes in the entire burst rather than peak rate to plot movement fields. In more detailed analyses of the changes in burst metrics (see RESULTS below), we also analyzed the peak discharge rate and its timing. Typical examples of open and closed movement fields in a unit's preferred direction are shown in Fig. 1. Open field neurons (Fig. 1A) discharged their highest burst rates for the largest saccades that we could elicit in the preferred direction, usually at least 40°. Closed field neurons exhibited their largest bursts for saccades of a preferred vector and smaller bursts for larger and smaller saccades (Fig. 1B) or saccades in nonpreferred directions (not shown). Plots of the number of spikes versus either saccade- or "desired saccade-" (i.e., target position–initial eye position) amplitude were fit by linear regression for open movement fields and by a spline fit for closed movement fields as has been done by others (Keller et al. 1996; Soetedjo et al. 2002b).

Third, we examined changes in the *discharge pattern* associated with adaptation. We compared 1) the bursts associated with the different sized pre- and postadapted saccades to the same target step and 2) the bursts associated with the same size pre- and postadapted saccades made to different target steps. If the bursts were similar in comparison 1), we would conclude that the neurons were reporting desired saccade amplitude, the difference between target position and eye position at saccade onset. If the bursts were similar in condition 2), we would conclude that they were reporting actual saccade amplitude.

All experiments were performed in accordance with the *Guide for the Care and Use of Laboratory Animals* (NRC 1997) and exceeded the minimal requirements recommended by the Institute of Laboratory Animal Resources and the Association for Assessment and Accreditation of Laboratory Animal Care International. All the procedures were evaluated and

approved by the local Animal Care and Use Committee of the University of Washington (ACC #2602-01).

RESULTS

In the NRTP of four monkeys, we recorded the activity of 51 saccade-related burst neurons (monkey K: 17, R: 15, M: 17, and A: two) during saccade adaptation. One animal (monkey A) had been used previously in another study and provided only two NRTP neurons. To obtain a significant amplitude change during adaptation, several hundred adaptation trials (optimally, more than ~400) were required in each session. For each usable NRTP unit, the preadaptation, adaptation, and postadaptation phases together lasted for at least 1 h and the search for and characterization of a saccade-related NRTP neuron often lasted ≥ 1 h. We were unable to subject a neuron to both forward and backward adaptation conditions or to continue recording while the animal underwent readaptation to baseline amplitudes because it was problematic to maintain recordings and robust saccadic tracking for that long. Even though experiments were limited to only forward or backward adaptation, we lost recording isolation or injured four neurons (two in K, one in R, and one in M) early in adaptation (< 150 adaptation trials) before noticeable adaptation had occurred so they were not analyzed further. For each of the 47 neurons reported here, we were able to obtain statistically significant amplitude adaptation ($P < 0.0001$, t -test) for the adapted target step size.

Types of NRTP neurons

All of our 47 neurons discharged a burst of spikes in association with the appropriate saccades. In addition to this motor response, 5/47 neurons also exhibited a visual response for target displacements near the preferred discharge vector of the motor response. Our categorization of a neuron as motor or visuomotor was based on alignment of the response rasters with either eye movement or target movement (Fig. 2). Those neurons with a purely motor response (e.g., R148, Fig. 2, *A* and *B*) discharged a burst that was aligned with saccade onset (Fig. 2 *A*) but very poorly aligned with the target step (Fig. 2 *B*). In contrast, visuomotor neurons (e.g., R144, Fig. 2, *C* and *D*) had not only a response component that was aligned with saccade onset (Fig. 2 *C*) but also a weaker response component that occurred at a relatively fixed latency (~70–90 ms; thick up arrows in Fig. 2 *D*) after the target step (marked by the 200 spikes/s calibration bar). Others have reported similar cell types in the NRTP (Crandall and Keller 1985). None of the five visuomotor neurons altered its discharge as a result of adaptation (see below).

Most of our NRTP neurons (33/47; 70%) had open movement fields. Of those with closed movement fields (30%), the preferred amplitudes ranged from 2 to 12° with an average of $7.7 \pm 3.4^\circ$.

Finally, before adaptation, our NRTP open field units exhibited robust relations between several aspects of the burst and properties of the associated saccade along the preferred direction. There were strong linear correlations between the number of spikes and saccade amplitude ($R^2 = 0.76 \pm 0.16$, $n = 31$), between burst duration and saccade duration ($R^2 = 0.72 \pm 0.16$), and between peak burst rate and peak saccade velocity ($R^2 = 0.78 \pm 0.16$). The average slopes of the linear regressions were 0.89 ± 0.54 spikes/°, 1.51 ± 0.97 , and 1.21 ± 0.61 spikes/s/°, respectively. After adaptation, neither the strong correlations between burst and saccade metrics [number of spikes and saccade amplitude ($R^2 = 0.76 \pm 0.17$, $n = 31$), burst duration and saccade duration ($R^2 = 0.68 \pm 0.19$), and peak burst rate and peak saccade velocity ($R^2 = 0.71 \pm 0.17$)] nor the slopes (0.91 ± 0.54 spikes/°, 1.37 ± 1.04 , and 1.28 ± 0.73 spikes/s/°, respectively) were significantly different.

Location of neurons

We sampled the NRTP within ± 4 mm of the midline from its rostral end under the oculomotor nucleus to its caudal pole where it abuts the nucleus raphe interpositus (rip). Tested neurons were all located in midline regions (± 2 mm) from at least 1 mm rostral to rip up to 4 mm anterior. This is the region where saccade-related neurons are most dense and is caudal to the pursuit-related neurons of the NRTP (Ono et al. 2005). Recording locations for neurons tested during adaptation were confirmed histologically in monkeys M and R (Fig. 3). Monkey A died unexpectedly so we were unable to reconstruct its tracks and monkey K was used for reconstructing the location of electrode tracks for another study. Figure 3 illustrates Nisslstained, parasagittal 50- μ m sections from monkeys M (*A, B*) and R (*C, D*) showing gliosis from tracks throughout the rostral pons. Clearly, many tracks in both monkeys ran through the NRTP. Figure 3*D* shows that NRTP cells were recorded at the correct depth; lesions ($\Rightarrow$) placed above and below unit R218 show that it was located in the NRTP).

We were able to reconstruct the relative location of most neurons recorded during adaptation on the basis of the cylinder coordinates, the depth of the recorded cell, the marking lesions, and the gliosis produced by the tracks (e.g., black arrows in *B* and *D*). In general, neurons with closed movement fields (14/19) were found more often (K: 2/2, R: 6/8, M: 5/7, and A: 1/2) in a narrow, mediolateral region of the rostral half (i.e., at or in front of the point that NRTP extends most dorsally) of NRTP, whereas open field neurons were more widely spread throughout NRTP (i.e., in more lateral and in more caudal portions). The three neurons that showed preferred directions within $\pm 45^\circ$ of the vertical were all closed movement field neurons. Neurons with preferred directions close to the horizontal were located mostly more laterally in the NRTP. All of their preferred vectors were ipsiversive. For the six neurons that were recorded from the medial portion of NRTP and the three neurons with nearly vertical preferred directions, we were unable to specify a contra- or ipsiversive preference. The mean ($\pm$ SD) width of the response field of all 47 neurons was $154.1 \pm 37.6^\circ$, based on our on-line estimates. Our methods did not allow a precise localization of types within the NRTP because many were recorded in clusters of closely spaced tracts. Nonetheless, we are quite confident that the great majority, if not all, of our neurons were recorded in the mediocaudal NRTP.

Effect of amplitude reduction adaptation

MOVEMENT FIELD CHARACTERISTICS—The activity of 34/47 NRTP neurons was recorded during backward adaptation. Thirty-one of 34 had open movement fields. Seven of these 31 neurons discharged a burst for saccades of all amplitudes in the preferred direction. The number of spikes in the burst increased with saccade size. For most of the neurons (the remaining 24/31), there was no burst for the smallest saccades tested ($\sim 2^\circ$) in the preferred direction (e.g., Fig. 1*A*). However, above an amplitude threshold, their numbers of spikes increased monotonically with saccade amplitude. For these neurons, the amplitude threshold was calculated from the regression line as the *x*-intercept. For the seven neurons that discharged a burst even for small saccades, we defined the amplitude threshold as zero because none showed a burst discharge for the direction opposite to the preferred direction. The mean ($\pm$ SD) amplitude threshold of all 31 neurons was $3.3 \pm 3.2^\circ$. For all 31 neurons, the relation between the number of spikes and saccade amplitude above threshold was a straight line with a variance (R^2) ranging from 0.26 to 0.95 (mean: 0.76 ± 0.16).

Only three closed field neurons were studied during backward adaptation. The preferred saccade amplitudes of these three neurons, taken as the peak of the smooth spline fit of number of spikes against saccade amplitude, were 8, 10, and 12° .

Twenty-eight open field and all three closed field neurons had preferred directions within $\pm 45^\circ$ of the horizontal.

BACKWARD ADAPTATION AFFECTS NEURONAL DISCHARGE—Figure 4 illustrates the features of the time course of a saccade amplitude reduction experiment (while recording unit R132). In this experiment, saccades to target steps (T1) of 15° triggered an adaptation step (T2) of −5° for trials 1 to 220 and then −7° for the remaining trials. In Fig. 4, *middle*, the amplitudes of the initial saccade are plotted as a function of the number of the adaptation trial. Figure 4, *bottom*, shows the amplitudes of superimposed saccades for adaptation trials 1 to 10, 211 to 220, and 522 to 531, respectively. This adaptation paradigm produced a 23% reduction in saccade amplitude over 531 trials when calculated as the difference between the mean amplitude of the first 20 trials and last 20 trials divided by that of first 20 trials. For all 34 neurons, the mean percentage amplitude reduction for all backward adaptations was $21.8 \pm 5.8\%$.

Figure 5 shows that the number of spikes of a representative open field neuron (M40) increases during a saccadic amplitude reduction. As the saccade amplitude (○) gradually *decreased* from a mean of 10.1 ± 0.6 to $6.4 \pm 0.7^\circ$, the number of spikes in the burst (▲) gradually *increased* from a mean of 9.8 ± 2.4 to 15.9 ± 2.4 . The mean saccade amplitude was significantly smaller and the mean number of spikes was significantly larger for post- than for preadaptation saccades ($P < 0.001$ for each).

Seven of the 34 neurons were lost before we obtained postadaptation data. For those seven, we compared data from the first and last 20 trials during adaptation. When we then consider the data from all 34 neurons together, all exhibited a significant decrease in initial saccade amplitude during backward adaptation. However, for the various neurons, the number of spikes in the associated bursts either increased ($n = 19$; 56%) or showed no statistically significant change ($n = 15$; 44%). This difference in neuronal behavior could not be attributed to different amounts of adaptation in the two sets of data. The mean percentage saccadic amplitude reduction associated with those two groups was $19.9 \pm 7.9\%$ (SD; $n = 19$) and $22.4 \pm 6.7\%$ ($n = 15$), respectively, and the mean number of adaptation trials in the two groups was 456.7 ± 165.1 and 476.4 ± 177.0 , respectively. Neither of these measures of adaptation was significantly different between the two groups.

ADAPTATION EFFECTS ON FIRING PATTERNS—All 19 neurons that exhibited an increased number of spikes during adaptation exhibited additional spikes early in the burst. The added spikes appeared gradually throughout adaptation as can be seen for the representative neuron M40 in Fig. 5 (*bottom*). A small change in the early part of the burst (oblique arrowhead) is noticeable after 250 trials and is quite prominent by the 800th trial. During adaptation, the end of the burst changes little. The peak discharge is somewhat delayed after only 250 saccades and exhibits little additional shift as adaptation progresses further.

The changes produced by adaptation in all our backward-adapted units are illustrated by comparing post- with preadaptation data. Postadaptation data of an assortment of saccade amplitudes were obtained for 15 of our 19 neurons. Figure 6 compares the post- and preadaptation behavior of two of these NRTP burst neurons, selected because they discharged at relatively high (M21, Fig. 6, *A* and *C*) and low (K65, Fig. 6, *B* and *D*) peak rates. For the unit illustrated in Fig. 6A, adaptation reduced the amplitude of saccades to a 15° target step from an average of 14.6 to 11.9°. Here we compare the rasters associated with selected saccades within $\pm 1^\circ$ of these two mean amplitudes to reduce the potential variability in discharge associated with saccades of different amplitudes. The rasters show that the burst occurring with postadaptation saccades has an earlier and greater presaccadic activity. The early increase, which is clearly revealed in the histograms of the averaged firing rate representing all responses (oblique arrows), was not seen before adaptation in these two or the other 13 neurons. The increase in early burst activity after adaptation does not represent the addition of another response component such as the prelude discharge seen in some SC neurons (Soetedjo et al.

2002a,b) because it occurred in neurons where no prelude activity was present (Fig. 5) as well as in NRTP short-lead burst neurons. Rather, it seems to reflect a broadening of the envelope of the burst associated with the saccade itself. Note that the modest increase in burst lead (<20 ms) also suggests a simple broadening of the saccade-related burst. In addition, the average histogram reveals a delay in the time of occurrence of peak burst rate (red down arrow vs. blue down arrow). Both the added presaccadic activity and delayed peak burst rate also can be seen in the rasters and average histograms of the neuron illustrated in Fig. 6B, where adaptation reduced saccade amplitude from 9.8 to 7.5°. In the comparisons of Fig. 6, A and B, different discharge patterns were elicited by the *same amplitude target step* (T), again suggesting that these neurons are not encoding “desired saccade amplitude,” which is the command relayed to the saccadic burst generator and is approximately equal to target displacement. Thus, the NRTP does not appear to lie in the direct pathway to the burst generator.

We next asked whether the discharge pattern associated with an adapted saccade was the same as that associated with a preadapted saccade of the same amplitude. Here the same amplitude saccade is elicited by a *smaller* target step before adaptation than after adaptation. For most amplitude reduction adaptations (11/15), pre- and postadaptation saccades of the same amplitude ($\pm 1^\circ$) had similar kinematics, as illustrated by the data in Fig. 6C, where the 15 position, velocity, and acceleration traces superimpose. As illustrated by the example in Fig. 6D, postadaptation saccades in the other four experiments were slightly slower. They exhibited longer decelerations (left oblique down arrows), slightly lower peak velocities, and longer durations. However, these changes in saccade duration, peak velocity, and peak deceleration were not significant for these four units or the other 11 NRTP neurons such as M21 ($P < 0.5$, *t*-test).

Although adaptation did not alter the kinematics of saccades of similar amplitude, adaptation did alter the discharge patterns as illustrated in Fig. 6, C and D. For both neurons, adaptation caused the development of added presaccadic activity (oblique arrows in average histogram), which increased the average burst duration from 38.3 ± 6.9 (SD) to 45.4 ± 10.7 ms for M21 (C) and from 16.5 ± 6.9 to 28.8 ± 9.3 ms for K65 (D). There was a corresponding increase in the average lead preceding saccade onset for both M21 (16.9 ± 4.6 to 23.9 ± 7.5 ms) and K65 (13.7 ± 3.0 to 24.1 ± 9.2 ms). However, the timing of the end of the burst was essentially unchanged (<0.1-ms difference for M21 and a nearly 0.9-ms difference for K65). Finally, after adaptation, the average peak firing rate occurred later than that before adaptation (red down arrow vs. blue down arrow) for both M21 (difference between post- and preadaptation times of peak firing: 10.2 ± 1.8 ms) and K65 (8.7 ± 2.1 ms).

As shown for the neuron illustrated in Fig. 5, the various postadaptation changes in the burst occurred gradually throughout adaptation. Figure 7 shows, for two neurons, the changes in saccade amplitude, saccade peak velocity, saccade duration, number of spikes, burst duration, and the timing of burst onset, burst end, and the timing of the peak firing rate relative to saccade onset as a function of the number of the adaptation trial. As the saccade amplitude gradually decreased, the number of spikes, burst duration, and the timing of burst onset gradually increased for both neurons. The peak burst rate also occurred later as adaptation progressed. Whereas the lag of peak burst rate increased steadily for unit K65, the lag for unit M21 increased only until about trial 250 or so, after which it stayed constant. A similar early expression of the lag of peak burst rate also occurred for unit M40 (Fig. 5). Finally, the timing of the end of the burst remained constant. Similar relations were observed for the other 13 (of 15) neurons. Therefore, gradual adaptive amplitude reductions are accompanied by several gradual changes in the burst of NRTP neurons.

Figure 8 compares these several features of the bursts associated with post- and preadaptation saccades of nearly the same amplitudes. Of the 27 neurons with postadaptation data (recall that

seven of our 34 neurons had no postadaptation data), 15 (•) each exhibited a significant increase in the number of spikes for saccades of similar size after adaptation, whereas the other 12 (□) showed no significant change (A). Each of the 15 neurons that exhibited an increased number of spikes during adaptation also showed an increase in burst duration (B) after adaptation ($P < 0.01$, paired t -test) because all points lay above the dashed line that indicates equal durations. This increase in burst duration was largely the result of a significant increase in the lead of burst onset ($P < 0.01$, paired t -test, Fig. 8C, points above the dashed line), with no increase in the lag of burst end ($P = 0.3$, paired t -test, Fig. 8D). Furthermore, although there was no significant difference in the peak firing rate after adaptation ($P = 0.5$, paired t -test, Fig. 8E), peak burst rate did occur significantly later ($P < 0.05$, t -test) for 13/15 neurons (Fig. 8F). As expected, the 12 neurons that exhibited no significant change in the number of spikes during adaptation also showed no significant changes in burst duration, burst onset, and time to peak burst rate.

For the 18 of 34 open field neurons that showed an increase in the number of spikes during backward adaptation of saccade amplitude, the average increase was from 11.3 ± 5.23 to 16.51 ± 6.25 , an average change of $45.7 \pm 16.8\%$. Burst duration increased by an average of $49.5 \pm 14.3\%$ (27.2 ± 9.1 to 40.7 ± 14.2 ms), burst lead increased by $59.1 \pm 8.9\%$ (15.1 ± 6.9 to 24.0 ± 10.6 ms), time-to-peak burst decreased by $71.7 \pm 18.9\%$ (5.2 ± 6.4 to 1.5 ± 7.7 ms), and peak burst frequency increased negligibly by $1.6 \pm 6.4\%$ (322.2 ± 143.4 to 327.3 ± 139.0 spikes/s).

BACKWARD ADAPTATION EFFECTS ON MOVEMENT FIELDS: OPEN FIELDS—

For the 27 neurons with postadaptation data (24 open and three closed movement field), we plotted the movement field along each unit's preferred direction both before and after adaptation to assess possible changes. We first evaluated the effect of backward adaptation on 24 open movement field neurons. On the basis of our previous comparison between pre- and postadaptation data, backward adaptation caused a significant increase in the number of spikes in 14 neurons and no change in the remaining 10. Figure 9 shows data from representative open field neurons that exhibited either an increase in the number of spikes (M32, A and B) or no change (R148, C and D). For each neuron, the number of spikes is plotted as a function of both actual initial saccade amplitude (A and C) and desired saccade amplitude (B and D).

For unit M32 (A and B), the number of spikes after adaptation was greater for all amplitudes, whether plotted against either the actual or desired saccade amplitude. Based on extrapolation of the linear fits, adaptation caused bursts for actual (A) and desired (B) saccade amplitudes that before adaptation had been accompanied by none (e.g., $\sim 6^\circ$). Furthermore, the slope of the linear regression with either actual or desired saccade size was steeper after adaptation than before (for actual: 0.78 spikes/ $^\circ$ vs. 0.41 ; for desired; 0.72 vs. 0.44). The regression analysis showed there was a significant difference of x -intercepts in Fig. 9A ($P < 0.05$, t -test) but not in Fig. 9B ($P = 0.7$). Also, there was significant difference of slopes in both Fig. 9, A and B ($P < 0.01$ for both). For all 14 neurons that exhibited an increased number of spikes after adaptation, the slopes of the number of spikes versus amplitude relations were significantly steeper when plotted against either actual or desired saccade amplitude. As for the x -intercepts, eight neurons showed significantly lower x -intercept(s) after adaptation for both for actual and desired saccade amplitude plots. The remaining six neurons showed significantly lower x -intercept(s) in plots against actual, but not desired, saccade amplitude. Therefore, for all 14 neurons, the number of spikes after adaptation was greater for all actual saccade amplitudes.

For unit R148, the linear regressions before and after adaptation are virtually identical whether plotted against actual (C) or desired (D) saccade amplitude. For this and nine other similar neurons, there was no significant difference between pre- and postadaptation fits for either the intercepts or the slopes (t -test).

BACKWARD ADAPTATION EFFECTS ON MOVEMENT FIELDS: CLOSED

FIELDS—For the three neurons with closed movement fields, backward adaptation produced data either like that in Fig. 10, *A* and *B* (one unit) or like that in Fig. 10, *C* and *D* (two units). For unit R103 (*A* and *B*), the number of postadaptation spikes appeared to be modestly higher for larger actual and desired saccade amplitudes, especially those around and greater than the amplitude that was adapted ($T1 = 10^\circ$, $T2 = -4^\circ$). For the other two units (e.g., *C* and *D*), pre- and postadaptation data overlapped over the entire amplitude range. Further experiments are needed to determine whether adaptation alters the movement fields of closed field neurons.

In summary, the majority of our NRTP neurons (19/34) discharged more spikes after backward adaptation had reduced the size of saccades to the adapted target step. Therefore, the number of spikes was not related to “desired eye displacement,” in which case there should have been no change in the number of spikes. Nor was the number of spikes related to “actual eye displacement,” in which case there should have been a decrease. Furthermore, adaptation also caused more spikes for different sized saccades to other target steps. Therefore, adaptation had influenced the entire movement field of these neurons whether the field was determined on the basis of actual or desired saccade amplitude.

Effect of amplitude increase adaptation

We recorded the activity of 13/47 neurons during forward adaptation to determine whether adaptation also increased the number of spikes in that situation. Based on their preadaptation movement fields, 11 neurons had closed movement fields and two had open movement fields. For the 11 closed field neurons, preferred amplitudes ranged from about 3 to about 10° . All 13 neurons had preferred directions within $\pm 45^\circ$ of the horizontal.

In general, the amplitude change produced by forward adaptation ($15.4 \pm 3.8\%$) was less than that produced by backward adaptation as has been reported by others (e.g., Straube et al. 1997). During a behavioral increase in saccade amplitude, we found no statistically significant changes in the number of spikes calculated by the comparison of either the sets of pre- and postadaptation trials ($n = 10$) or the first and last 20 adaptation trials ($n = 2$). The other neuron did show a statistically significant decrease in the number of spikes. With the data collected in this study, we are unable to determine whether amplitude increase adaptation affects the shape of closed movement field neurons.

DISCUSSION

Saccadic adaptation changes NRTP bursts

During adaptation of saccade amplitude, we found that over 50% (19/34) of our NRTP neurons exhibited statistically significant changes in burst characteristics when amplitudes were reduced. Of these, 95% (18/19; 14 with and four without postadaptation data) had open movement fields. Two of the three closed field neurons exhibited no significant change in their burst characteristics, but clearly their numbers are too small to reach a firm conclusion.

The change for the open field neurons was a significant increase in the number of spikes in the burst. This was revealed in two ways. First, during adaptation, the number of spikes increased as saccade amplitude decreased. The mean percentage increase (based on the change in the slopes of the linear regression fits to the scatter plots of saccade amplitude and number of spikes) across all 18 neurons was $45.4 \pm 16.3\%$. Because the target step that elicited the saccade was always the same but the saccade was decreasing in size, the increase in the number of spikes could not be associated with the “desired” saccade amplitude demanded by the target step. Second, adaptation caused changes in the entire movement field of an open field NRTP neuron and not just for the saccade size that was adapted. Saccades of all amplitudes were

associated with more vigorous bursts after adaptation than before. Indeed, small saccades that were accompanied by no burst before adaptation acquired one after adaptation (Fig. 9, A and B). We conclude that the majority of NRTP open field neurons alter their burst discharge during saccadic amplitude reduction, whereas a minority does not. This finding may suggest that these two groups of NRTP neurons have different roles in the generation of saccades.

In contrast, 12 of the 13 NRTP neurons tested during *saccadic amplitude increases* showed no significant changes in the number spikes. However, most had closed movement fields (11/13). A tentative conclusion from these data is that forward adaptation produces no changes in the discharge characteristics of closed field neurons but additional open field neurons probably should be tested because of the technical difficulties in producing the large adaptive amplitude increases that would be necessary to produce convincing results.

A similar asymmetry in adaptation of gain increases and decreases occurs in the vestibuloocular reflex (VOR; for recent review, see Boyden et al. 2004). VOR gain increases and decreases have been posited to occur separately at one of the multiple sites of adaptive motor plasticity that have been demonstrated in the VOR circuitry (for review, see Carey and Lisberger 2002). Therefore, it is possible that the site of amplitude increases in the saccadic system also is different from that underlying amplitude decreases.

Comparison with previous studies

Crandall and Keller (1985) reported previously that 56% of their NRTP had open fields and 44% had closed fields. Their percentages are more equal than our 70% open field and 30% closed field neurons. It is possible that this difference is the result of different recording sites in the anatomically complicated NRTP because their recordings seem to have been concentrated more rostrally than ours.

Although previous investigations (Crandall and Keller 1985; Hepp and Henn 1983) did not quantify the correlations between NRTP neuron discharge and movement kinematics, we show here that many of these correlations are significant. These strong correlations in some NRTP neurons between discharge properties and saccade kinematics are in contrast to those of SC neurons, their primary input, which are weak. Nonetheless, these correlations are not as robust as pontine saccade-related burst neurons (see Scudder et al. 2002 for recent review).

Can the increased NRTP spikes account for the reduction in saccade amplitude?

Figure 11 shows two feed-forward pathways by which saccadic commands may reach the brainstem burst generator (BG) from the superior colliculus (SC). One hypothesis is that the CFN helps shape the duration of the burst produced by the BG. Because burst duration is intimately related to saccade duration, which in turn increases linearly with saccade amplitude, control of the duration of the burst produced in the BG provides a mechanism to control saccade amplitude. During reduction of ipsiversive saccade amplitudes, the burst of CFN units, which is well timed with saccade end, tends to occur earlier (Scudder and McGee 2003) and/or with increased rates as saccades decrease in size (Inaba et al. 2003; Scudder and McGee 2003). These earlier and more vigorous bursts are believed to terminate saccades earlier through inhibitory influences either by OPNs, which turn the BG on and off, or IBNs, which inhibit abducens neurons (cf. Fuchs et al. 1993).

CFN neurons are inhibited by Purkinje cells (P-cells) of the oculomotor vermis (OMV; Ohtsuka and Noda 1991), which, in turn, receives a major input from the NRTP (Yamada and Noda 1987). P-cell firing has not yet been studied during adaptation. However, we show here that the number of spikes in the burst of NRTP neurons increases during behavioral reduction of saccade amplitude. The increase is manifest as an earlier onset of activity (Figs. 5–8). The

increase in early NRTP activity could shape the timing of the phasic activity of oculomotor vermis P-cells, which for normal (i.e., nonadapted) saccades varies with saccade size (Ohtsuka and Noda 1995). In this scenario, such changes in the timing of P-cell discharge during adaptation would alter the timing of the CFN neurons to which they project to produce alterations of BG activity appropriate for the adapted saccade.

The site of saccade adaptation

Our finding that most open field NRTP neurons change their discharge patterns with saccadic amplitude reduction suggests that adaptation occurs at or before the NRTP. The fact that extra spikes are added at the beginning of the burst argues that adaptation occurs upstream of the NRTP in one of its inputs from either the FEF or the SC. To our knowledge, the effect of saccadic amplitude adaptation on the behavior of FEF neurons is unknown. The SC, however, has been studied and the consensus of both stimulation (Edelman and Goldberg 2002; Melis and van Gisbergen 1996) and recording (Frens and van Opstal 1997) studies is that adaptation occurs downstream of the SC. The only unit recording study found no change in the discharge of SC burst neurons before and after adaptation (Frens and van Opstal 1997), leading those authors to conclude that the SC always signals the desired and not actual (adapted) saccade amplitude. However, an equally parsimonious explanation is that the movement field of the SC neuron has shifted to lower saccade amplitudes (like the shift illustrated in Fig. 9, A and B). Therefore, it seems prudent to revisit the SC to determine whether the effect of adaptation is causing a shift or distortion of movement fields there. If so, the effects of adaptation indeed are already reflected at the SC, suggesting adaptation occurs there or at an upstream site.

In addition to inputs from the SC and FEF, the NRTP also receives feedback from the CFN (Stanton 2001). However, the change in NRTP activity associated with adaptation occurs early in the burst before saccade onset. Therefore, it is unlikely to be the result of activity occurring in the CFN where changes arising from amplitude reduction adaptation are most prominent in association with saccade end (Inaba et al. 2003; Scudder and McGee 2003).

Consequences for models of saccade plasticity

Our observation that one of the largest inputs to the oculomotor vermis already reflects the effects of saccade adaptation complicates existing models of saccadic plasticity. For example, in some models, a pontine nucleus, either the NRTP (Dean et al. 1994) or the dorsolateral pontine nucleus (Schweighofer et al. 1996), simply serves as a passive relay for a saccadic command to the OMV. In another popular model (Quaia et al. 1999), there is no pontine relay nucleus at all. All models assume that adapted signals will show up only at the cerebellum or downstream from it. Our finding that adaptation already influences cerebellar inputs will need to be incorporated into existing and future models of saccadic plasticity.

NRTP neurons behave differently for adapted and normal saccades of the same size

Current models for the role of the cerebellum in shaping the burst in the BG assume that the discharge pattern of a CFN neuron is the same for a given size saccade, say 7° , whether it is generated in response to a 7° target step before adaptation or a 10° target step after a 30% adaptation. However, this assumption was never tested in the two studies that documented CFN activity during saccade adaptation (Inaba et al. 2003; Scudder and McGee 2003). If this assumption is true, the SC always sends a command for desired saccade amplitude to the BG and after adaptation the CFN presumably truncates that command earlier. Therefore, we were surprised to find that NRTP units discharge with different burst patterns for saccades with similar kinematics that are elicited by different target steps before and after adaptation. Our observation suggests that CFN neurons, if tested, might also exhibit different discharge patterns for adapted and nonadapted saccades of the same amplitude. In the highly simplified schematic of Fig. 11, the BG always delivers the same burst for all saccades that have the same metrics

no matter how they are elicited. If adaptation indeed produces a difference in the CFN discharge for the same saccade before and after adaptation, then the signal from the SC must change accordingly. Although this argument is admittedly highly speculative, it would suggest that adaptation affects signals not only in the SC pathway through the cerebellum but also in the direct SC pathway to the BG.

Relation to motor learning in other systems

Much is known about the neuronal substrate for the motor learning of reflex behaviors, such as the blink reflex and the VOR (e.g., Boyden et al. 2004; Raymond et al. 1996). In both, motor learning seems to be distributed between sites in the cerebellum and in the more direct reflex pathways. Distributed sites also may be used in saccade adaptation. In addition, considerable progress has been made in inferring the synaptic mechanisms underlying motor learning in both reflexes. In contrast, although the oculomotor cerebellum certainly is involved in the motor learning of the voluntary saccade, we have yet to identify either the mechanisms or even all the pathways involved in this motor learning. However, our finding that motor learning in the saccadic system already affects the input signals that reach the cerebellum may reveal a strategy that is important not only for saccade adaptation but also for the motor learning of involuntary reflexes.

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FIG. 1.

Nucleus reticularis tegmenti pontis (NRTP) neuron movement fields. For both the open field neuron (M13: preferred direction $190 \pm 70^\circ$) in A and the closed field neuron (K132: preferred direction $160 \pm 50^\circ$) in B, number of spikes in a burst are plotted against saccade amplitude along the preferred direction associated with the greatest discharge. Data are fit by a linear regression ($y = 0.79x - 2.6$, $R^2 = 0.94$) in A and a spline curve in B.

FIG. 2.

Typical discharge patterns of a motor (R148) and visuomotor (R144) NRTP neuron for saccades of different sizes along the units' preferred directions. In A–D, traces from *top* to *bottom*: vector eye position, associated rasters, and average aligned on either saccade onset (A and C, dashed vertical lines) or target onset (at calibration, B and D). D: 2 arrows indicate a response component that occurs from 70 to 90 ms after the target step.

FIG. 3.

Photomicrographs of sagittal sections showing reconstructed tracks and lesions made during penetrations into the NRTP. *A, C*: low-power photomicrographs and labeled outlines of the same areas shown in *B* and *D* at higher magnification. In *D*, 2 electrolytic lesions ($\Rightarrow$) were made 2.5 mm apart above and below unit R218 (*) using 30- μ A anodal current for at least 30 s. Gliosis produced by other tracks is indicated by $\rightarrow$ in *B* and $\leftarrow$ in *D*. Abbreviations: MLF, medial longitudinal fasciculus; nVI, abducens nucleus; NRTP, nucleus reticularis tegmenti pontis; PMPN, paramedian pontine nucleus; Pyr, pyramidal tract; SC, superior colliculus.

FIG. 4.

Representative saccadic amplitude reduction experiment for monkey R. *Top*: schematic of the backward adaptation paradigm. After 1 to 1.4-s fixation, a target steps by an amount T1. Triggered by the onset of the saccade (E), the target steps in the opposite direction by T2. *Middle*: saccade amplitude as a function of the number of the adaptation trial. For trials 1 to 220, T1 = 15° and T2 = 5°. For trials 221 to 531, T2 = 7°. *Bottom*: superimposed amplitudes of saccades for adaptation trials 1 to 10, 211 to 220, and 522 to 531. Traces are aligned on saccade onset. Horizontal dotted lines in each box indicate the displacements of T1 and T2.

FIG. 5.

Change in the number of spikes in a burst during the course of backward adaptation for unit M40. *Top*: adaptation of saccades made to 10° initial target steps with adapt steps of 3° between trials 1 to 364 and 5° from trials 365 to 806. Saccadic amplitude ($\circ$) and number of spikes ($\blacktriangle$) are plotted as a function of the number of the adaptation trial. Pre- and post-adaptation trials with their mean saccade amplitudes (larger open circles) and the mean number of spikes (larger solid triangles) $\pm$ SD (vertical bars) are shown at the *left* and *right*, respectively. *Bottom*: rasters and histograms of the averaged firing rates (bin width of 10 ms) for trials 1 to 15, 251 to 265, 501 to 515, and 792 to 806. Averaged histogram for trials 1 to 15 is superimposed as red outline on other 3 histograms. Open arrowheads show increase of presaccadic activity. All rasters and histograms are aligned on saccade onset ($\blacktriangle$).

FIG. 6.

Comparison of pre- and postadaptation saccades and associated discharge of neurons with increasing numbers of spikes during adapted decreases in saccade amplitude. *A, B*: vector eye amplitudes (*E*) before and after adaptation to a 15° (*A*) and 10° (*B*) target step (*T*) while recording representative units M21 and K65, respectively. Selected saccade amplitudes ranged from 13.6 to 15.6° before to 10.9 to 12.9° after adaptation for unit M21 and from 8.8 to 10.8° before to 6.5 to 8.5° after for K65. Associated activity for those saccade trials is shown as rasters and averaged histograms (bin width of 50 ms). Arrows show the added presaccadic activity $\Rightarrow$ and the time of peak discharge before (blue down arrow) and after (red down arrow) adaptation. *C, D*: saccades of the same vector amplitude elicited by different target steps before and after adaptation. Superimposed traces (~ 15) and mean (thick line) of vector eye position, velocity, acceleration, histogram of the average firing rate, and rasters for the same saccades. In all 4 panels, traces are aligned on saccade onset (vertical dashed line).

FIG. 7.

Change in the burst during the course of backward adaptation for unit M21 (*left column*) and K65 (*right column*). *Top to bottom*: saccade amplitude, peak velocity, saccade duration, number of spikes, burst duration, timing of burst onset (re saccade onset), burst end (re saccade onset), and timing of the peak burst rate plotted against the number of the adaptation trial.

FIG. 8.

Comparison of features of the burst accompanying saccades of similar size before and after amplitude reduction adaptation for 27 neurons with postadaptation data. Fifteen neurons with significant increases in the number of spikes after adaptation are shown as • and 12 neurons with no change as □. Features include number of spikes in the burst (A), burst duration (B), burst onset (re saccade onset) (C), burst end (re saccade onset) (D), peak discharge rate (E), and timing of peak rate (re saccade onset) (F). Data of unit M21 and K65 are identified by crosses, which also indicate $\pm$ SD.

FIG. 9.

Comparison of pre- and postadaptation movement fields along the preferred direction for representative open field neurons with either an increasing number of spikes (M32, *A* and *B*) or no change in the number of spikes (R148, *C* and *D*) after backward adaptation. Number of spikes are plotted both as a function of actual saccade amplitude (*A* and *C*) and desired saccade amplitude (*B* and *D*) for each neuron. Pre- and postadaptation data ($\circ$ and $\bullet$, respectively) are fit by linear regression.

FIG. 10.

Comparison of pre- and postadaptation movement fields along the preferred vector for representative closed field neurons with either an increased number of spikes (R103, *A* and *B*) or no change in the number of spikes (R188, *C* and *D*) after backward adaptation. Number of spikes are plotted both as a function of actual saccade amplitude (*A* and *C*) and desired saccade amplitude (*B* and *D*) for each neuron. Pre- and postadaptation data ($\circ$ and $\bullet$, respectively) are fit by spline curves.

FIG. 11.

Highly simplified schematic showing pathways by which saccadic commands may reach the brainstem burst generator for horizontal saccades. →: excitatory connections; ⇨: inhibitory connection; dashed arrows: feedback connections. BG, brainstem burst generator; CFN, caudal fastigial nucleus; FEF, frontal eye field; NRTP, nucleus reticularis tegmenti pontis; OMV, oculomotor vermis; SC, superior colliculus.