Substantia Nigra Stimulation Influences Monkey Superior Colliculus Neuronal Activity Bilaterally

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Submitted 20 September 2007; accepted in final form 21 June 2008

Liu P, Basso MA. Substantia nigra stimulation influences monkey superior colliculus neuronal activity bilaterally. J Neurophysiol 100: 1098 –1112, 2008. First published June 25, 2008; doi:10.1152/jn.01043.2007. The inhibition drive arising from the basal ganglia is thought to prevent the occurrence of orienting movements of the eyes, head, and body in monkeys and other mammals. The direct projection from the substantia nigra pars reticulata (SNr) to the superior colliculus (SC) mediates the inhibition. Since the original experiments in the SNr of monkeys the buildup or prelude neuron has been a focus of SC research. However, whether the SNr influences buildup neurons in SC is unknown. Furthermore, a contralateral SNr–SC pathway is evident in many species but remains unexplored in the alert monkey. Here we introduced electrical stimulation of one or both SNr nuclei while recording from SC buildup neurons. Stimulation of the SNr reduced the discharge rate of SC buildup neurons bilaterally. This result is consistent with activation of an inhibitory drive from SNr to SC. The time course of the influence of ipsilateral SNr on the activity of most SC neurons was longer (∼73 ms) than the influence of the contralateral SNr (∼34 ms). We also found that the variability of saccade onset time and saccade direction was altered with electrical stimulation of the SNr. Taken together our results show that electrical stimulation activates the inhibitory output of the SNr that in turn, reduces the activity of SC buildup neurons in both hemispheres. However, rather than acting as a gate for saccade initiation, the results suggest that the influence of SNr inhibition on visually guided saccades is more subtle, shaping the balance of excitation and inhibition across the SC.

INTRODUCTION

Cortical signals relaying eye movement information to the midbrain traverse at least two pathways. One arises from cerebral cortical neurons and directly targets the superior colliculus (SC) (Fries 1984; Harting et al. 1992; Stanton et al. 1988b). The cortical neurons are excitatory and convey the results of their processing to the SC for the generation of volitional saccades (Segraves and Goldberg 1987; Sommer and Wurtz 2000). A second pathway also arises from neurons of the cerebral cortex and targets the SC through a series of synapses within basal ganglia (BG) nuclei (Hikosaka et al. 1993; Parthasarathy et al. 1992; Seiblon and Goldman-Rakic 1985, 1988; Stanton et al. 1988a; Weyand and Gafka 1998). Of the two output nuclei of the BG, ocularmotor studies in monkey emphasize the substantia nigra pars reticulata (SNr) (Basso and Liu 2007; Basso and Wurtz 2002; Basso et al. 2005; Bayer et al. 2002; Handel and Glimcher 1999, 2000; Hikosaka and Wurtz 1983a,b,c,d; Sato and Hikosaka 2002) due to its direct projections to the SC (e.g., Jayaraman et al. 1977).

Using antidromic stimulation of the SC and recording of SNr neurons, a relationship between SNr neurons that pause transiently and SC neurons that discharge robustly during saccades was established in the monkey (Hikosaka and Wurtz 1983d). These experimental results led to the hypothesis that SNr inhibits the SC tonically, preventing the occurrence of saccades. The transient pause in SNr neurons is thought to remove the tonic inhibition from SC neurons, thereby gating the burst of activity within the SC. This series of events results in the initiation of a saccade. Consistent with this, experiments in rodents, cats, and monkeys reveal that disinhibition is a mechanism by which the SNr influences SC (Boussaoud and Joseph 1985; Chevalier and Deniau 1990; Chevalier et al. 1985; Hikosaka and Wurtz 1985a,b; Joseph and Boussaoud 1985).

Since the original experiments in monkeys, a second class of neuron within the monkey SC was characterized more fully (Glimcher and Sparks 1992; Munoz and Wurtz 1995; Sparks 1975). This class of neuron appears distinct from the saccade-related burst neuron in that it has a low level of tonic discharge well in advance of the burst of action potentials thought to initiate the saccade. Such neurons have been referred to as prelude or buildup neurons (Glimcher and Sparks 1992; Munoz and Wurtz 1995). The low-level, tonic discharge appears while monkeys wait for a cue to make a saccade and is associated with processes such as saccade selection, target selection, attention, movement preparation, and even decision making (Basso and Wurtz 1997, 1998; Glimcher and Sparks 1992; Horwitz and Newsome 1999, 2001; Ignashchenkova et al. 2004; Kim and Basso 2008; Krauzlis and Dill 2002; Kustov and Robinson 1996; McPeek and Keller 2002; Ratcliff et al. 2003). Recent evidence exploring the role of the BG in reward tasks points toward a possible role of the SNr in modulation of the tonic activity of SC buildup neurons (Hikosaka et al. 2006; Sato and Hikosaka 2002), but whether SNr can influence buildup neurons in monkey SC is unknown. Orthodromic stimulation experiments in the anesthetized cat show that SNr influences tecto-reticulospinal neurons (Karabelas and Moschovakis 1985), a subclass of which is likely to be the cat homolog of the monkey buildup neuron (Karabelas and Moschovakis 1985; Rodgers et al. 2006). Recording experiments in SNr, however, show that decreases in tonic activity of SNr neurons do not exactly mirror the increases in tonic activity of SC neurons. For example, although SC neuronal activity scales approximately linearly with saccade likelihood (Basso and Wurtz 2002; Dorris and Munoz 1998), the tonic activity of SNr
neurons does not (Basso and Wurtz 2002). Therefore the first goal of the present work was to test the hypothesis that SNr influenced the activity of SC buildup neurons. Our second goal was to determine whether the SNr influenced buildup neurons in the contralateral SC. Recent experiments in cat, combined with anatomical evidence in rat, cat, and monkey indicate that the SNr targets the contralateral SC (Beckstead 1983; Gerfen et al. 1982; Jiang et al. 2003; Redgrave et al. 1992), but this pathway has not been explored physiologically in the monkey.

Here we used stimulation of the SNr and recording of SC neurons to test whether alterations of SNr activity influenced buildup neuronal activity. To drive SC neurons maximally monkeys performed visually guided saccades. Importantly, we used an on-line, spectral filter to remove the stimulus artifact (Gnadt et al. 2003; Paul and Gnadt 2003), so were able to record SC neurons throughout the duration of the electrical stimulus train. When electrical stimulation of the SNr occurred at the time a cue to make a saccade appeared, SC buildup activity was reduced for the duration of the stimulation. Neurons recorded on the same side as the SNr stimulation as well as those recorded on the opposite side of the stimulated SNr showed a reduced rate of discharge during the stimulus train. Based on our results we conclude that the SNr influences buildup neurons within the monkey SC bilaterally.

METHODS

General behavioral procedures

We used a real-time experimental data acquisition and a visual stimulus generation system (Tempo and VideoSync; Reflective Computing) to create the behavioral paradigm and acquire eye position and neuronal data. Trained monkeys sat in a custom-designed primate chair with head fixed during the experimental session (typically 3–5 h). Visual stimuli were rear-projected onto a tangent screen at 51-cm distance using a DLP projector (LP335; Infocus) with a native luminance of 0.28 cd/m². The background luminance was 0.08 cd/m². The visual stimulus presentation was controlled by VideoSync software (Reflective Computing) running on a dedicated PC with a 1.024 × 768 VGA video controller (Computer Boards). The video PC was a slave to the PC used for experimental control and data acquisition. Two photocells attached to the screen provided accurate measurements of stimulus onset and offset.

Monkeys performed visually guided delayed saccades (Fig. 1, A and B). Initially a centrally located visual spot appeared and monkeys fixated this spot. After a random time of 500–1,500 ms, a peripheral spot appeared in the visual field. After another delay (800–1,200 ms), the fixation spot disappeared. At this time, monkeys were required to initiate a saccade to the visual spot located in the periphery (Fig. 1, A and B). When monkeys performed a trial correctly they received a drop of water or fruit juice as reward.

Surgical procedures

For electrophysiological recording of single neurons and monitoring eye movements, cylinders and eye loops were implanted in four rhesus monkeys (Macaca mulatta) using procedures described previously (Basso and Liu 2007). Anesthesia was induced initially with an intramuscular injection of ketamine (5.0–15.0 mg/kg). Intramuscular injection of atropine (0.5 mg/kg) minimized salivation. Monkeys were intubated and maintained at a general anesthetic level with isoflurane. An eye-movement-monitoring device was implanted (Judge et al. 1980). A plastic head holder for restraint and three cylinders (2 SNr and 1 SC) for subsequent microelectrode recording and stimulation were mounted on top of the exposed skull over craniotomies and secured with titanium screws and dental acrylic. Plastic hardware allowed subsequent magnetic resonance (MR) images to be obtained with minimal artifact. For access to the SNr, the two recording cylinders were targeted toward stereotaxic coordinates A10, L5 and angled mediolaterally about 40°–45°, depending on the angle of the SNr as determined by presurgical MR images. An antibiotic (cefadroxil, 25 mg/kg) was given 1 day before and each day for a minimum of 4 days after the operation. For access to both SCs, one cylinder was angled caudorostrally at about 38° and targeted toward coordinates A0–2, L0. Buprenorphine (0.01–0.03 mg/kg) and flunixin (1–2 mg/kg) were administered 48 h postsurgically, as needed, to provide analgesia. Monkeys recovered for 1–2 wk
before experiments commenced. All experimental protocols were approved by the University of Wisconsin–Madison Institutional Animal Care and Use Committee and complied with or exceeded standards set by the Public Health Service policy on the humane care and use of laboratory animals.

Stimulation and recording procedures

For each experiment, electrodes were aimed at the SC and SNr through stainless steel guide tubes held in place by a plastic grid secured to the cylinder (Crist et al. 1988). In a typical experiment, an electrode was advanced each day into the visual-oculomotor region of the SNr (Basso and Wurtz 2002; Handel and Glimcher 1999; Hikosaka and Wurtz 1983d). This region is very small, generally extending 1 mm AP (anterior–posterior plane) and 1 mm ML (medial–lateral plane). With our cylinders angled at 40° laterally, we often traverse the entire dorsal–ventral extent of the SNr, which can be as long as 4 mm. Using the grid system for recording (Crist et al. 1988) the visual–oculomotor region is usually found in only one or two grid holes (separated by 1 mm ML). In our experience, the different SNr neuronal response profiles are intermingled throughout this region (Basso and Liu 2007; Handel and Glimcher 1999).

Microelectrodes were introduced into each SNr first. Once an SNr neuron was isolated, we mapped the response field (RF) by having monkeys make visually guided saccades to six different locations (0, 180, and 45° up and down, left and right, excluding the directly upward and downward locations). We then introduced a third microelectrode into the SC (uncrossed, Fig. 1C), isolated a neuron, and assessed its RF by moving a visual spot throughout the visual field, having monkeys make saccades to the same locations and listening for the maximal discharge. These experiments are difficult and RF mapping is time consuming, so we opted to assess SC fields qualitatively having monkeys make saccades to the same locations and listening for the maximal discharge. For each experiment we monitored the unfiltered and the filtered waveforms independently on separate channels of an oscilloscope to ensure successful artifact removal on each trial. Since the device requires an “image” of the stimulus artifact to perform the artifact subtraction, a series of stimulation trials were presented in order for the image acquisition. During this time we were vigilant about not driving the isolated SC neuron, ensuring confidence that SC neuronal waveforms were not included in the subtracted artifact image. Figure 2 shows an example set of spike trains from one

![Figure 2](http://jn.physiology.org/)

FIG. 2. Examples of spike trains before and after stimulus artifact learning. A: 1,000-ms sweep of the voltage trace (in analog-to-digital [A/D] units) plotted against time. A 300-Hz, 50-μA train of pulses recorded as artifact from the electrode in the SC. B: 1,000-ms sweep of the voltage trace from the same recording day but a different trial after the Artifact Zapper learned the stimulus artifact. C: the same recording as shown in A in expanded view. Only 18 pulses (60 ms) of the 300-Hz, 400-ms stimulus train are seen. D: the same trace as in B expanded in time. The oblique dotted lines indicate the regions of the top traces that were expanded in time. The filled gray rectangles show the regions of the traces where the artifact occurred. There is a small amount of temporal jitter between the onset of the stimulation train shown in B and C compared with the onset shown in A and D because the exact time of the onset of the stimulation varied across trials.
recording within the SC with and without stimulation. Figure 2, A and C shows a spike train before the zapper learned the artifact. Figure 2, B and D shows a train after the learning and removal of the artifact.

**Data acquisition**

Single neurons were recorded with tungsten microelectrodes (FHC) with impedances between 0.1 and 1.0 MΩ measured at 1 kHz. Action potential waveforms were identified with a window discriminator (Bak Electronics) that returned a TTL pulse for each waveform meeting voltage and time criteria. The waveform discriminator (Bak Electronics) was placed in series with the Artifact Zapper (Riverbend Instruments) and waveform discrimination occurred after removal of the stimulus artifact. In some albeit rare cases, we could isolate single waveforms independent of the stimulus artifact removal system, providing a second way to ensure that the stimulation artifact did not contaminate the spike train data (Anderson et al. 2003). The TTL pulses were sent to a digital counter (PC-TIO-10; National Instruments) and were stored with a 1-ms resolution. Once an SNr neuron was isolated and characterized in the delayed-saccade task, using the same electrode, electrical stimulation commenced. By this time, the electrodes had impedances between 100 and 300 kΩ. For eye movement recording, we used the magnetic induction technique (Fuchs and Robinson 1966) (Riverbend Instruments). Voltage signals proportional to horizontal and vertical components of eye position were filtered (eight-pole Bessel; −3 dB, 180 Hz), digitized at 16-bit resolution, and sampled at 1 kHz (CIO-DAS1602/16; Measurement Computing). The analog eye position data were saved for off-line analysis using an interactive computer program designed to display and measure eye position and calculate eye velocity. We used an automated procedure to define saccadic eye movements by applying velocity and acceleration criteria of 25°/s and 8,000°/s², respectively. The result of the algorithm was confirmed or corrected if necessary on a trial-by-trial basis by the experimenter.

**Neuronal classification**

Previous work in the cat suggests that there is a topography of SNr response types within the SNr projecting to SC. To see whether we could find a similar topography in our experiments, we kept a careful record of the SNr response types recorded at each stimulation site. SNr neurons were classified as visual, saccadic, or visual-delay-saccadic as done previously (Basso and Liu 2007). For classification, we measured 200 ms of baseline discharge rate while monkeys fixated and before a visual stimulus appeared. We then measured the first 200 ms of neuronal discharge after the onset of the visual stimulus. The delay interval was defined as the discharge rate occurring 600–800 ms after the target spot appeared. The saccade interval was defined as the discharge rate occurring 50 ms before to 50 ms after the onset of the saccade. SNr neurons were classified as visual if they contained statistically significant differences (t-test, P < 0.05) in discharge rate during the visual interval compared with baseline. Saccade neurons were defined as those showing a significant difference in discharge rate during the saccade interval compared with baseline (t-test, P < 0.05). Visual-delay-saccade neurons were classified as those with statistically significant discharge rates during all three intervals compared with baseline (t-test, P < 0.05). Some visual and saccade neurons also had significant modulation during at least one other interval. These were classified as either visual-delay neurons if the delay period modulation was also significant or visual saccade if the saccade period was also significant. Of our sample, five neurons had increases in activity and appeared like those described as pause-burst neurons (Handel and Glimcher 1999). In our classification scheme, two of five were visual-delay-saccade neurons, two of five were visual neurons, and one of five was a visual-delay neuron. Consistent with a lack of topography, the effects of stimulation at sites where these neurons were recorded were not obviously different from the effects observed at locations where other neuronal response profiles were found.

**RESULTS**

While monkeys performed a visually guided delayed-saccade task (Fig. 1, A and B), we recorded from SC neurons during stimulation of either the contralateral or the ipsilateral SNr (Fig. 1C). We recorded from eight SCs and stimulated in eight SNrs of four monkeys. Thirty SC neurons were recorded during stimulation of the SNr in the same hemisphere as the recorded SC neuron (referred to as uncrossed). Twenty SC neurons were recorded during stimulation of the SNr in the opposite hemisphere as the recorded SC neuron (referred to as crossed). For eight of the uncrossed SC neurons, short, fixed-latency responses appeared with SNr stimulation. Although we did not perform the collision test (Bishop et al. 1962; Fuller and Schlag 1976), we interpreted this observation as evidence of...
antidromic activation of the tectoniral pathway (Comoli et al. 2003; Karabelas and Moschovakis 1985; York and Faber 1977). Because our interest here concerned orthodromic responses, we excluded these eight neurons from further analysis. The results reported here are from 22 SC neurons recorded with stimulation of the uncrossed SNr–SC pathway and 20 SC neurons recorded with stimulation from the crossed SNr–SC pathway. Thirteen of these were the same SC neurons recorded with stimulation of both SNr nuclei (Fig. 1C). Therefore the data set consists of 29 SC neurons. By recording SC neurons and having monkeys make saccades of the preferred vector for the recorded SC neurons, stimulating the ipsilateral SNr assessed the influence of the uncrossed pathway. Stimulation of the contralateral SNr (with respect to the SC) assessed the influence of the crossed pathway.

In what follows, we first describe the overall result of electrical stimulation in SNr on SC neurons by illustrating two examples: one uncrossed and one crossed. We then present the results from the sample of recorded neurons and then we present the results showing the influence of SNr stimulation on the corresponding saccade behavior.

**SNr stimulation and SC neuronal activity**

**UNCROSSED INFLUENCE.** The results from one SNr stimulation and SC recording experiment are shown in Fig. 3. As is typical for SC neurons with delay activity (prelude or buildup neurons), this example neuron had a low level of tonic discharge leading up to the time of the cue to make a saccade (Fig. 3A, dashed vertical line). This SC neuron preferred saccades directed to the right hemifield. When aligned on the saccade onset (Fig. 3B) the robust discharge of action potentials associated with saccade onset was evident. By introducing stimulation of the SNr at the time of the cue to make a saccade and extending it for 400 ms, we ensured that there was adequate activity of the SC neurons to be influenced by the SNr stimulation. We took this approach under the premise that with extracellular recordings, the detection of inhibition in neurons with little discharge would be difficult.

Applying electrical stimulation to the SNr in the same hemisphere as that of the recorded SC neuron resulted in a transient cessation of activity in the SC neuron (Fig. 3C). Within about 100 ms, the SC neuron resumed a high rate of discharge, although this resumed discharge did not reach the same high rate as that seen in the trials without stimulation (Fig. 3, A and C). This can be seen most clearly in the saccade-aligned traces in which the peak and the duration of the saccade-related burst appeared smaller with SNr stimulation than without SNr stimulation (cf., Fig. 3, B and D). To quantify the change in neuronal activity we measured the mean discharge rate of the SC neuron during a 300-ms window beginning at the time of the disappearance of the fixation spot in the no-stimulation trials (Fig. 3A, gray shaded region). The discharge rate was 72.91 spikes/s in this example. The mean discharge rate of the SC neuron during the same epoch on trials with SNr stimulation (the stimulation onset and the fixation spot offset occurred simultaneously; Fig. 3C, gray shaded region) was 50.22 spikes/s. The difference in discharge rate across trials for this example SC neuron with and without SNr stimulation was statistically significant (t-test, \( P < 0.01 \)). Despite the change in discharge around the time of the saccade, the amplitude of the saccade changed little with electrical stimulation of the SNr (mean amplitude without stimulation = 10.45°; mean amplitude with stimulation = 10.55°; Wilcoxon, \( P = 0.77 \)). For this example, SNr stimulation reduced the average saccade velocity across the trials (mean without stimulation = 581.30°/s; mean with stimulation = 555.25°/s; Wilcoxon rank-sum test, \( P < 0.01 \)). This example provides direct evidence that the SNr inhibits presaccade and saccade-related discharge of SC buildup neurons and is associated with a reduced velocity of saccades.

**CROSSED INFLUENCE.** Stimulation of the SNr in the hemisphere opposite to the recorded SC neuron produced similar results as seen for stimulation within the same hemisphere (Fig. 4). Stimulation of the SNr opposite the recorded SC produced a transient reduction in the discharge of the SC neuron (Fig. 4, A, B, C).
velocities was 292.76°/s, whereas in trials with SNr stimulation, the mean of the radial saccade velocities increased slightly to 297.44°/s. These differences failed to reach statistical significance (Wilcoxon, $P = 0.71$). Taken together, these two examples show that SNr stimulation inhibits the activity of SC buildup neurons whether stimulation occurs in the same hemisphere as the recorded SC neuron or in the opposite hemisphere. Furthermore, in spite of the significant changes in the discharge rate of the SC neurons, there was little evidence of change in the characteristics of saccades. The latter result is consistent with our previous observations that electrical stimulation of the SNr had little effect on visually guided saccades (Basso and Liu 2007).

**SNr stimulation suppresses SC neuronal activity: group results**

To determine whether the change in discharge rate of SC neurons associated with electrical stimulation of the SNr occurred consistently across our sample of SC neurons, we measured the discharge rate during a 300-ms interval beginning at the time of the fixation spot offset. This time corresponded to the onset of the electrical stimulation of the SNr. Figure 5 shows the mean of the discharge rates measured across trials for each SC neuron with SNr stimulation against the mean of the discharge rates of the SC neurons without SNr stimulation. For uncrossed neurons (Fig. 5A), the mean discharge rate without stimulation was 73.80 spikes/s. The mean discharge rate dropped to 64.43 spikes/s with stimulation. The decreases in discharge rate for uncrossed SC neurons between stimulation and no-stimulation trials were individually significant in 9 of 22 (41%) of the neurons (Fig. 5A, filled circles below unity line; $t$-test, $P < 0.05$). Thus stimulation of the SNr on the same side as the recorded SC neuron resulted in an overall reduction in SC neuronal activity.

For crossed neurons (Fig. 5B), the mean discharge rate without stimulation was 73.78 spikes/s. With stimulation of the SNr, the discharge rate dropped to 62.68 spikes/s. The decreases in discharge rate for crossed SC neurons between stimulation and no-stimulation trials were individually significant in 13 of 20 (65%) of the neurons (Fig. 5B, filled circles below unity line; $t$-test $P < 0.05$). Across the sample of SC neurons regardless of the side of SNr stimulation, three neurons had slight but statistically significant increases in neuronal activity with SNr stimulation (Fig. 5, A and B, filled circles above the line of unity; $t$-test $P < 0.05$). Taken together we conclude that SNr stimulation primarily suppresses SC buildup neuronal activity bilaterally.

Figure 6 shows the average response profiles of uncrossed and crossed SC neurons when aligned on the disappearance of the fixation spot (Fig. 6, A and C) and when aligned to the onset of the saccade (Fig. 6, B and D). In the uncrossed neurons as a group, there was a slight reduction in activity followed by an apparent, accelerated rise in the saccade-related burst. The saccade-related burst overall was reduced slightly in the stimulated trials compared with the unstimulated trials (Fig. 6A). When the same data were aligned on the saccade, there was a slight reduction in discharge rate for most of the duration of the stimulus train (Fig. 6B). Even the transient visual activation appearing at the end of the saccade was reduced in the stimulated trials (Fig. 6, A and B, arrowheads). The difference
The filled square shows the result for the example neuron shown in neurons recorded in the hemisphere opposite the side of SNr stimulation reduced with SNr stimulation (Fig. 6, neuronal activity was reduced for most of the duration of the robust (Fig. 6, In this case, however, the reduction in SC activity was more statistically significant (Kruskal–Wallis, the SNr across the sample of uncrossed SC neurons was in neuronal activity measured with and without stimulation of the hemisphere opposite the stimulated SNr (Fig. 6, A similar finding was obtained for SC neurons recorded in the same side as the stimulated SNr, 18 of 22 (82%) of the SNr–SC pairs had the same preferred hemifield. For the SC neurons recorded from the opposite side of SNr stimulation, 0 of 22 (0%) had the same preferred hemifield, 20 of 20 (100%) of the SNr–SC stimulation-recording pairs from opposite sides had opposite preferring hemifields. Only 4 of 22 (18%) of the pairs from the same side had opposite preferring hemifields.

Time course of SNr influence on SC neuronal activity

We next explored the timing of the influence of SNr stimulation on SC neuronal activity. Often visual inspection is adequate to determine the time of an increase in neuronal discharge with extracellular recording. Determining the time of decreases in extracellular neuronal discharge however, is less straightforward. We opted to use the statistically rigorous and sensitive method based on signal detection theory (Green and Swets 1966): receiver operating characteristic (ROC) analysis. This method, combined with the fact that we are measuring extracellular action potentials, likely overestimates the actual time the SNr is able to influence SC (Karabelas and Moschovakis 1985). By computing ROC curves combined with a bootstrapping procedure (see METHODS) we determined the time point at which the spike density functions from stimulated trials and nonstimulated trials became significantly different from one another. For this analysis, ROC areas of 0.50 indicate no difference between the stimulated and nonstimulated spike trains; values >0.50 indicate increases in activity, whereas values <0.50 indicate decreases in activity.

Figure 7A shows the results of the ROC analysis performed for all the neurons in our sample. ROC area is plotted against time in milliseconds, beginning 100 ms before the onset of the SNr stimulation. The result for the 20 crossed neurons is shown in black and the result for the 22 uncrossed neurons is shown in red. Shortly after the stimulation train began there was a

![Graph showing the influence of SNr stimulation on SC neuronal activity.](image-url)
SNr stimulation and saccade characteristics

Our previous work using the stimulation parameters identical to those used here showed that SNr stimulation affected visually guided saccades only slightly, at least compared with memory-guided saccades (Basso and Liu 2007). Since we observed differences in SC neuronal activity around the time of the saccade-related burst, we explored whether saccades were altered in a predictable fashion. To assess changes in saccade parameters, we examined the saccades in the stimulation and no-stimulation conditions only for those data in which the SC neurons showed statistically significant ROC areas (18 crossed and 20 uncrossed).

We first explored alterations in the latency of saccades since our previous work revealed changes in saccade latency with stimulation of the SNr (Basso and Liu 2007). Since we observed changes in the tonic activity of SC neurons with SNr stimulation and this activity is associated with saccade latency (Basso and Wurtz 1998; Dorris et al. 1997), we reasoned that we should see predictable changes in saccade latency with SNr stimulation. Figure 8, A and B shows the cumulative distributions of saccade latencies with and without SNr stimulation for uncrossed and crossed neurons. For the data obtained from uncrossed neurons (saccades contralateral to both the SNr and the SC), the mean latency of saccades without stimulation was 203.85 ms, whereas the mean latency of saccades with stimulation was 184.67 ms. The median latency without stimulation was 204 ms, whereas the median latency with stimulation of the SNr was 185 ms. These differences were statistically reliable (Fig. 8A, Wilcoxon rank-sum test, P < 0.001).

For the data obtained from the crossed neurons (ipsilateral to the SNr but still contralateral to the SC), the mean saccade latency was 207.72 ms, whereas the mean saccade latency with stimulation of the SNr was 211.11 ms. The median latency without stimulation was 209 ms, whereas the median latency with stimulation of the SNr was 207 ms. These differences were statistically unreliable (Fig. 8B, Wilcoxon rank-sum test, P = 0.71). At the tails of the distribution there appeared to be...
TABLE 1. Distribution of SNr and SC neurons

<table>
<thead>
<tr>
<th>Hemisphere</th>
<th>Crossed</th>
<th>Uncrossed</th>
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<tbody>
<tr>
<td><strong>A. SNr neurons</strong></td>
<td></td>
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</tr>
<tr>
<td>Visual</td>
<td>2</td>
<td>4</td>
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<tr>
<td>Visual delay</td>
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<td>1</td>
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<tr>
<td>Visual delay saccade</td>
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<td>10</td>
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<tr>
<td>Visual saccade</td>
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<td>5</td>
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<tr>
<td>Saccade</td>
<td>20</td>
<td>22</td>
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<tr>
<td><strong>B. SC neurons</strong></td>
<td></td>
<td></td>
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<tr>
<td>Visuomotor (burst)</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Buildup (prelude)</td>
<td>18</td>
<td>20</td>
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<tr>
<td>Total</td>
<td>20</td>
<td>22</td>
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<tr>
<td><strong>C. Response field</strong></td>
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<tr>
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<td>Crossed</td>
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<tr>
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<td>4/22</td>
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<td>Nonoverlapped/Opposite</td>
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<td>Uncrossed</td>
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The response characteristics of the SC and SNr neurons were determined as described in METHODS. SNr neuron types are listed and the numbers of each type indicated under the columns labeled “Crossed” or “Uncrossed.” If the SNr neuron was located in the hemisphere opposite the recorded SC neuron, the SNr neuron type is indicated in the column labeled “Crossed.” If the SNr neuron was located in the same hemisphere as the recorded SC neuron, the type is indicated in the column labeled “Uncrossed.” A total of 20 SNr stimulation sites and 22 SC neurons were from opposite sides of the brain (crossed). In all, 22 SNr sites and SC neurons were stimulated and recorded from the same side of the brain (uncrossed). The SC neuron types are indicated and included in the columns labeled “Crossed” and “Uncrossed” according to the same criteria as for SNr neuron types. The same RFs indicate that the approximate centers of the SNr and SC neurons were located in the same hemifield. Nonoverlapping RFs indicate that the centers did not overlap. Most were located in the opposite hemifield.

differences in the saccade latency (Fig. 8B). If we divided the saccades into >200- and <200-ms groups, the small differences between the nonstimulated and stimulated saccade latency distributions were statistically reliable (Fig. 8B, Kolmogorov–Smirnov, P = 0.04). Consistent with our previous observations (Basso and Liu 2007), stimulation of the SNr reduced the latency of saccades made contralateral to the stimulated SNr (uncrossed), whereas stimulation tended to increase the latency of saccades made ipsilateral to the stimulated SNr (crossed). Interestingly, this occurred despite the transient suppression of tonic activity of buildup neurons bilaterally.

Closer inspection of the saccades shown in Figs. 3, A and C and 4, A and C suggested that the latency of the saccades not only became shorter or longer with stimulation of the SNr, but also became more consistent on trials with SNr stimulation. To quantify a change in variability of saccade onset time and to determine whether this was a reliable observation across our sample of stimulation sites, we computed the SD of the saccade latency on trials with and without SNr stimulation. Across the sample of sites, the median of the SDs of saccade latencies on no-stimulation trials for uncrossed neurons was 31.75 ms, whereas the median of the SDs on stimulated trials was 23.72 ms. The difference in the medians of the SDs was statistically reliable (Wilcoxon rank-sum test, P = 0.03). For the data collected during the crossed SNr stimulation–SC recordings (saccades ipsilateral to the SNr but still contralateral to the SC), the median of the SDs of saccade latency was 28.33 without SNr stimulation, whereas the median of the SDs with SNr stimulation was 24.47. This smaller difference in saccade latency variability was not significant (Wilcoxon, P = 0.10).

Figure 8C shows the means of the SDs of the saccade latencies for the 38 stimulation sites with significant ROC areas (see earlier text). In addition to decreases or increases in saccade latency with SNr stimulation, SNr stimulation in the same hemisphere as the SC responsible for generating the saccade reduced the variation in the onset time of saccades.
and no-stimulation trials, radial velocity of the eye movements made in the stimulation endpoints of saccades. We computed the radial amplitude and stimulation as determined by ROC and the permutation test (see text) are shown.

Points falling below the line indicate reduced SDs in the stimulated trials. Only the stimulation (18 crossed neurons). The oblique dashed line is the line of unity. (20 uncrossed neurons). The black circles show the data obtained from trials in which the SC neurons recorded were on the same side as the SNr stimulation. Each point is the mean computed from a single experiment and mean of the SDs of the saccade latencies measured on trials without SNr stimulation. The blue lines show the cumulative proportions for the stimulation trials. The red lines show the cumulative proportions for the no-stimulation trials. The blue arrowheads indicate the cumulative proportion of saccades across all stimulation sites is plotted. We found no significant effect of SNr stimulation on the amplitude variability of saccades (Wilcoxon rank-sum test; \( p = 0.15 \): crossed; \( p = 0.17 \): uncrossed). To determine whether there were changes in the variability of saccade direction, we computed the angle of the eye movement in degrees for the stimulated and nonstimulated trials and then determined the circular SD of the distribution of saccade directions (Fisher 1993). In contrast to the amplitude, the variability of the directions of the saccades differed with SNr stimulation. The median of the circular SDs measured on trials without stimulation was 2.32°, whereas the median of the circular SDs measured on trials with stimulation was 2.19°. This small decrease in variability was statistically significant (Wilcoxon rank-sum test, \( p = 0.01 \)). The change in variability was absent in saccades when the stimulation occurred in the crossed pathway (Wilcoxon rank-sum test, \( p = 0.21 \)). Thus as occurred with saccade latency, electrical stimulation of the SNr on the same side as the SC generating the saccade decreased the variability of saccade direction.

**DISCUSSION**

Our first goal was to test the hypothesis that electrical stimulation of the SNr influenced SC buildup neurons. Our second goal was to test the hypothesis that SNr influenced SC neurons bilaterally. Our combined stimulation and recording experiments provide direct evidence that the SNr influences buildup neurons bilaterally. The principal effect of electrical stimulation of the SNr was to suppress buildup neuronal activity within the SC of both hemispheres. We first discuss the relationship between our findings on SC buildup neurons and previous work on the uncrossed SNr–SC pathway. We then discuss the relationship between our findings and previous work on the crossed SNr–SC pathway. We then discuss the alterations in saccade characteristics and the implications for the role of the SNr–SC pathway in saccade generation.

We also determined whether there were changes in the endpoints of saccades. We computed the radial amplitude and radial velocity of the eye movements made in the stimulation and no-stimulation trials, \( r = \sqrt{x^2 + y^2} \), where \( r \) is the radial amplitude or velocity, \( x \) is the horizontal amplitude or velocity, and \( y \) is the vertical amplitude or velocity. Figure 9 shows the distribution of saccade vectors in the nonstimulated (Fig. 9, A and B, black arrows) and the stimulated trials (Fig. 9, A and B, cyan arrows). The mean radial amplitude of the saccades made in no-stimulation trials was 10.88° and in stimulation trials was 10.87°. These two distributions were statistically indistinguishable (Wilcoxon rank-sum test, \( p = 0.67 \); data not shown). We obtained a similar result when comparing the radial velocity of the saccades made in stimulation trials and no-stimulation trials. The mean radial velocity of the saccades in no-stimulation trials was 523.80°/s and the mean radial velocity of the saccades made in stimulation trials was slightly increased to 528.00°/s. These differences were statistically indistinguishable (Wilcoxon rank-sum test, \( p = 0.56 \); data not shown). Thus despite statistically reliable changes in the neuronal discharge rate of SC neurons around the time of saccades, the endpoint amplitude and velocity of visually guided saccades remained unaltered with SNr stimulation.

Because we found changes in the variability of saccade latency with SNr stimulation we were also interested in whether there were more subtle changes in saccade characteristics such as in the variability of the amplitude or direction of the eye movement. We compared the SD of the saccade endpoint amplitudes across the sample of 38 sites. We found no significant effect of SNr stimulation on the amplitude variability of saccades (Wilcoxon rank-sum test; \( p = 0.03 \): uncrossed; \( p = 0.01 \): crossed). To determine whether there were changes in the variability of saccade direction, we computed the angle of the eye movement in degrees for the stimulated and nonstimulated trials and then determined the circular SD of the distribution of saccade directions (Fisher 1993). In contrast to the amplitude, the variability of the directions of the saccades differed with SNr stimulation. The median of the circular SDs measured on trials without stimulation was 2.32°, whereas the median of the circular SDs measured on trials with stimulation was 2.19°. This small decrease in variability was statistically significant (Wilcoxon rank-sum test, \( p = 0.01 \)). The change in variability was absent in saccades when the stimulation occurred in the crossed pathway (Wilcoxon rank-sum test, \( p = 0.21 \)). Thus as occurred with saccade latency, electrical stimulation of the SNr on the same side as the SC generating the saccade decreased the variability of saccade direction.
Relationship to previous work on the uncrossed SNr–SC pathway

In the original studies of the ipsilateral SNr–SC pathway in monkeys (Hikosaka and Wurtz 1983d), SNr neurons were driven antidromically with stimulation of the SC. SNr neurons were activated with short and fixed latencies, consistent with their known input to SC in multiple species (e.g., Chevalier et al. 1981; Graybiel 1978; Jayaraman et al. 1977). Furthermore, locations within the SC resulting in antidromic activation of SNr neurons occurred at multiple depths, suggesting that SNr axons branch extensively along the vertical dimension within the SC.

The work of Hikosaka and Wurtz (1983d) in the monkey emphasized the dorsolateral aspect of the SNr. This region provides input to the upper half of the intermediate layers of the SC, which is also presumably the location of the saccade-related burst neurons (Harting et al. 1988; Huerta et al. 1991; May and Hall 1984; Munoz and Wurtz 1995). There is some suggestion that the buildup neurons are located below the burst neurons, in the lower part of the intermediate layers (Munoz and Wurtz 1995; Rodgers et al. 2006; Wurtz and Munoz 1994). We generally find burst and buildup neurons intermixed within the intermediate layers of the SC (Basso and Wurtz 1998; Krauzlis et al. 2000; Li and Basso 2005; Li et al. 2006). The present finding that SNr influences SC buildup neurons is consistent with the fact that we explored the SNr outside of the most dorsolateral region and with recent electrophysiological recordings in the monkey showing that neurons modulated during saccades and the occurrence of visual stimuli can be found throughout the extent of the SNr nucleus (Basso and Liu 2007; Handel and Glimcher 1999). Our result of SNr stimulation influencing buildup neurons also supports the hypothesis that the SNr influences many neuron types within the SC in addition to the saccade-related burst neurons (Karabelas and Moschovakis 1985). Future experiments will target other neurons within the SC such as the visual-tonic neurons, which generally are located more dorsally than saccade-related neurons in the SC (Li and Basso 2005; Li et al. 2006; McPeek and Keller 2002).

Relationship to previous work on the crossed SNr–SC pathway

A physiological demonstration of a contralateral SNr–SC pathway was recently identified in cats (Jiang et al. 2003), but as far as we are aware, such a pathway has not been explored systematically in the monkey (Karabelas and Moschovakis 1985). The current conceptual model of the role of the SNr–SC in saccade generation in the monkey emphasizes the uncrossed SNr–SC projection, yet there is anatomical evidence in rodents, cats, and monkeys that the SNr targets the SC bilaterally (Deniau and Chevalier 1992; Gerfen et al. 1982; Jayaraman et al. 1977; Jiang et al. 2003; Redgrave et al. 1992). Our results showing that stimulation of the SNr influences buildup neurons in the SC on the opposite side of the brain provide further, direct evidence for a crossed SNr–SC pathway in monkeys.

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**FIG. 9.** SNr stimulation alters visually guided saccade direction. **A:** saccade vectors are indicated by the arrows. Black arrows are no-stimulation trials and blue arrows are stimulation trials. Each saccade recorded from each trial and each experiment is plotted in polar coordinates for the uncrossed data. **B:** the same as in A for the crossed data. The direction of each arrow indicates the saccade direction and thus the preferred direction of the SC neuron for that recording day. Note that multiple experiments may have had multiple similar directions. **C:** the circular SD of saccade directions measured across trials with SNr stimulation is plotted against the circular SD of saccade directions measured across trials without SNr stimulation. The red circles show the data obtained from trials in which the SC neurons recorded were on the same side as the SNr stimulation (20 uncrossed neurons). The black circles show the data obtained from trials in which the SC neurons recorded were on the opposite side as the SNr stimulation (18 crossed neurons). The oblique dashed line is the line of unity. Points falling below the line indicate a reduced SD in the stimulated trials. Only the neurons with statistically significant suppression of neuronal activity during SNr stimulation as determined by ROC and the permutation test (see text) are shown.
Also, the current model of the SNr–SC involvement in saccades focuses on the transient pause around the time of a contralateral saccade (with respect to the SNr) and the temporally correlated increase in discharge of burst neurons in the SC (Hikosaka et al. 2006; Lo and Wang 2006). However, neurons in the cat and monkey SNr display a variety of response profiles around the time of head or eye movements and the onset of visual stimuli both ipsilaterally and contralaterally (Basso and Wurtz 2002; Basso et al. 2005; Bayer et al. 2002; Boussaoud and Joseph 1985; Handel and Glimcher 1999, 2000; Hikosaka and Wurtz 1983a,b,c). Taken together, the model of the role of the SNr in saccades should be revisited.

In the cat, two distinct neuronal populations in the SNr contribute to the crossed and uncrossed pathways to the SC (Jiang et al. 2003). Characteristics of uncrossed SNr neurons include a broad distribution throughout the extent of the SNr nucleus, lower conduction velocities compared with crossed SNr neurons, discharge rates ranging between 11 and 86 spikes/s, RF locations centered on the contralateral hemifield, RF sizes smaller than those of crossed pathway neurons, and transient pauses in tonic activity associated with the onset of visual stimuli. Crossed neurons, in contrast, are located within the anterolateral portion of the SNr, have higher conduction velocities compared with those of uncrossed neurons, discharge rates ranging between 0.12 and 40 spikes/s, have large RFs with locations centered on the ipsilateral hemifield, and transient increases in neuronal discharge associated with a visual stimulus moving through the RF. Based on these differences, and the finding that both uncrossed and crossed SNr neurons receive input from prestriate visual cortex, the authors suggested that the crossed and uncrossed pathways work in concert to produce a wanted movement through disinhibition of the SC on the same side, while simultaneously preventing an unwanted movement by inhibition of the SC on the opposite side.

Our results in the monkey are consistent with the cat results. For example, in the cat, using orthodromic stimulation, a 100-μs, 100- to 300-μA stimulation pulse to the SNr suppressed the visual response of SC neurons recorded on the opposite side of the brain (n = 4) (Jiang et al. 2003). Although we used trains of electrical stimulation (60 μA, 150 μs, 300 Hz, 400-ms duration), we found a similar suppression of SC activity, indicating that the crossed SNr–SC pathway exerts inhibition on SC neurons like its uncrossed counterpart. However, a number of differences are evident between the cat results and the monkey results reported here.

First, in general, SNr sites of stimulation influencing the same or opposite SC were intermingled within the SNr nucleus. We did not find an obvious segregation between crossed and uncrossed SNr–SC neurons. Indeed, an inability to drive SNr neurons antidromically does not indicate conclusively that the input does not exist. The stimulating electrodes in the cat experiments were located along a rostrocaudal axis. Perhaps antidromic activation would have been obtained had the stimulating electrodes been oriented along the mediolateral axis. Anecdotal reports in the cat suggest that single SC neurons are inhibited equally well from either SNr (Karabelas and Moschovakis 1985). We report here 13 SC neurons that were inhibited by stimulation from either SNr. If the monkey crossed and uncrossed pathways arise from segregated neuronal pools within the SNr as antidromic experiments in the cat suggest, then our ability to influence the same SC from either SNr must have resulted from systematically stimulating two different regions of the SNr. Although possible, we think this is unlikely. Second, the great majority of our SNr neurons had tonic discharge rates in excess of 40 spikes/s. We did not find a systematic difference in discharge rate of neurons recorded at sites in the SNr where stimulation influenced the opposite SC. Third, despite the profound suppression of SC activity, the saccade-related burst and the resulting saccade still occurred in our experiments with SNr stimulation. This result is not predicted from the cat results.

There are at least two possible explanations for the finding that the SC burst was only scarcely affected by the SNr stimulation. The first possibility is that the stimulation train used in our experiments depleted γ-aminobutyric acid or saturated postsynaptic receptors and thus was no longer effective at suppressing SC activity. We think this is unlikely because when we realigned the traces to the onset of the saccade, we found that suppression of SC activity, although weak, extended for most of the train duration (Fig. 6). A second possibility is that the combination of the persistent visual drive to the SC, likely arising from extrastriate cortex (eg., Paré and Wurtz 2001), and the recurrent excitation among pools of SC neurons (Moschovakis et al. 1996; Özen et al. 2004) was able to override the inhibition arising from SNr. If this is true, stimulation of the SNr in the absence of a visual drive should be maximally effective on SC neurons. Consistent with this hypothesis, we previously found that stimulation of the SNr affected memory-guided saccades more profoundly than visually guided saccades (Basso and Liu 2007). Because of the known “upward shift” of memory-guided saccades (Gnadt and Andersen 1988; White et al. 1994) and the differences in discharge among SC neurons for memory-guided saccades (Stanford and Sparks 1994), we did not test memory saccades in the present experiments. Therefore future experiments will have to be performed to determine whether a greater effect of SNr stimulation exists on SC neurons for saccades made to locations without visual stimuli present.

A final difference between our results and those reported in the cat is that in our sample of SNr neurons the most common response profile was a decrease in activity (data not shown). In the cat, SNr neurons projecting to the same side SC showed pauses in neuronal activity and the SNr neurons projecting to the opposite SC showed increases in neuronal activity for the appearance of visual stimuli. In the sample of SNr neurons reported here, 5 of 42 SNr neurons might fall within the category described by Handel and Glimcher (1999) as pause bursters. At the sites where three of these were recorded, stimulation of the SNr influenced the SC in the opposite hemisphere. Thus based on this limited sample, we find SNr neuronal response properties intermingled within the nucleus and we find no clear difference in the neuronal response types located at sites of stimulation within the SNr capable of influencing SC activity.

Relationship of stimulation effects to saccade behavior

A surprising finding reported here was the overall small effect of stimulation on the amplitude and velocity of the saccades. Also surprising was the large decrease observed for contralateral saccade latency, in spite of the decreases in SC
buildup neuronal activity. Surprising and in our view, most interesting, was the observation that the variability in saccade latency and direction was reduced with stimulation of the SNr. Combining these results suggests that the influence of the SNr on the SC and visually guided saccade behavior is more subtle than previously thought. We first discuss the changes in saccade latency and then discuss the changes in latency and direction variability.

Across the sample of neurons reported here, we found reliable decreases in discharge rate of SC neurons with SNr stimulation. We also found very reliable decreases in contralateral saccade latency with SNr stimulation. There are at least two explanations for this. First, electrical stimulation of the SNr may have activated descending corticofugal fibers excising the SC (Chevalier et al. 1984; Karabelas and Moschovakis 1985). Second, stimulation of the SNr could antidromically activate cholinergic pedunculopontine neurons (Scarnati et al. 1984). Activation of pedunculopontine neurons would excite SC saccade-related neurons (Watanabe et al. 2005). Consistent with this, we initially found in the uncrossed SC neurons a lower level of suppression of neuronal activity, compared with that seen in the crossed SC neurons. This may indicate that both excitatory and inhibitory drives were activated in the uncrossed pathway. Certainly, local injections of glutamate into the SNr combined with recording of SC neurons will be required to determine conclusively whether the decreases in latency depend on activation of fibers of passage.

Another possibility that could explain the decrease in contralateral saccade latency is that SNr neurons that project to the buildup neurons also have a collateral axon that targets an inhibitory interneuron within the SC. In this scheme, stimulation of the SNr would produce an initial inhibition of the buildup neuron through its direct input and then a subsequent disinhibition arising from the collateral input to the inhibitory interneuron. The initial suppression followed by the apparently faster rise of the saccade-related burst are consistent with this idea (Fig. 6A). We favor this hypothesis over the hypothesis that the stimulation activated excitatory inputs for three reasons. One, if the stimulation activated the excitatory input we should have observed increases in SC neuronal activity more often than we did. Only three neurons showed only modest increases in activity with SNr stimulation in our sample. Second, recent in vitro work in the rodent has identified a projection from the SNr to GAD+ inhibitory interneurons within the SC (Yanagawa et al. 2007). Third, based on our previous results, SNr stimulation affects memory saccades more than visually guided saccades (Basso and Liu 2007). If the effects of stimulation resulted primarily from activation of excitatory inputs to the SC, the effects on saccades should be independent of context.

It is interesting that the decreases in saccade latency as well as the decreases in variability of saccade latency and saccade direction all occurred with stimulation of the SNr on the same side as the SC generating the saccade. It is not immediately obvious how these changes would result from activation of an excitatory drive. Rather, we think these kinds of changes in behavior are more easily understood with disinhibition, as would occur if the SNr targets an inhibitory interneuron that also influences buildup neurons. Regardless of the mechanism, the result is consistent with the hypothesis that the influence of the SNr on SC is not to gate the occurrence of saccades—at least visually guided saccades—in an all-or-none fashion. Rather, the results suggest that the input from the SNr to the SC plays a more subtle role (Hikosaka et al. 2000), perhaps by altering the balance of excitatory drives arising from cortex and the inhibitory influences arising from intrinsic circuits.

Acknowledgments

We thank Dr. Xiaobing Li, B. Kim, and Dr. Xu Yang for assistance with data collection and B. Kim for Matlab code. We also thank the Parkinson Disease Foundation for funding the summer student fellowship of T.J.G. Day, who participated in preliminary data collection and analysis. We also thank the anonymous reviewers for helpful comments on the manuscript.

Grants

This work was supported by National Eye Institute Grant EY-13692 and the Esther A. and Joseph Klingenstein Foundation to M. A. Basso, and National Center for Research Resources Grant P51 RR-00167 to the Wisconsin National Primate Research Center.

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J Neurophysiol • VOL 100 • AUGUST 2008 • www.jn.org


