Multisecond Oscillations in Firing Rate in the Basal Ganglia: Robust Modulation by Dopamine Receptor Activation and Anesthesia

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Ruskin, David N., Debra A. Bergstrom, Yoshiki Kaneoke, Bindu N. Patel, Michael J. Twery, and Judith R. Walters. Multisecond oscillations in firing rate in the basal ganglia: robust modulation by dopamine receptor activation and anesthesia. J. Neurophysiol. 81: 2046–2055, 1999. Studies of CNS electrophysiology have suggested an important role for oscillatory neuronal activity in sensory perception, sensorimotor integration, and movement timing. In extracellular single-unit recording studies in awake, immobilized rats, we have found that many tonically active neurons in the entopeduncular nucleus (n = 15), globus pallidus (n = 31), and substantia nigra pars reticulata (n = 31) have slow oscillations in firing rate in the seconds-to-minutes range. Basal oscillation amplitude ranged up to ±50% of the mean firing rate. Spectral analysis was performed on spike trains to determine whether these multisecond oscillations were significantly periodic. Significant activity in power spectra (in the 2–60-s range of periods) from basal spike trains was found for 56% of neurons in these three nuclei. Spectral peaks corresponded to oscillations with mean periods of ~30 s in each nucleus. Multisecond baseline oscillations were also found in 21% of substantia nigra dopaminergic neurons. The dopamine agonist apomorphine (0.32 mg/kg iv, n = 10–15) profoundly affected multisecond oscillations, increasing oscillatory frequency (means of spectral peak periods were reduced to ~15 s) and increasing the regularity of the oscillations. Apomorphine effects on oscillations in firing rate were more consistent from unit to unit than were their effects on mean firing rates in the entopeduncular nucleus and substantia nigra. Apomorphine modulation of multisecond periodic oscillations was reversed by either D1 or D2 antagonists and was mimicked by the combination of selective D1 (SKF 81297) and D2 (quinpirole) agonists. Seventeen percent of neurons had additional baseline periodic activity in a faster range (0.4–2.0 s) related to ventilation. Multisecond periodicities were rarely found in neurons in anesthetized rats (n = 29), suggesting that this phenomenon is sensitive to overall reductions in central activity. The data demonstrate significant structure in basal ganglia neuron spiking activity at unexpectedly long time scales, as well as a novel effect of dopamine on firing pattern in this slow temporal domain. The modulation of multisecond periodicities in firing rate by dopaminergic agonists suggests the involvement of these patterns in behaviors and cognitive processes that are affected by dopamine. Periodic firing rate oscillations in basal ganglia output nuclei should strongly affect the firing patterns of target neurons and are likely involved in coordinating neural activity responsible for motor sequences. Modulation of slow, periodic oscillations in firing rate may be an important mechanism by which dopamine influences motor and cognitive processes in normal and dysfunctional states.

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these oscillations were present in a large fraction of SNPR neurons (Twery et al. 1996). DA agonist-induced changes in the period and power of these multisecond periodicities in firing rate are investigated, as well as the effects of general anesthetics and D₁ and D₂ receptor blockade. Also, in addition to slow (~0.5 Hz) oscillations, some basal ganglia neurons have firing rate oscillations in a slightly faster range (Twery et al. 1996). This range roughly coincided with the ventilation rate, suggesting that it might represent periodic activity related to a periodic external stimulus. The present study directly examined the relationship of these two phenomena by simultaneously recording neuronal activity and ventilator action in a subset of animals.

**METHODS**

Sprague-Dawley rats weighing 250–400 g were used. Extracellular recordings of tonically active single units (with biphasic waveforms) were performed in artificially respired, locally anesthetized rats or in chloral hydrate (400 mg/kg) or urethan (1.2 g/kg) anesthetized rats as previously described (Bergstrom et al. 1984). All surgical procedures have been described previously (Bergstrom et al. 1984) and were conducted in accord with National Institutes of Health guidelines (Cohen et al. 1985). In the artificially respired, locally anesthetized preparation, rats were tracheotomized under halothane anesthesia, and the trachea was intubated with a cannula. To prevent discomfort of the animals, incision and pressure sites were thoroughly infiltrated with the long-acting local anesthetic mepivacaine HCl, anesthetic gel (2% lidocaine) was applied to the outside of the trachea cannula and the tips of the stereotaxic ear bars, and corneal drying was prevented with Lacri-Lube (Allergan Pharmaceuticals). After placement in a stereotaxic instrument and the completion of all surgical procedures, halothane anesthesia was discontinued, and rats were paralyzed with the injection of gallamine triethiodide (16 mg/kg) through a tail vein. Rats were then artificially ventilated at a rate adjusted to maintain expired CO₂ levels between 3.4 and 4.5%. Supplements of gallamine were given as needed. Body temperature was maintained with a heating pad. Studies in a parallel group of paralyzed rats demonstrated that heart rate and blood pressure were within normal physiological ranges, suggesting that the immobilized, artificially ventilated state did not produce significant amounts of stress (D. A. Bergstrom, C. Helke, and J. R. Walters, unpublished observations).

Glass microelectrodes (2.5–6 MΩ, 2 M NaCl filling solution) were directed stereotaxically through drilled skull holes to the EPN, GP, or substantia nigra. Electrical signals were passed through an Axoclamp 2A amplifier in bridge mode, and amplified single-unit activity was isolated with a window discriminator and collected with Spike2 software (version 2.18, Cambridge Electronic Design). In the substantia nigra, both pars reticulata and DAergic pars compacta neurons were recorded; DAergic neurons were identified by their characteristic long-duration waveform and firing pattern. After a baseline recording period of at least 5 min, DA agonist or vehicle (water) was injected intravenously, and units were held another 10–15 min. Typically, a DA antagonist drug was then injected intravenously. Only one unit from each rat was recorded after agonist injection. Recordings were typically 25–35 min in length. At the end of recording, Pontamine Sky Blue was iontophoresed, and the recording site was later verified histologically. Apomorphine was obtained from Sigma; domperidone was obtained from Janssen Pharmaceutica; SCH 23390, eticlopride, SKF 81297, and quinpirole were obtained from Research Biochemicals Inc.

To study neuronal activity related to the process of artificial respiration, a switch was installed in the ventilator apparatus (Harvard, model 683), which produced a voltage pulse at the time of greatest piston extension, i.e., one pulse per ventilation cycle. In the majority of recordings, this voltage signal was recorded simultaneously with neuronal activity (in separate channels) by the data acquisition software (Spike2). The ventilator rate during any particular epoch could then be measured post hoc and also the ventilator signal could be used as a trigger to construct poststimulus time histograms (PSTHs) of neuronal activity.

Data segments (180 s) were selected from baseline and postdrug times for analysis of firing rate periodicities. One segment was selected from each of baseline, postagonist and (when present) posttannagonist epochs. Data segments (180 s) were selected so as to be representative of the activity of the entire epoch, and data segments after drug treatments were generally taken from the 5- to 10-min time range postinjection. Spike trains were smoothed by binning (nonoverlapping square bins). Visual inspection of spike trains smoothed at different binwidths indicated that the prominent periodic firing rate changes that typically occurred with periods in the range of 2–60 s were best seen with binwidths of <1 s, and so spike trains were smoothed with 500- or 200-ms bins in the current analysis. Smoothed spike trains were analyzed with the Lomb algorithm to characterize periodicities in the spike train, with the method of Kaneoke and Vitek (1996), which has been previously used to assess oscillatory activity in the basal ganglia (Boraud et al. 1998; Kaneoke and Vitek 1996). In the current analysis, the program was modified so that power spectra were taken from smoothed spike trains instead of smoothed autocor- elograms. The Lomb algorithm was selected over the fast Fourier transform because of the ability of the Lomb algorithm to evaluate the statistical significance of spectral features (Scargle 1982), allowing classification of spike trains as either having or lacking significant power within a particular range of periods. Significant periodicities were examined within the range of 2–60 s (0.5–0.017 Hz) with 500-ms bins for analysis of multisecond oscillations, or within the range of 0.4–2 s (2.5–0.5 Hz) with 200-ms bins for analysis of ventilation-related oscillations. Periods longer than 60 s would exhibit less than three possible cycles within the 180-s spike train and so were not considered. Peaks in the periodogram power spectra were considered to be significant at P < 0.01 in comparison with independent Gaussian random values. Only 1 of 100 spectra of segments of random Gaussian noise would be expected to have peaks above the power level represented by the P = 0.01 line; hence peaks above this line are highly likely to indicate true periodic activity (Horne and Baliunas 1986; Press et al. 1992). Only significant spectral peaks are considered here, and relative power of spectral peaks is reported as the ratio of the spectral peak height to the height of the P = 0.01 significance line.

Drug-induced changes in the periods of spectral peaks were statistically analyzed in two ways. First, all significant spectral peaks were included in distribution tests: within a condition, the numbers of spectral peaks within defined ranges (2–10 s, 10–20 s, 20–30 s, . . . ) from all spike trains were noted, and drug-induced changes in this distribution were analyzed with χ² tests. Second, for many spike trains much of the spectral power is concentrated into one peak, which was defined as the “main” peak, i.e., the tallest (most powerful) spectral peak within the studied range. Drug-induced changes in the period of main spectral peaks were analyzed with Student’s t-tests. Also, drug-induced changes in the power (height) of main spectral peaks were analyzed with Wilcoxon tests; cases in which there were no significant peaks were assigned a zero value in this test.

**RESULTS**

**Basal oscillations**

Visual inspection of the basal activity of basal ganglia neurons (15 EPN, 31 GP, and 31 SNPR) in awake rats demonstrated that the baseline firing rate in many of these neurons was not stationary, but rather fluctuated at long time scales. Examples of these basal variations are shown in Figs. 1 and 2.
These fluctuations had a large amplitude in some neurons. For instance, the basal firing rate of the neuron in Fig. 2 reached up to 156% and down to 58% of the mean firing rate. Lomb algorithm analysis revealed that these fluctuations were often periodic; significant periodicities (P < 0.01) in basal firing rate within the presently examined range of periods (2–60 s) were exhibited by many neurons in each nucleus (Table 1). In many cases, more than one significant spectral peak was found in a given spike train. Figure 3 (left column) illustrates basal periodicity data from all EPN neurons, and subsets of GP and SNPR neurons. In all three nuclei, peaks from basal spike train spectra were broadly distributed across the examined range of periods. When considering only the most powerful spectral peak for each spike train (the main spectral peak), means for main spectral peak period of basal spike trains were 30 s in each nucleus (Table 1).

Basal activity of 14 DA neurons of the substantia nigra pars compacta (SNPC) (identified by characteristic long extracellular waveforms as well as histology) was also recorded in awake rats. Although basal firing rates of these neurons were, as expected, much slower than in the other nuclei presently investigated, significant (but relatively low power) spectral peaks were still found in three of these cells, with similar periods as in the other nuclei (Table 1). These oscillations in DA neuron activity, however, were less obvious on visual inspection of the spike trains, probably due to their low power and also the slow overall firing rate of these cells.

**Effects of dopamine agonist and vehicle injection**

The mixed D1/D2 agonist apomorphine at 0.32 mg/kg iv (an intravenous dose that increased apparent arousal level and induced strong stereotypic sniffing in freely moving rats) modulated firing rate oscillations in virtually all tested neurons (15 EPN, 10 GP, and 10 SNPR) in awake rats in a manner that was readily visible on inspection of smoothed spike trains (Figs. 1 and 2, A–C). Apomorphine-induced effects appeared within 1–3 min after injection in most units and typically persisted until antagonist injection (Fig. 1) or the end of the recording. The oscillations in firing rate after apomorphine were often remarkably large in amplitude. For example, the postapomorphine oscillations in Fig. 2B range between 166 and 40% of the mean firing rate, whereas the postapomorphine oscillations in Fig. 2C range between 220 and 58% of the mean. Spectral analysis revealed that the proportion of units with significant oscillatory activity increased after apomorphine in the EPN (from 67 to 87%), GP (from 44 to 90%), and SNPR (from 58 to 100%). Apomorphine also increased the rate of oscillations in each structure, leading to increased numbers of peaks in the 5- to 20-s period range, and decreased numbers of peaks in the 30- to 60-s period range (Fig. 3; P < 0.01 for all 3 structures). This increase in oscillation rate is also reflected in main spectral peaks, which are significantly shifted to shorter periods in all three structures (P < 0.001 in all cases; Fig. 4, examples in Fig. 2). Group means for main spectral peak
FIG. 2. Lomb periodogram power spectra and the spike trains from which they were derived, showing examples of basal and postdrug neuronal activity from awake rats (A–C) and anesthetized rats (D and E). Spike trains are smoothed with 500-ms bins and are shown scaled to their highest point (in Hz). Mean firing rate is given in the bottom left corner of each spike train plot. Ninety-second segments of the 180-s trains used for analysis are shown. Beneath spike trains are the corresponding power spectra, which are shown with a line signifying the $P = 0.01$ significance level; spectral peaks that cross this line indicate significant periodicities (Horne and Baliunas 1986; Kaneoke and Vitek 1996). Several cases have multiple significant peaks. Spectra for a neuron are scaled to the highest spectral peak for that neuron (except in D and E in which there are no significant spectral peaks). Basal and post-dopamine (post-DA) agonist epochs are illustrated for each unit; some postantagonist epochs are also shown. A: EPN. B and E: globus pallidus (GP). C and D: SNPR. Of the 3 illustrated neurons recorded in awake rats, units A and C have significant baseline periodicities, and unit B does not. After apomorphine (0.32 mg/kg iv), all 3 units have strong periodicities. The smoothed spike trains from postapomorphine time segments demonstrate the periodic and repetitive nature of the rate oscillations. They are also indicative of the various shapes of the oscillations. In the 2 cases (A and C) where periodicities are present both before and after apomorphine, the drug increases the oscillation frequency. In these 3 neurons, DA antagonists given after apomorphine completely block periodic activity (A: D$_2$ antagonist eticlopride 0.2 mg/kg iv; B and C: D$_1$ antagonist SCH 23390 0.5 mg/kg iv). In D, a typical SNPR neuron from a chloral hydrate-anesthetized rat that has a baseline firing rate that is stationary on a time scale of many seconds. Apomorphine (and subsequent haloperidol, 0.2 mg/kg) has little effect. Power spectra from these spike trains reveal no significant periodicities. Similarly, in E a typical GP neuron from a urethan-anesthetized rat demonstrates a very stationary firing rate both in baseline and after injection of combined SKF 81297 and quinpirole (1.0 mg/kg iv each). There are no significant peaks in the accompanying power spectra.
TABLE 1. Baseline firing rates and periodicities in basal ganglia nuclei

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>n</th>
<th>Firing Rate, Hz</th>
<th>Proportion With Periodicities</th>
<th>Period of Main Spectral Peak, s</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPN</td>
<td>15</td>
<td>31.7 ± 3.0</td>
<td>10/15 (67)</td>
<td>32.8 ± 4.6</td>
</tr>
<tr>
<td>GP</td>
<td>31</td>
<td>35.7 ± 2.8</td>
<td>16/31 (52)</td>
<td>31.8 ± 3.8</td>
</tr>
<tr>
<td>SNPR</td>
<td>31</td>
<td>28.1 ± 2.0</td>
<td>17/31 (55)</td>
<td>26.7 ± 3.1</td>
</tr>
<tr>
<td>SNPC (DAergic)</td>
<td>14</td>
<td>2.8 ± 0.4</td>
<td>3/14 (21)</td>
<td>36.0 ± 7.8</td>
</tr>
</tbody>
</table>

**Anesthetized**

- GP (urethane) 10 | 20.6 ± 2.7* | 1/10 (10)† | 35.8
- SNPR (CH) 19 | 19.6 ± 2.7* | 0/19 (0)† | NP

Firing rate and main spectral peak period data are given as means ±SE; n is number of neurons; numbers in parentheses are percentages. Baseline data on all recorded neurons. Data for periodicities cover the range from 2 to 60 s. “Proportion with Periodicities” refers to the proportion of neurons having statistically significant periodic activity. The individual value is given for main spectral peak period for the one anesthetized GP unit that had significant periodic activity: EPN, entopeduncular nucleus; GP, globus pallidus, SNPR, substantia nigra pars reticulata; DA, dopamine; CH, chloral hydrate; NP, none present. * P < 0.05, † P < 0.03 compared with the same nucleus in awake rats, Student’s t-test and Fischer Exact test, respectively.

Effects of selective D1 and D2 antagonists

Apomorphine effects on periodic oscillations in firing rate were reversed in most cases by intravenous administration of the D1 antagonist SCH 23390 or the D2 antagonist eticlopride (examples in Figs. 1 and 2, A–C). After 0.5 mg/kg SCH 23390 (tested in 19 cases) or 0.2 mg/kg eticlopride (6 cases), relatively few neurons had significant periodicities. Combined data for SCH 23390 and eticlopride demonstrate decreases in the proportion of units with periodicities compared with 0.32 mg/kg apomorphine alone (EPN: 87 to 25%; GP: 90 to 25%; SNPR: 100 to 40%). For both antagonists, in those cases where any significant periodicities remained, the spectral peaks were typically of low power and/or long period (Fig. 3, right column). The combined data for SCH 23390 and eticlopride demonstrate significant antagonist-induced changes in the distribution of spectral peaks compared with 0.32 mg/kg apomorphine alone in the EPN and SNPR (P < 0.01), due mainly to a loss of spectral peaks in the 5- to 20-s range (Fig. 3). This effect did not reach statistical significance for the GP. SCH 23390 and eticlopride also caused similar reversals of the effects of combined SKF 81297 and quinpirole in the GP (Fig. 3).

To investigate the possible involvement of peripheral DA receptors in the effect of apomorphine, in a small number of cases the peripheral D2 antagonist domperidone (0.2 mg/kg) was injected ~10 min after apomorphine (0.32 mg/kg). In tested neurons (EPN, n = 2; GP, n = 2), domperidone had minimal effect on the amplitude or frequency of postapomorphine oscillations in firing rate (example in Fig. 1C).

Effects of general anesthetics

Nineteen SNPR neurons and 10 GP neurons were recorded from chloral hydrate– or urethane-anesthetized rats, respectively. Basal firing rates were significantly slower than those of neurons from awake rats (Table 1), although the ranges widely overlapped (data not shown). In contrast to neurons in awake rats, neurons in chloral hydrate- or urethane-anesthetized rats had basal firing rates that typically appeared stationary on time scales of many seconds, with few and minor variations (Fig. 2, D and E). Lomb algorithm analysis of baseline activity revealed that only 1 of these 29 neurons (a GP unit) had significant periodicities in basal firing rate in the 2- to 60-s range of periods, which represents significant decreases in the proportion of oscillatory neurons compared with awake rats (Table 1).
DA agonists were administered intravenously during the majority of anesthetized-animal recordings. In contrast to the data from locally anesthetized rats, apomorphine (0.32 mg/kg) given during chloral hydrate anesthesia failed to induce significant oscillatory activity in any neurons within the 2- to 60-s range (n = 10 SNPR neurons; Fig. 2D). Also, the combination of SKF 81297 and quinpirole (1.0 mg/kg each) was given to urethan-anesthetized rats, and significant oscillatory activity was found after this treatment in only 1 of 10 GP neurons (1 neuron had a significant spectral peak with a period of 57 s).

Oscillatory baseline activity related to ventilation

Spectra of smoothed baseline spike trains from a subpopulation of neurons (4/15 EPN, 2/24 GP, 6/31 SNPR; overall 17%) in awake rats had significant spectral peaks within the 0.4- to 2.0-s range of periods (almost all were between 0.8 and 1.1 s, coinciding with the range of typical ventilator rates). Spectral peaks in this faster range differed from typical longer period (2–60 s) peaks in that they appeared to be sharper (Fig. 6), and, in virtually all cases, there was only one spectral peak in this range, compared with the multiplicity of significant spectral peaks at the longer periods in many neurons.

A separate sample of GP neurons (including 7 of the units in rats receiving combined D₁ and D₂ agonist) were recorded during concomitant recording of ventilator action. Baseline spike trains from 6 of these 44 GP neurons (14%) had significant spectral peaks within the 0.4- to 2.0-s range of periods, and spectral peak periods and ventilator periods had essentially the same value (within 1%; Fig. 6), except in one case in which the spectral peak period (1.69 s) was double the ventilator period (0.85 s).

The relationship between artificial ventilation and these 0.4- to 2.0-s range periodicities was revealed not just by the similarity of periods of the two phenomena, but also by inspection of PSTHs of neuronal activity. In neurons with at least moderately strong spectral peaks in this range, PSTHs triggered on the ventilator signal demonstrated a regular variation in neuronal activity apparently related to the action of the ventilator (Fig. 6). In neurons with a lower power (but still significant) spectral peak in this range, there was typically no strong pattern in the PSTH. This result suggests that in these neurons, the ventilation-related variations in firing rate were of low amplitude, but through the large number of repetitions within the analyzed epoch (180 s), these periodic variations built up power in the Lomb algorithm analysis.

Overall, the 18 neurons with ventilation-related periodicities did not appear to differ in any other way from the general population of neurons: 56% also had significant spectral peaks in the slower 2- to 60-s range in baseline spike trains, and the effects of drug treatments on the 2-to 60-s range periodicities and overall firing rates were generally typical.
DISCUSSION

The current spectral analyses of spike trains reveal slow periodic oscillations in firing activity in the EPN, GP, and substantia nigra. Although some of these firing rate periodicities (namely those with a frequency faster than 0.5 Hz) were found to be related to ventilation, those with longer periods are presumably generated by endogenous processes, and these processes are sensitive to general anesthesia and DA receptor activation. Previous studies of basal ganglia electrophysiology have reported periodic activity in faster frequency ranges (Bergman et al. 1994; Hutchison et al. 1997; Wilson et al. 1977). The present data show that basal ganglia firing activity can also have significant structure at the seconds-to-minutes scale, which is not commonly examined. Although slow changes in central activity are often associated with sleep or anesthesia, the present data demonstrate that slow periodic activity can also occur in the waking condition in the basal ganglia, and that the power of these oscillations and the proportion of units demonstrating oscillations actually increase in response to a drug treatment that increases arousal and induces strong stereotypic behavior in freely moving animals. Because strong apomorphine-induced periodicities in firing rate are observed in the two output nuclei of the basal ganglia, the SNPR and EPN, the present study suggests that multisecond firing rate oscillations are transmitted to targets of the SNPR and EPN, particularly during the behavioral activation caused by apomorphine.

Multisecond oscillations in baseline cerebral cortical activity during waking have been found in a number of species, including humans, with measurements of direct cortical potentials (Aladjalova 1957; Norton and Jewett 1965), electroencephalogram (Ehlers and Foote 1984; Keidel et al. 1990; Pfurtscheller 1976; Trimml et al. 1990), and blood flow/oxygenation (Biswal et al. 1995; Cooper et al. 1966; Lowe et al. 1998) and appear to relate to slow periodicities in motor output and in state of vigilance or arousal (Ehlers and Foote 1984; Keidel et al. 1990). Like the presently described periodicities in the basal ganglia, these slow cerebral cortical oscillations are not present during deep anesthesia (Aladjalova 1964; Norton and Jewett 1965). Oscillations measured with these techniques reflect synchronous activity of large neuronal
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populations. The cerebral cortical data demonstrate that baseline multisecond oscillations in the basal ganglia have counterparts in the cerebral cortex, and furthermore suggest that there could be significant interneuronal synchrony in the basal ganglia at these periodicities. The cerebral cortical data also suggest that multisecond oscillations are not restricted to artificially ventilated, paralyzed subjects, because most of the above studies were performed in freely moving (but resting) or loosely restrained subjects, and specifically, Aladjalova reported that similar slow oscillations in cerebral cortical potentials were found in both freely moving and paralyzed rabbits (Aladjalova 1957).

The remarkable lack of significant oscillatory activity (within the presently studied range of periods) in both basal and post-DA agonist spike trains from rats under chloral hydrate or urethane anesthesia suggests that the slow oscillations in firing rate seen in awake rats are dependent on ongoing activity in afferent structures and are not a neuronal response to methodological factors (e.g., the proximity of the electrode to the recorded unit) per se. The common use of general anesthesia in studies of in vivo electrophysiology may partially explain why multisecond oscillations are typically not reported. Because evidence suggests that chloral hydrate and urethane induce anesthesia at least in part by augmenting inhibitory and attenuating excitatory neurotransmission (Garrett and Gan 1998; Peoples and Weight 1994, 1998), it appears that excessive reductions in central activity disrupt the processes that lead to slow oscillations in basal ganglia neuron firing rates both in basal conditions and after DA receptor stimulation.

The changes in multisecond periodicities in awake animals caused by apomorphine treatment, namely the increase in frequency and spectral power, are specifically drug related and not simply related to the intravenous injection procedure, because intravenous injection of vehicle (or of a low dose of apomorphine) did not induce these changes. Nor are apomorphine effects secondary to respiratory changes (artificial respiration rates were held constant in the large majority of recordings and were in a shorter period range: mean ~0.9 s) or to activation of peripheral D2 receptors (effects were not reversed by domperidone). The comparable apomorphine effects on oscillatory pattern in the SNPR, EPN, and GP suggest that similar mechanisms may underlie slow oscillations in these nuclei, and that powerful firing rate oscillations due to DA receptor activation may be pervasive in the basal ganglia. Indeed, similar basal and postapomorphine oscillations in firing rate are found in neurons of the subthalamic nucleus (Allers et al. 1998).

Analyses of post-DA antagonist spike trains show that the effects of DA agonists on firing rate periodicities are reversible and further emphasize the DA receptor–mediated nature of these effects. Also, when injected before a DA agonist, DA antagonists prevent the agonist-induced changes in periodicities (unpublished data). Results from experiments with specific antagonists demonstrate that DA agonist-induced changes in multisecond periodicities in firing rate appear to depend on the activation of both D1 and D2 receptor subtypes. Preliminary results with the separate and combined administration of specific D1 and D2 agonists support the involvement of both DA receptor subtypes, and a positive interaction between these subtypes, in the modulation of slow periodicities in basal ganglia firing rate (Walters et al. 1998).

Sixteen percent of all GP, EPN, and SNPR neurons in awake rats had significant spectral peaks with periods in the range of 0.4–2.0 s. Distinct from slower periodic activity, which is presumably generated by endogenous processes, periodic activity in the 0.4- to 2.0-s range was clearly related to an external process, namely the artificial ventilation of the immobilized rats. Firing rate oscillations in this range in the SNPR have been previously reported in artificially ventilated rats (Wilson et al. 1977); however, these authors concluded that the oscillatory activity was not related to ventilation. Although it is possible that basal ganglia neurons in the present study are oscillating spontaneously in the 0.8- to 1.1-s range, the precise correspondence between ventilator period and spectral peak period strongly suggests driving (or at least entraining of a spontaneous oscillation) by some aspect of artificial ventilation. GP, EPN, and SNPR neurons can respond to sensory input of various modalities (Chernyshev and Weinberger 1998; DeLong et al. 1985; Joseph and Boussaoud 1985; Rothblat and Schneider 1995; Schwarz et al. 1984), and it is difficult in the preparation used here to determine which modality mediates the present influence of artificial ventilation on GP activity. Firing rate periodicities related to ventilation did not preclude the presence of significant periodicities in the slower range (2- to 60-s periods). Simultaneous oscillatory activity in two different bands has also been reported in other structures in awake rats (Chrobak and Buzsáki 1998).

In many cases, spectral analysis of spike trains resulted in multiple statistically significant peaks in the power spectrum in the 2- to 60-s period range. Such multiple peaks may represent multiple simultaneous oscillations with different periods, sidelobes of a particularly powerful spectral peak, or harmonics due to a nonideal sinusoidal oscillation shape. Visual inspection of smoothed spike trains, particularly from epochs after DA agonist administration (Figs. 1 and 2), suggests a different interpretation. Even when firing rate oscillations were particularly strong and regular, their regularity was not perfect or “clockwork,” but often demonstrated phase shifts (most common), gradual drift in period, or skipped cycles. It is likely that these various irregularities contribute to the appearance of multiple significant spectral peaks in many cases. Notably, periodic neuronal activity related to artificial ventilation, which is extremely regular, resulted almost exclusively in single spectral peaks without significant sidelobes (Fig. 6). On the other hand, in baseline spike trains, in which 2- to 60-s periodic activity (when present) was typically less regular than in post-DA agonist spike trains, and in which multiple spectral peaks sometimes spanned a relatively wide range of periods (e.g., Fig. 2C), it is not possible to rule out the presence of multiple simultaneous firing rate oscillations.

Numerous lines of research have emphasized the behavioral importance of periodic neuronal activity (Cohen and Wallen 1980; Engel et al. 1997; Komisaruk 1970; Llinas and Ribary 1993; Smith et al. 1991). The modulation of slow periodicities in firing rate in the present study by DAergic agonists suggests the involvement of these patterns in behaviors and cognitive processes that are affected by DA. Firing rate oscillations in the seconds-to-minutes range may act to coordinate neuronal activity responsible for motor sequences, much as faster oscillations in sensory pathways may coordinate neuronal activity underlying perceptual binding (Engel et al. 1997). The behavioral actions of stimulants have been theorized to be due to an
increase in the rate of expression of motor sequences (Lyon and Robbins 1975). The DA agonist-induced increase in basal ganglia firing rate oscillation frequency could, therefore, be a physiological basis for this increased expression rate. The increase in frequency could also be a substrate for the DA agonist–induced increase in internal “clock speed,” which has been associated with the perception of time in the seconds-to-minutes range in animals and humans (Meck 1996).

Alternatively, concerning the thalamocortical sensory pathways, it has been hypothesized that a switch in firing pattern from a relay mode to a slow oscillatory mode (as from waking to slow-wave sleep) indicates that useful information is no longer being transmitted (Steriade et al. 1993). In the basal ganglia, a shift from normal firing patterns (which include slow oscillations across a range of frequencies) to a DA agonist–induced state of more powerful oscillations within a narrower frequency range might also signal a reduction of meaningful temporal patterning in output to motor-related thalamic nuclei. The abnormal interaction of an animal with its environment during stereotypic behaviors may indicate that motor programs are proceeding without normally patterned sensorimotor feedback. In summary, modulation of slow, periodic oscillations in firing rate may be an important mechanism by which DA influences motor and cognitive processes in normal and dysfunctional states.

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