A Region in the Dorsolateral Striatum of the Rat Exhibiting Single-Unit Correlations With Specific Locomotor Limb Movements

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SUMMARY AND CONCLUSIONS
1. To examine the activity of single units in the lateral striatum of the awake rat with respect to sensorimotor function, 788 units were recorded during locomotion and passive testing. The focus of this report is on 138 units (18%) that fired in relation to sensorimotor activity of a single limb. The remaining units were related to other body parts (16%), to general body movement (38%), or were unresponsive (28%).

2. Firing rates of limb-related units were near zero during resting behavior but increased markedly during treadmill locomotion. Each of the 138 units exhibited a rhythmic pattern of discharge in phase with the locomotor step cycle. Passive testing revealed that 86/97 units tested (89%) responded to passive manipulation of a single limb, exhibiting increased firing rates. Of these, 77 (90%) were related to contralateral and 9 (10%) to ipsilateral limbs. Sixty-one units (71%) were related to a forelimb and 25 (29%) to a hindlimb. Of the 86 units responding to passive manipulation, 34/48 units tested (71%) also responded to cutaneous stimulation of the same limb but no other part of the body.

3. To study in greater detail the rhythmic unit discharge in phase with the locomotor step cycle, computer-synchronized video-tape recordings were used to generate perimovement time histograms constructed around discrete locomotor movements of each limb (n = 17 units). Activity of each unit was shown to be restricted to a specific portion of a particular limb's step cycle. The majority of units discharged throughout (8 units) or during a portion of (3 units) the swing phase, whereas other units fired during a portion of stance (3 units), footfall (2 units), or foot off (1 unit).

4. The specificity of unit firing was further demonstrated by the finding that rhythmic discharges, related to discrete locomotor limb movements in the forward direction, were completely absent during spontaneous deviations such as backward or disrupted locomotion.

5. Units related to limb movement were located in the far lateral, especially the dorsolateral, subregion of the striatum. This subregion extended rostrocaudally from A-P +1.6 to −1.0 mm relative to bregma. No clear somatotopic organization was observed, but this issue requires further study.

6. These results show that functional representations of individual limbs can be demonstrated in the lateral striatum of the rat, within a subregion containing terminals of projections from somatic sensorimotor cortex. Taken together with the lack of this type of specificity previously shown for units in more medial striatal subregions, these findings support the idea of a functional differentiation between the medial and lateral striatum of the rat.

INTRODUCTION

Important for understanding the striatum (caudate putamen) is the characterization of functionally different striatal subregions. Toward this end, anatomic studies have demonstrated topographical projections to the striatum from the cerebral cortex in monkeys (Goldman-Rakic 1982; Goldman and Nauta 1977; Jones et al. 1977; Kunze 1975, 1977, 1978; Schwartz et al. 1988; Van Hoesen et al. 1981), rats (Domesick 1981; Kelley et al. 1982; McGeorge and Faul 1989), and cats (Rowe 1982). Moreover, electrophysiological studies in cats (Garcia-Rill et al. 1979) and monkeys (Liles 1975; Liles and Updyke 1985) have shown that projections to the striatum from primary somatosensory (SI) and motor (MI) cortices are somatotopically organized. DeLong and associates have demonstrated electrophysiologically a detailed somatotopy in monkeys, in which a dorsolateral-to-ventromedial arrangement of leg, arm, and face representations was found throughout the rostrocaudal length of the putamen (Alexander and DeLong 1985; Crutcher and DeLong 1984a).

Little electrophysiological information of this type, however, exists regarding the striatum of the rat. The importance of this species to basal ganglia research motivates a detailed characterization of single-cell activity with respect to sensorimotor function during waking behavior. In the few single-unit studies that have been reported, most units were recorded from central regions of the striatum and were related to global body movements but rarely showed specific relationships to individual body parts (Haracz et al. 1989; Ryan et al. 1989; West et al. 1987b). Correlations with skilled forelimb reaching (Moroz and Bures 1984) or limb manipulation (Richards and Taylor 1982; West et al. 1987b) have been shown for only a small number of units, which were located in the lateral striatum. The dorsolateral subregion of the rat striatum, as shown by anatomic studies in recent years, is the primary striatal target of projections from SI and MI cortices (Cospito and Kultas-Ilinsky 1981; Donoghue and Herkenham 1986; Kelley et al. 1982; McGeorge and Faul 1989; Webster 1961; Wise and Jones 1977). We recently provided preliminary evidence that a percentage of units in this subregion were related to locomotor limb movements (Cohen et al. 1988; West et al. 1987a). To extend these findings, these experiments investigated the prevalence and distribution in the lateral striatum of units related to specific locomotor movements—as well as passive manipulation and cutaneous stimulation—of only one limb. These findings indicate that cells in the lateral striatum of the rat do process detailed and specific sensorimotor information. The reproducibility of these results across animals, coupled with the previously demon-
stratified absence of unit activity related to particular body parts in central portions of the striatum, supports the idea that there is a functional differentiation between medial and lateral portions of the rat striatum.

A description of lateral striatal neurons related to individual parts of the body other than limbs is in preparation (Carelli and West, unpublished observations).

**METHODS**

**Surgery and recording**

Adult Long-Evans rats (250–350 g) of either sex were surgically prepared for chronic recording by implantation of a miniature microelectrode drive (microdrive) assembly (Josef Biela Engineering, Anaheim, CA). The microdrive base was attached to the skull overlying the striatum (M–L, 3.5–4.0 mm; A–P, ±1.0 to ±2.0 mm with respect to bregma, level skull) at an angle of 6–10° away from the midline, on either side of the brain. Details of the surgical preparation and microdrive have been reported (Deadwyler et al. 1980; West and Woodward 1984). One week after surgery the microdrive was equipped daily with a tungsten microelectrode (10 MΩ, Haer, Brunswick, ME) and attached to the base on the animal’s skull. A unique feature of the microdrive was that, because electrodes were lowered without rotation, they could be positioned eccentrically (up to 0.8 mm from the long axis of the microdrive) to reach a larger area. Thus the A–P and M–L ranges available for testing were extended by 0.8 mm on either side of the coordinate at which each animal was implanted. Signals were amplified, filtered, and led through a window discriminator (World Precision Instruments, no. 121).

A Plexiglas recording chamber (length 35 × width 17 × height 40 cm) was mounted above a treadmill (Sears belt sander, no. 113.22590), the belt of which served as the floor of the chamber. The belt was coated with a thin layer of silicone gasket material (General Electric, no. 343). The treadmill (TM) was activated periodically (30 s on, 30 s off) by a computer-timed Zeromax motor (M-3 E-3) and moved at a rate of 12 cm/s, which produced a slow-to-moderate walking pace. Animals were maintained on a reversed light-dark cycle (on 20.00, off 08.00) so that daily experiments were conducted during their active period.

**Videotape analysis of locomotion**

A computerized system was used for analyzing relationships between neural activity and videotaped locomotor behavior. A videocamera (Panasonic WV–F2) and videocassette recorder (Sony Super Beta SL-HF750) provided a resolution of movement of 30 frames/s. A minicomputer (Data General model 20) with software for neurophysiology (Unitlab, Dallas, TX) collected neural data and sequentially numbered each frame via a videoframe counter (Thadner Electronics VC-436), which displayed the number of each frame on the TV monitor. By the use of off-line videotape analysis, a specific locomotor event could be isolated on a single video-frame. All frames in which the event occurred were compiled and entered into the computer as nodes. Raster displays and peri-event time histograms (PEH) were constructed around the nodes to depict unit activity time-locked to the locomotor event. To present the data in terms of the percentage of trials in which a unit responded in a time-locked manner with respect to the node, the ordinate of PEHs was expressed as discharges per sweep (i.e., per occurrence of the locomotor event). This represents the probability of firing on each step, within each particular “bin” (typically 3 ms/bin). Although each videoframe was 33 ms in duration, greater resolution was routinely achieved by interpolating between frames. The maximum resolution of movement employed was in increments of 11 ms, with a maximum error of ±1 increment. Similar methods have been used successfully in studies of cortical neurons, in which relationships were characterized between film and videotape and both electromyographic and electronic means of determining locomotor footfall patterns (Chapin et al. 1980; Chapin and Woodward 1982a,b, 1986).

**Identification of the limb related to unit activity**

Three methods were used for determining neuronal relationships to activity of individual limbs: passive examination, PEHs constructed around active movement, and regression analysis. Passive manipulation and cutaneous probing of the limbs were used solely to identify which limb was related to unit firing. No attempts where made 1) to relate unit firing to the activity of particular muscles or joints; 2) to rule out active movements made during passive limb manipulation; or 3) to determine precise receptive-field boundaries. Passive manipulation consisted of the experimenter’s grasping each limb manually or with a probe and gently moving it in a manner approximating active locomotor movements. A handled probe calibrated to deliver 1–2 g of force (tip = 2.5 mm) was used for lightly tapping the skin or fur. Animals became accustomed to both forms of testing, which were performed while the animals were awake and at rest in the experimental chamber.

PEHs were constructed as follows: for each limb two locomotor events were used as nodes because of the ability to clearly distinguish them—initial paw contact with the ground (soft contact or S), referred to here as footfall, and the onset of the swing phase (the lifting of the paw out of contact with the ground), referred to here as foot off (Cohen and Gans 1975). Thus eight PEHs were generated for each unit. To identify the limb most highly related to unit discharge, the eight PEHs were compared, as in previous studies (Chapin and Woodward 1986), on the basis of (J) peak amplitude; (2) peak duration (i.e., sharp vs. dispersed); and (3) the temporal relation of the peak to the node. For descriptive purposes in the text, the step cycle was divided into two major phases, stance (paw down) and swing (paw up), defined by the two events, footfall and foot off.

Regression analysis of rhythmic unit discharge was performed as follows: rhythmic unit discharge consisted of a discrete period of elevated firing rate occurring once per step cycle, the onset of which was clearly identified against background firing rates near zero. For each step cycle, the cycle time of the unit (onset time of discharge minus that of the preceding step cycle) was compared with the cycle time of each limb (time of footfall minus that of the preceding step cycle). Regression analysis was prohibitively time consuming and provided no information regarding which phase of the limb’s movement was related to unit firing. This determination required PEH analysis. For these reasons regression analysis was used to analyze a limited portion of the data.

**Electrophysiological characterization of electrode position**

Because histological verification of recording site could not be obtained until after the last recording from each animal, measures were taken to ensure that only striatal neurons were recorded for study. As electrodes were advanced toward the striatum, a depth profile was constructed by observing unit firing patterns as a function of depth (400 µm/tturn of the microdrive). The large unitary spikes recorded in deep cortical layers were always located immediately dorsal to a “silent zone,” exhibiting no unit activity, the dorsoventral thickness of which was 0.3–0.7 mm. Histologic reconstructions verified that this zone corresponded to the subcortical white matter overlying the striatum. The absence of unit activity in this zone indicated that the electrodes used in this study did not detect the extracellular action potentials of axons in the subcortical white matter. It follows that the units of this study did
not represent discharges of cortical axons descending through the striatum.

Compared to striatal units, cells in deep cortical layers were larger in amplitude and generally showed higher spontaneous firing rates during resting behavior. Striatal units characteristically fired infrequently during resting behavior (0–1.8 spikes/s) but increased firing during locomotion (0.6–7.6 spikes/s) (also cf. West et al. 1987b). These differences in firing pattern have been observed consistently and verified histologically in the course of >1,000 electrode penetrations during several years of striatal recordings in this laboratory. Any recording tracks not exhibiting this profile were discontinued.

Histological reconstruction of electrode position

After the last experiment in each animal, an electrolytic lesion (0.03 mA, 10–30 s) was made using the microdrive to position a low-impedance wire (0.25 mm diam, teflon insulated) at the same location as that at which a particular unit recording had been obtained. Animals were intracardially perfused with 10% Formalin, and coronal sections (50 μm thick) were stained with cresyl violet. The location of the lesion was used to reconstruct the three-dimensional positions within the striatum of all limb-related units recorded from the animal. In illustrating the position of each unit (Fig. 7), the relative distances between units are not representative because 1) enlargement of the symbol for each unit (to provide legibility) in many cases produced an appearance of proximity and 2) the illustration contains the data from all animals.

RESULTS

Categorization of units

Seven hundred eighty-eight units were recorded from the lateral striatum of 19 rats. Firing patterns of 138 units (18%) were related to sensorimotor activity of an individual limb and are the focus of this report. Other units (302 units; 38%) discharged during generalized, whole-body movements such as locomotion but showed no relation to movement or probing of specific body parts. Two hundred twenty-two units (28%) were unresponsive to any of the testing conditions employed. The remaining 26 units (16%) increased firing in relation to movement or sensory probing of specific body parts other than limbs, a description of which is in preparation (Carelli and West, unpublished observations). Across all categories, no differences were observed in unit waveform or amplitude (0.15–0.25 mV). Units showed an initial negative wave of 0.18- to 0.24-ms duration, followed by a positive or positive-negative wave (total duration of unit waveform 0.5–1.0 ms).

Rhythmic unit discharges during locomotion

Units related to limb movement (n = 138) exhibited very low-spontaneous firing rates (0–0.4 spikes/s) during resting behavior (animal alert, resting on all 4 paws, with no move-
TABLE 1. Limb-related units

<table>
<thead>
<tr>
<th>Units Tested</th>
<th>Units Responding</th>
</tr>
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<tbody>
<tr>
<td>Active locomotion</td>
<td>138 138 (100)</td>
</tr>
<tr>
<td>Passive manipulation</td>
<td>97 86 (89)</td>
</tr>
<tr>
<td>Contralateral</td>
<td>86 77 (90)</td>
</tr>
<tr>
<td>Ipsilateral</td>
<td>86 9 (10)</td>
</tr>
<tr>
<td>Forelimb</td>
<td>86 61 (71)</td>
</tr>
<tr>
<td>Hindlimb</td>
<td>86 23 (29)</td>
</tr>
<tr>
<td>Cutaneous stimulation</td>
<td>48 34 (71)</td>
</tr>
<tr>
<td>Videotape analysis</td>
<td>17</td>
</tr>
</tbody>
</table>

Number in parentheses is percent of total units tested showing response. All units tested showed a rhythmic pattern of discharge in phase with the locomotor step cycle and, hence, were characterized as firing during active limb movement.

In marked contrast to firing rates at rest, large increases in firing rate were exhibited during TM locomotion (Fig. 1A). A unique property of limb-related units was that they showed a rhythmic pattern of discharge in phase with the locomotor step cycle (Fig. 1B). That is, a discrete period of elevated firing, spanning up to 400 ms, occurred once during each step cycle. This was true of all 138 limb-related units (Table 1). To identify the particular limb related to rhythmic unit firing, three approaches were used (not all approaches were applied to every unit): 1) passive probing of each limb; 2) construction of perimovement time histograms; and 3) regression analysis.

Identification of the limb related to unit activity

Ninety-seven units showing rhythmic discharges in phase with the locomotor step cycle were examined during passive manipulation of the limbs and/or light tapping of the skin or fur. Eighty-six units (89%) responded to passive manipulation of one limb but no other body part. Responses consisted of increased firing rate; no decreases were observed. (Baseline firing rates in the absence of movement were 0 for the majority of limb-related units.)

Of the 86 units responding to passive manipulation, 77

![Image of discharge per sweep](attachment:image.jpg)

**Fig. 2.** Use of passive responses to identify limb related to unit activity. A: PEH analysis of active locomotor movements showed that unit fired during last 0.4 s of contralateral hindpaw stance (total stance duration = 0.7 s); 60 trials (sweep), 4 ms/bin. B: PEH constructed around cutaneous tap on contralateral hindlimb shows evoked unit firing, whereas tapping other limbs produced no response. Exact latency to response could not be determined with use of videotape analysis (11-ms resolution); 33 trials, 2 ms/bin. C: strip chart shows that passive manipulation of contralateral hindlimb (but no other limb) produced unit firing.
(90%) were related to contralateral and 9 (10%) to ipsilateral limbs. Sixty-one units (71%) were related to forelimbs and 25 (29%) to hindlimbs. Forty-eight of these 86 units were also tested for responsiveness to light-cutaneous stimulation, and 34 (71%) responded, in each case to stimulation of the same limb identified with the use of passive manipulation (Table 1).

Figures 1B and 2A illustrate one unit that showed a rhythmic discharge during active movements of the step cycle. This unit was responsive to both passive manipulation (Fig. 2C) and cutaneous tapping (Fig. 2B) of the contralateral hindlimb but no other body part. Videogenrated histograms showed that the rhythmic locomotor discharges of this unit were time locked to active movement of the contralateral hindlimb—specifically, the latter portion of the stance phase (Fig. 2A).

Obtaining histograms through videotape analysis was a useful tool for identifying active limb movements related to unit firing, as in previous studies (Chapin and Woodward 1982a,b, 1986). Figure 3 shows four units that exhibited sharp peaks in PEHs constructed around specific locomotor events related to one particular limb (see below for details). In contrast, PEHs constructed around movements of a limb not related to unit firing typically showed peaks that were flattened, diffuse, and remote in time from the nodes corresponding to that limb. This is illustrated for one unit in Fig. 4. The unit activity that occurred during 60 regular step cycles is shown in four different raster-PEH displays, each synchronized around the footfall of a different limb. The peak in the unit firing pattern was largest and nearest to the node for the contralateral forepaw (CFP; top left) but was smaller, more diffuse, and remote from the node in PEHs corresponding to the other limbs. Similarly, raster displays showed that the most dense alignment of unit discharges was obtained when the CFP footfall was used as the node.

**FIG. 3.** Rasters and PEHs from 4 animals, each showing a unit related to discrete locomotor movements of a particular limb. Each raster/PEH is synchronized around a specific event or node. Nodes (time 0.0) utilized were footfall (FF) and onset of the swing phase (foot off) of each paw. CFP, contralateral forepaw; CHP, contralateral hindpaw; 60 trials (sweeps) in each. Time base: 3 ms/bin. For these and all subsequent PEHs, duration of swing phase (beginning at foot off and ending at FF) averaged 0.3 and 0.4 s for fore- and hindlimb, respectively. Duration of stance (beginning at FF and ending at foot off) averaged 0.8 and 0.7 s for fore- and hindlimb, respectively.
FIG. 4. PEHs and rasters displaying 1 unit's activity relative to node at footfall (time 0.0) for each of 4 limbs. Note that unit activity showed both the highest peak and closest proximity to the node for contralateral (C.) forepaw (top left). When the same unit discharges were displayed relative to other paws, peaks were smaller and shifted away from node. 1, ipsilateral. Sixty trials in each. Time base: 3 ms/bin. Refer to Fig. 3 legend for durations of stance and swing.

FIG. 5. Regression analysis confirmed histogram analysis. For unit shown in Fig. 4, timing of rhythmic unit burst (dependent variable) was compared with timing of step cycle of each paw (independent variable). Contralateral forepaw step cycle clearly was most highly correlated with unit firing.
To obtain a separate, quantitative measure of the degree to which rhythmic discharges were correlated with the rhythmic movements of each limb, regression analysis was performed. The timing of the unit discharge was compared with the timing of each paw’s step cycle. The results of this analysis were unambiguous and are described for the unit shown in Fig. 4. The CFP step cycle (1.12 ± 0.20 s, mean ± SD) was highly correlated (r² = 0.95) with rhythmic unit discharges (mean = 1.11 ± 0.21 s). Step cycles of the other paws showed lower r² values: contralateral hindpaw (CHP) r² = 0.33, mean = 1.13 ± 0.25 s; ipsilateral forepaw (IFP) r² = 0.49, mean = 1.10 ± 0.20 s; ipsilateral hindpaw (IHP) r² = 0.60, mean = 1.13 ± 0.22 s.

Because of the synchrony among limb movements during locomotion, it was possible for a noncorrelated limb to show an elevated r² value. A strategy employed to minimize any confound of this type was to perform regression analysis on spontaneously occurring “irregular” step cycles; during irregular cycles, straight-ahead locomotion and unit firing were maintained, but footfalls of the four paws occurred out of their regular sequence. When this analysis was applied (Fig. 5) to the unit shown in Fig. 4, the CFP retained the same high correlation (r² = 0.95; 0.91 ± 0.25 s, mean ± SD) with the cycle of unit discharges (mean = 0.92 ± 0.27 s) as shown during regular step cycles. In contrast, r² values for the other paws were extremely low (CHP r² = 0.00, mean = 1.53 ± 0.46 s, unit-cycle mean = 0.91 ± 0.34 s; IFP r² = 0.12, mean = 0.93 ± 0.24 s, unit-cycle mean = 0.94 ± 0.25 s; IHP r² = 0.00, mean = 1.50 ± 0.37 s, unit-cycle mean = 1.03 ± 0.26 s). Thus regression analysis identified the same paw that had been singled out by analysis of histograms (CFP, Fig. 4). A unit from another animal, which was shown in PEH analysis to be related to the CHP, was subjected to the same regression analyses, yielding similar results (CHP r² = 0.84, CFP r² = 0.32, IHP r² = 0.46, IFP r² = 0.28, irregular step cycles). Regression analysis provided no information regarding which phase of the limb’s movement was related to unit firing; this determination required PEH analysis.

Specificity of neuronal relationships to active movement

Perimovement histograms (e.g., Fig. 3) showed that individual units fired during one discrete phase of a particular limb’s step cycle, showing little or no activity during the limb’s movements throughout the remainder of its cycle. Fifty-four units, after passive probing to identify the limb

![Diagram showing limb-related unit activity during forward vs. backward locomotion for 2 rats. Left: unit that discharged reliably during the last 250 ms of contralateral hindpaw swing phase (average of 4.7 discharges/cycle, i.e., 18.8 Hz) during forward locomotion was completely silent during backward locomotion. Right: rasters and PEHs from another animal show that unit firing was related to contralateral forepaw swing phase only during forward locomotion. Thirty trials in each, 3 ms/bin. Top PEHs: refer to Fig. 3 legend for durations of stance and swing.](image-url)
FIG. 7. Diagrams of coronal sections through the rat striatum (CPu) illustrating reconstructed 3-dimensional location of each limb-related unit (across 19 animals). Sections are arranged in sequence from 1.6 mm anterior (top left) through 1.3 mm posterior to bregma (bottom right). Majority of units were located on dorsolateral edge of striatum. F, forelimb; H, hindlimb. Letter followed by number indicates the number of units (F or H) at that location. Distances between letters do not represent actual distances between units (see METHODS). cc, corpus callosum; Acb, nucleus accumbens; AcbSh, nucleus accumbens, shell; VP, ventral pallidum; GP, globus pallidus (from Paxinos and Watson 1986).
related to unit firing, were evaluated (by the use of on-line observation) to determine the unit's relation to the phase of active movement of the limb. Forty units (74%) were related to the swing phase and 14 (26%) to the stance phase of locomotion.

More detailed analysis was applied to 17 units by constructing PEHs from videotape. Figure 3 shows four cases. In the two top PEHs, unit firing occurred during the last 0.2 s of the swing phase, abruptly terminating at footfall (FF) (total swing phase duration = 0.3 s, left PEH; 0.4 s, right PEH). In the two bottom PEHs, unit discharges were grouped around the node (swing onset, left PEH; FF, right PEH). Overall, the sample was categorized as follows: eight units discharged throughout swing (e.g., Fig. 4, top left), and three fired during the last one-half of swing (e.g., Fig. 3, top right). Two units fired during the last one-half of stance (e.g., Fig. 2, top left) and one during the first one-half of stance. Two units fired immediately before and after footfall (e.g., Fig. 3, bottom right), and one fired immediately before and after foot off (Fig. 3, bottom left).

Unit correlations with locomotor limb movements were absent during spontaneous deviations from straight-ahead locomotion, including backward, as well as disrupted locomotion. On several occasions animals walked backward on the moving TM for periods long enough to analyze (>30 s).

In each case the clear pattern of discharge related to a particular phase of rhythmic forward locomotion was completely absent during backward locomotion (Fig. 6) but returned immediately on resumption of forward locomotion. Several of these units exhibited not a single action potential during backward locomotion (e.g., Fig. 6, left). Also, during disrupted-TM locomotion, which was characterized by frequent breaks in locomotor rhythm (such as changes in direction and speed), side-stepping, rearing, etc., limb-related units typically showed little or no activity despite abundant limb and body movements.

Localization of limb-related units to the dorsolateral striatum

A striking feature of limb-related units was their restricted location on the dorsolateral edge of the striatum. This was demonstrated 1) electrophysiologically during daily construction of depth profiles and 2) histologically, as reconstructed in Fig. 7. A lesser number of units related to limbs were recorded more ventrally in the lateral striatum. Limb-related units were observed throughout an anterior-posterior range of the lateral striatum extending from A-P +1.6 to −1.0 mm from bregma (Fig. 7). However, few limb-related units were observed in penetrations posterior to bregma, and none were found posterior to −1.0-mm

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**FIG. 8.** Simultaneous recordings from a number of units vs. a single unit from a cluster. Left: top PEH shows activity of several units in cluster, detected by one level of window discriminator. Bottom PEH shows pattern of a single unit of the same cluster, detected by the other level of discriminator. Right: similar results obtained from a different recording session. Sixty trials in each. 3 ms/bin. Refer to Fig. 3 legend for durations of stance and swing.
A-P from bregma. No conspicuous somatotopic pattern was observed within this lateral region, in that units related to either the forelimb or hindlimb were located throughout the three dimensions of the dorsolateral subregion containing limb-related units.

**Identification of the limb related to unit activity**

Rhythmic discharges, in phase with the locomotor step cycle, of 138 units suggested that they were related to active limb movement. Passive testing was the most useful method for demonstrating that unit firing was restricted to only one limb. Histograms constructed around distinct events during active locomotor movements, such as footfall, corroborated the identification of the particular limb related to unit firing and showed that unit discharges were related to discrete portions of the limb's step cycle. Regression analysis verified the results of analyzing histograms and emphasized the magnitude of individual correlations, showing that limb-related unit discharges were strongly linked to movement of a single limb.

A high percentage (89%) of units related to active movement discharges during passive limb manipulation by the experimenter, in agreement with a previous study (Crutcher and DeLong 1984a). Responses to passive probing were relatively weak for some units (e.g., Fig. 2) but strong for others. The possibility that such discharges may have been related, in some cases, to active limb movements made during passive manipulation cannot be ruled out of this study. However, this possibility is less likely to be the basis of responses to cutaneous stimuli observed for 71% of the units tested, which produced no discernable movements. Single-cell responsiveness to all three conditions (active movement, passive manipulation, and cutaneous probing) could result from striatal integration of information projected from functionally different cortical areas (Hall and Lindholm 1974; Jones et al. 1977; Kunzle 1977; Liles 1975; Malach and Graybiel 1986; Wise and Jones 1977) or, in the rat, from signals projected from the MI-SI overlap area of cortex (Chapin and Woodward 1986). Alternatively, the diverse response properties of SI and MI neurons (Chapin and Woodward 1986; Evarts 1966; Fetz et al. 1980; Soso and Fetz 1980; Tanji and Kurata 1985) indicate that the present range of striatal responsiveness could be a result of input from either of these cortical areas. Awaiting further study are issues such as the relative contributions of early central drive versus sensory feedback in determining striatal activity.

A small number of cells (10%) were related to movement of an ipsilateral limb. Strial units related to ipsilateral forelimb reaching have been found in other studies (Buser et al. 1974; Dolbakyan et al. 1977). Such discharges may be a result of transmission via bilateral, overlapping projections to the striatum from MI (Cospito and Kultas-Ilinsky 1981; Jones et al. 1977; Kelley et al. 1982; Kunzle 1978; Tanaka and Sakai 1985) or SI cortices (McGeorge and Faull 1989).

There is some disagreement between these results and those reported for the anesthetized rat (Richards and Taylor 1982). In that study the majority of responsive striatal neurons responded only to noxious stimuli, whereas a low percentage of units responded to brushing the fur or to joint movement. Clearly, the present data indicate a greater responsiveness of rat striatal neurons to innocuous, discrete somatosensory stimuli (noxious stimuli were not administered in the present experiments). The most likely explanation for this difference is the influence of anesthe-

**Clustering of units having similar relationships to movement**

As electrodes were advanced through the striatum, units were encountered in clusters. A typical cluster was distributed over a dorsoventral distance ranging from 100 to 400 μm and consisted of an undetermined number of cells. The dorsoventral distance between clusters ranged from 200 to 400 μm, over which no single unit or evoked unit activity was recorded under the conditions tested, i.e., during motor behaviors or sensory probing.

Within a cluster of units related to limb movement, different units were related to the same limb. (It should be noted that clusters of units related to general body movement or unrelated to movement were also encountered but were not systematically studied.) To illustrate this, Fig. 8 shows two recordings from different clusters. The two levels of the window discriminator were adjusted to sort unitary waveforms into two mutually exclusive categories on the basis of amplitude. One level was set, as in all experiments, to isolate a single unit. The other level was set to measure the activity of several units in the cluster (Fig. 8, *top PEHs*). These PEHs show that units within a given cluster were related to active movements of the same limb. However, clustered units were capable of showing differences in the detail of their relationships to limb movement. This is illustrated in the *left* of Fig. 8. The single unit (*bottom PEHs*) was related to a later, more restricted portion of the swing phase than the summed discharges of other units in the cluster, which occurred throughout the swing phase (*top PEHs*).

**DISCUSSION**

These findings demonstrate that certain units in the lateral striatum of the rat exhibit functional representations of individual limbs. Recordings showed several important similarities to those obtained from the striatum of awake primates (Alexander and DeLong 1985; Crutcher and DeLong 1984a,b; Liles 1983, 1985; Liles and Updyke 1985; Rolls and Williams 1987) in terms of 1) neuronal firing characteristics; 2) unit relations to active and passive limb movements; 3) the occurrence of clusters of units related to the same limb; and 4) localization of units within striatal regions having extensive synaptic input from SI and MI cortices. These findings go further to provide the first detailed characterizations of the discharge properties of striatal neurons in mammals during locomotion. As shown in studies of cortical units (Chapin and Woodward 1982a,b, 1986), the use of TM locomotion (coupled with videotape analysis) was a useful experimental paradigm for producing frequent and repetitive neuronal signals, in the form of unit relationships to locomotor limb movement, that serve as measures of striatal processing during unrestrained movement.
LIMB-RELATED UNITS IN RAT LATERAL STRIATUM

Sia, which was absent from the present experiments. Indeed, unit recordings from our laboratory (in preparation) in the dorsolateral striatum of anesthetized rats have shown a lack of responsiveness to the same stimuli that produced responses in the unanesthetized animals of this study. Analogous differences have been observed between awake (Schneider and Lidsky 1981) and anesthetized (Krauthamer 1979) cats. Taken together, these findings suggest that anesthesia qualitatively affects sensory responses of striatal neurons.

A further difference from these results is that a somatotopic arrangement was found (Richards and Taylor 1982) in which units responsive to forelimb, head, and neck stimulation were located rostrally, whereas those responsive to hindlimb, scrotum, and tail were located caudally in the lateral striatum, thus corresponding to the corticostriatal topography suggested by Webster (1961). Our study failed to corroborate that differentiation of forelimb-versus-hindlimb representations in the A–P dimension. Instead, both forelimb and hindlimb representations were located at all rostrocaudal levels of the lateral striatum between +1.6 and −1.0-mm A–P, thus corresponding more closely to recent conceptualizations (Cospito and Kultas-Illinsky 1981; McGeorge and Faull 1989; Wise and Jones 1977) of longitudinally distributed corticostriatal topographic projections in the rat (see below).

Specificity of striatal discharges

Unit discharges related to active limb movement were specific in that they 1) showed minimal or no activity when the animal was at rest; 2) showed high correlations with one particular limb but no other body part; 3) fired, in many cases exclusively, during one discrete phase of the limb's movement during the step cycle, and 4) showed no relation to the same limb's movements during deviations from forward locomotion.

All portions of the locomotor step cycle, as brief as 0.2 s and as long as 0.4 s, were represented by different limb-related units. The data fell into certain categories corresponding to particular phases of the step cycle (although a more detailed parcellation of the step cycle is certainly possible): throughout swing, late swing, first or second one-half of stance, footoff, and footfall. More information must be added to these limited data to identify divisions of the step cycle appropriate for understanding the functional significance of striatal involvement in locomotion. With respect to these data, a high proportion of units (11/17) fired during the swing phase compared with stance. Interestingly, a similar predominance of units related to swing and forelimb reaching has been shown in sensorimotor cortex (Chapin and Woodward 1986), which putatively provides afferent signals contributing to limb-related striatal discharges.

No attempt was made to systematically vary locomotor parameters (e.g., TM speed) during these studies. Thus the only variations from straight-ahead locomotion occurred spontaneously, consisting of backward or disrupted locomotion. Unit firing patterns under these conditions would be expected to differ from the rhythmic discharges observed during forward locomotion. However, the absence of any relation to limb movement, including the total lack of any activity on the part of several limb-related units during these variations, was surprising. Striatal unit discharges related to forward locomotor limb movements apparently are not due to a simple tracking of sensory input regarding limb position but, instead, may be related to 1) an aspect of intention or command signal to move in a prescribed manner (Alexander 1987; Schultz and Romo 1988) or 2) inputs from SI cortex, in which different unit responses to foot contact were obtained during rhythmic, straight-ahead locomotion versus locomotion disturbed by experimental probing (Chapin and Woodward 1982a).

Finally, specificity was observed for only a portion of cells in the lateral striatum (18% were related to limbs; 16% to other body parts). A sizeable proportion of the sample lacked this type of specificity (38% were related to global body movement; 28% were unresponsive). The functional implications of these proportions remain to be determined. Across categories, units exhibited similar waveforms. Although these recordings did not detect two cell types, as in certain previous studies (Alexander and DeLong 1985; Orr et al. 1987; Skirboll and Bunney 1979), the units of this study appear to correspond to the type I cells recorded by Alexander and DeLong (1985).

Localization of neurons related to limb movement

Neurons related to specific limb movements occupied a restricted area in the lateral (particularly the dorsolateral) striatum. Histologic verification of recording sites, which was highly consistent across animals, showed a remarkable confinement of most units to a subregion on the lateral edge of the striatum, with a M–L width of ~1.0 mm. The lengthy rostrocaudal extent of this subregion (A–P +1.6 to −1.0 mm from bregma) included all but the most posterior subregions of the striatum. This corresponds with the substantial rostrocaudal range of the primate putamen throughout which units showed a somatotopic organization (Alexander and DeLong 1985; Crutcher and DeLong 1984a). A similar longitudinal distribution was shown for functional cell types in the primate caudate nucleus (Hikosaka et al. 1989). These data show that both fore- and hindlimbs were represented at all A–P levels studied. Whether there is a somatotopic organization that can be observed in unit recordings in the rat is currently under investigation.

These findings provide evidence for functional differentiation of the rat striatum. The specificity of lateral striatal unit relationships to limb movement stands in contrast to recordings obtained from central regions of the striatum, where such specificity was rarely observed (West et al. 1987b). (It should be repeated that not all lateral units were related to specific body parts. Thirty-eight percent of this sample fell into the general-body–movement category, thus resembling units recorded medially, and 28% were unresponsive. The difference emphasized here is that no limb-related units were observed in subregions medial to the dorsolateral region.) Thus there appears to be a functional distinction between medial and lateral subregions of the rat striatum.

A distinction between the medial and lateral striatum is strongly supported by a growing literature derived from
diverse experimental approaches. Topographic projections to the striatum from cortex (Cospito and Kultas-Illinsky 1981; Domesick 1981; Kelley et al. 1982; McGeorge and Faul 1989; Wise and Jones 1977), substantia nigra (Beckstead et al. 1980; Carter and Fibiger 1977; Fallon and Moore 1978; Van Der Kooy 1979), and intralaminar thalamic nuclei (Van Der Kooy 1979) terminate in medial-versus-lateral zones running longitudinally. Medial-to-lateral gradients have been demonstrated for cholinergic markers (Guyenet et al. 1977; Rea and Simon 1981; Takano et al. 1980), D2 receptor density (Boyson et al. 1986; Joyce et al. 1985), and the behavioral effects of local injections of dopamine agonists (Delfs et al. 1990; Joyce and Van Hartesveldt 1984; Neill and Herndon 1978). Impaired forelimb motor performance followed lateral, but not medial, striatal lesions produced by 6-OHDA (Sabol et al. 1985) and ibotenic acid (Pisa 1988a,b). Orientation to somatosensory stimuli was impaired after 6-OHDA (Dunnott and Iversen 1982; Fairley and Marshall 1986) and kainic acid (Dunnott and Iversen 1982) lesions of the lateral, but not medial, striatum. The akinesia, aphagia, and adipsia after large dopamine-depleting lesions has been shown to be correlated with increased single-unit activity in the lateral, but not medial, striatum (Orr et al. 1987). Conversely, cognitive, rather than motor, deficits appeared to be responsible for impairments in a delayed-alternation task after kainic-acid lesions of the antemoduler striatum (Divac et al. 1978); the anterolateral region was shown not to be critically involved in this task (Oberg and Divac 1975).

Limb-related units in this study were located within the subregion (i.e., the dorsolateral subregion) containing the terminals of projections from somatic sensorimotor cortex in the rat (Cospito and Kultas-Illinsky 1981; Domesick 1981; Donoghue and Herkenham 1986; Joyce et al. 1985; McGeorge and Faul 1989; Wise and Jones 1977). Also, single units in the lateral striatum have been shown to exhibit short-latency responses to electrical stimulation of SI and MI (Hirata et al. 1984). A similar correspondence exists between electrophysiologic (Alexander and DeLong 1985; Crutcher and DeLong 1984a,b; Garcia-Rill et al. 1979; Liles 1975; Liles and Updyke 1985) and anatomic (Garcia-Rill et al. 1979; Jones et al. 1977; Kuzonzo et al. 1986; Kunzle 1977, 1978; Liles and Updyke 1985; Malach and Graybiel 1986; Oka 1980) studies in cats and monkeys. The fact that the sensorimotor patterns of striatal unit firing in this study resemble those that have been demonstrated repeatedly in SI (e.g., Chapin and Lin 1984; Chapin and Woodward 1986; Evarts 1974; Soso and Fetz 1980) and MI (e.g., Chapin and Woodward 1986; Evarts 1986; Fetz et al. 1980; Schultz et al. 1983; Tanji and Kurata 1985) cortices during behavior supports the concept that they were, at least partially, determined by SI and MI corticostral afferents. This concept is further supported by the absence of this type of activity in afferents to the striatum from substantia nigra (DeLong et al. 1983; Schultz 1986; Steiniefs et al. 1981) or intralaminar thalamic nuclei (Peschanski et al. 1981). The differences that presumably exist between striatal and cortical activity patterns, as a function of other inputs to the striatum or of intrinsic striatal processing, are not yet clear.

It is interesting to speculate on whether these recordings relate to recent concepts of striatal compartmentalization. In agreement with previous electrophysiological studies (Crutcher and DeLong 1984a; Liles and Updyke 1985; Richards and Taylor 1982), microelectrode penetrations revealed clusters containing units related to movement of the same body part. Although a systematic measurement of the dorsoventral dimensions of individual clusters was not utilized (but is currently in progress), this range was 100–400 μm. Spaces of 200–400 μm containing no spontaneous or evoked activity were observed between clusters. These values are in general agreement with those obtained from the monkey (Crutcher and DeLong 1984a). Such clusters may correspond to the targets of patchy cortico-striatal terminal fields (Gerfen 1989; Goldman and Nauta 1977; Jones et al. 1977; Kunzle 1977, 1978) and/or to the mosaic pattern of striatal compartmentalization (Goldman-Rakic 1982; Graybiel et al. 1979, 1981; Herkenham and Pert 1981). The clusters studied in this report may be representative of similar modules throughout the striatum, which await further physiological characterization. Also remaining to be clarified is the relationship between electrophysiologic and morphologic cell clusters, to better understand them within the context of the striatal mosaic (Donoghue and Herkenham 1986; Gerfen 1984; Graybiel and Hickey 1982; Herkenham et al. 1984; Jimenez-Castellanos and Graybiel 1987; Penny et al. 1988).

In conclusion, these findings contribute important new information toward understanding the functional organization of the rat striatum. A significant aspect of these findings is their potential to guide future studies in the rat to obtain further characterizations of the sensorimotor and behavioral properties of striatal neurons.

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