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A STUDY OF SINGLE AXONS IN THE CAT'S MEDIAL LEMNISCUS

By A. G. BROWN,* G. GORDON and R. H. KAY

From the University Laboratory of Physiology, Parks Road, Oxford OX1 3PT

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SUMMARY

1. A method was developed for locating the rostral part of the medial lemniscus in anaesthetized cats and then exploring it with a microelectrode selective for single axons. Records were made from 165 axons, all shown histologically to lie in the lemniscus.

2. Almost all lemniscal axons responded at short latency to a shock through surface electrodes over the dorsal columns at C2. The great majority probably belonged to the dorsal column-lemniscal system, though some may have belonged to other (e.g. spinocervicothalamic) systems.

3. Resting discharge was seen in almost all axons in the absence of any stimulation, and must have been generated almost entirely in the relevant relay nuclei, particularly since in many axons it was easily depressed or totally inhibited by appropriately placed mechanical stimulation of skin or a shock to the dorsal columns.

4. For each fibre held for an adequate length of time, the receptive field, if accessible, was classified as accurately as possible. Fifty-two axons were precisely categorized in this way: many more were studied for long enough to yield useful information.

5. One half (twenty-six) of the best categorized axons had receptive fields suggesting excitation by only one type of receptor: fifteen by tylotrich hairs, four by rapidly adapting tactile foot pad receptors, two by claw movement, two by cutaneous touch corpuscles and three by Type II cutaneous receptors. Rigidly held probes driven by electromechanical transducers were used to establish stimulus/response relations. Adjacent or surround inhibition was seen in nearly all these fields, except for the Type II category.

6. The other half (twenty-six) of the best categorized axons showed various degrees of inter-receptive excitatory convergence. Five responded

* Beit Memorial Research Fellow during part of this investigation. Present address: Department of Physiology, Royal (Dick) School of Veterinary Studies, University of Edinburgh, Edinburgh EH9 1QH.

to all types of hair, twelve to hair movement and foot-pad displacement, and nine to hair movement combined with inputs from a variety of slowly adapting receptors in skin or deep tissues, thresholds for the latter ranging from light contact to noxious pressure.

7. Forty axons responded with a slowly adapting discharge to joint movement, some with properties suggesting that their receptors did not lie in the joint capsule itself. The high threshold of most of these axons to dorsal column stimulation suggested that the relevant primary axons lay either deep in the dorsal column or in some other tract.

8. Of axons whose receptive fields were accurately located, 88% lay in forelimb or upper trunk – the remainder in lower trunk, hind limb or tail. The forepaw accounted for 41% of the former group. Axons with receptively 'pure' properties tended to lie in central or deep parts of the main lemniscal mass at the level studied. Axons responding to joint movement tended to lie deep in the main mass and in the ventromedial lemniscal bundle. There was some clustering of axons with identical receptive properties.

INTRODUCTION

A considerable body of anatomical and electrophysiological information is now available on the various types of cutaneous, subcutaneous and joint receptors present in the cat, particularly on those innervated by myelinated afferent fibres (for reviews see Burgess & Perl, 1973; Hensel, 1973; Skoglund, 1973). This knowledge opens up the possibility of using electrophysiological experiments to identify precisely the types of afferent unit which project on to central neurones in ascending systems. Such experiments have been done for axons in the dorsal columns (Brown, 1968; Petit & Burgess, 1968) for neurones of the spinocervical tract (Brown & Franz, 1969), the dorsal spinocerebellar tract (Mann, 1971) and for some neurones in the somatosensory cortex of monkeys (Mountcastle, Talbot, Sakata & Hyvärinen, 1969). Some information is also available on receptor input to the cells of the dorsal column nuclei. In a population of cells excited by a variety of cutaneous or subcutaneous mechanoreceptors, Gordon & Jukes (1964) recognized, in addition to the familiar 'hair-sensitive' units, neurones selectively excited by activation of Pacinian corpuscles or receptors responding to claw movement or receptors in foot-pad skin. At the time these experiments were done, however, several types of receptor in cat's skin had not been clearly distinguished, e.g. the individuality of the two types of slowly adapting mechanoreceptors in hairy skin and of the various types of hair follicle receptor (Brown & Iggo, 1967).

We had two reasons for recording from single axons in the medial

lemniscus in the present experiments. The first was to avoid the vascular and respiratory pulsations which are especially severe when recording from medullary nuclei such as the gracile and cuneate, and thereby to provide enough time for examining the receptive fields and typing them correctly, and for studying stimulus-response relations quantitatively. The second was to remove the recording electrode to a distance from synaptic regions so that the output of the neurones could be studied without fear of upsetting transmission properties. This approach has the one disadvantage that the medial lemniscus receives axons both from the contralateral dorsal column nuclei and from the contralateral lateral cervical nucleus and is therefore not a strictly homogeneous system. However, the dorsal column nuclei themselves are not homogeneous in this sense, since they receive an ascending input not only from the dorsal columns but also from the dorsolateral funiculus and this latter may arise through collateral branches of spinocervical tract axons (Dart & Gordon, 1973). As the great majority of lemniscal axons come from the dorsal column nuclei (Busch, 1961), which in turn receive their major afferent input from the dorsal columns, we assume that most of our sample is composed of axons belonging to this path.

A preliminary report of some of the results has been published (Brown, Gordon & Kay, 1970).

METHODS

The experiments were performed on six cats, all but one very thin cat weighing between 2·0 and 2·5 kg. Under anaesthesia with halothane and nitrous oxide in oxygen, the trachea and the left femoral artery and vein were cannulated, and the upper cervical spinal cord exposed by removing the dorsal arch of the second vertebra. The anaesthetic was then changed to I.V. sodium pentobarbitone and throughout the experiment anaesthesia was maintained at a level sufficient to prevent spontaneous movements of the animal or movements in response to any stimulation used. The head was fixed in a holder aligned in Horsley-Clarke coordinates, a small hole was made in the skull over the left parietal cortex and the dura incised and reflected. The surface of the cortex was protected by a mixture of liquid paraffin and petroleum jelly. The femoral arterial blood pressure was monitored and the rectal temperature maintained at 38° C by a thermostatically controlled electric blanket on the ventral body surface.

Identifying and recording from lemniscal axons. To find the medial lemniscus in the upper brain stem we first found the position of the caudal ends of the thalamic nuclei N. ventralis posterolateralis and N. ventralis posteromedialis. The nuclei were roughly mapped out using a coarse steel needle, insulated to near its tip, as a recording electrode, while the body surface was stroked with hand-held probes. The characteristic mass responses were amplified and followed on a loud-speaker. The caudal ends of the nuclei having been approximately found in this way, a high impedance tungsten micro-electrode was then inserted vertically about 2 mm caudal and 1 mm lateral to the caudal tip of the N. ventralis posteromedialis. Systematic tracking with the fine micro-electrode to find and survey the medial lemniscus was performed by making a succession of tracks through the same hole in the cortex, and

inclining the angle of insertion, usually in 2° steps, in both medial and lateral directions, so producing a fan-shaped series of tracks (see Fig. 1 and Pl. 1). The same micro-electrode was used for the whole series of tracks in each experiment. Caution in preserving this electrode intact sometimes led us to terminate a track before reaching its full useful depth (see Fig. 1*B*).

The micro-electrode was advanced in steps (2 or 5 μm steps when in or near the lemniscus) by a stepping motor drive while the dorsal columns at C2 were stimulated with single shocks locked to the time-base sweep, using a pair of silver-ball electrodes oriented longitudinally on the surface of the columns. Typical records from single axons were either almost pure monophasic positive potentials or positive-negative potentials with a large positive phase, and were like those recorded near the surface of the spinal cord with similar electrodes (see Brown, 1971). They ranged from a few hundred μV to about 10 mV in size. Units were assigned to the lemniscus if they responded at short latency to the dorsal column shock (less than 5 msec for the first impulse although most units had latencies less than 3 msec) or if their response properties were of a kind previously recognized in cells of the dorsal column nuclei or of the lateral cervical nucleus whose axons were shown to project in the lemniscus (see, e.g. Gordon & Jukes, 1964; Horrobin, 1966). Final assignment to the medial lemniscus depended entirely on histological reconstructions of the recording positions with respect to marked positions (see below).

Recorded potentials were amplified and displayed on an oscilloscope by conventional means and in addition were led to one track of a seven-track tape recorder (Ampex SP 300) and recorded in the direct mode. On the other tracks we recorded a sweep-triggering pulse, a time scale, electrical stimulus parameters, a commentary and the electrical output from the electromechanical transducers (see below), using frequency-modulated recording for the latter with a recording bandwidth chosen to allow faithful representation of the movements of the probe.

Receptor identification and mechanical stimulation. When a single unit had been isolated the position and nature of the receptive field were determined as accurately as possible. Initial classification into cutaneous, subcutaneous and joint categories was made by manual exploration with brushes and blunt probes and movement of the limbs. For subcutaneous and joint units the site of the receptors was determined, the type of stimulation necessary to excite (light or heavy pressure, kneading of muscle, flexion or extension of limbs, etc.) and whether the response was rapidly or slowly adapting.

Cutaneous receptive fields were examined more carefully under a binocular operating microscope, often after the hairs in the field had been cut with scissors. For units with receptive fields in hairy skin we used the classification of Brown & Iggo (1967) into Types D, G and T hairs (down, guard and tylotrich respectively) and Types I and II slowly adapting units. Other receptor types identified were rapidly adapting and slowly adapting foot-pad receptors (the rapidly adapting ones were not subdivided in the manner of Jänig, Schmidt & Zimmermann, 1968), and slowly adapting claw units (Gordon & Jukes, 1964). When more than one type of receptor excited a lemniscal unit attempts were made to determine the degree of convergence.

Stimulus–response relations were determined quantitatively by using electromechanical stimulators. These consisted of Pye-Ling Type V 47 electromagnetic transducers, with the spatial position of their moving probes (tip diameter 1·8 mm) monitored by Hewlett-Packard Type 7 DCDT-050 length transducers which controlled their drive circuits. The general principles of operation were similar to those used in the second type of moving coil transducer described by Brown & Iggo (1967; Methods (2), p. 709). The driven transducers provided controlled ramp movements with separately variable rise time, fall time, dwell time and amplitude (Bannister, 1965). Rise and fall time were variable within three ranges (5–50 msec,

50–500 msec and 0·5–5 sec), dwell time was continuously variable within two ranges (5–500 msec and 0·5–5 sec) and amplitude within two ranges (0–150 μm and 0–1·5 mm). There was also a 'zero' position-setting control variable over $\pm$ 1·5 mm, and the transducers had a large position range for initial setting before use of the 'zero' since they were held in snake flexible arms (Verdict Ltd) and mounted on movable stands with magnetic clamps.

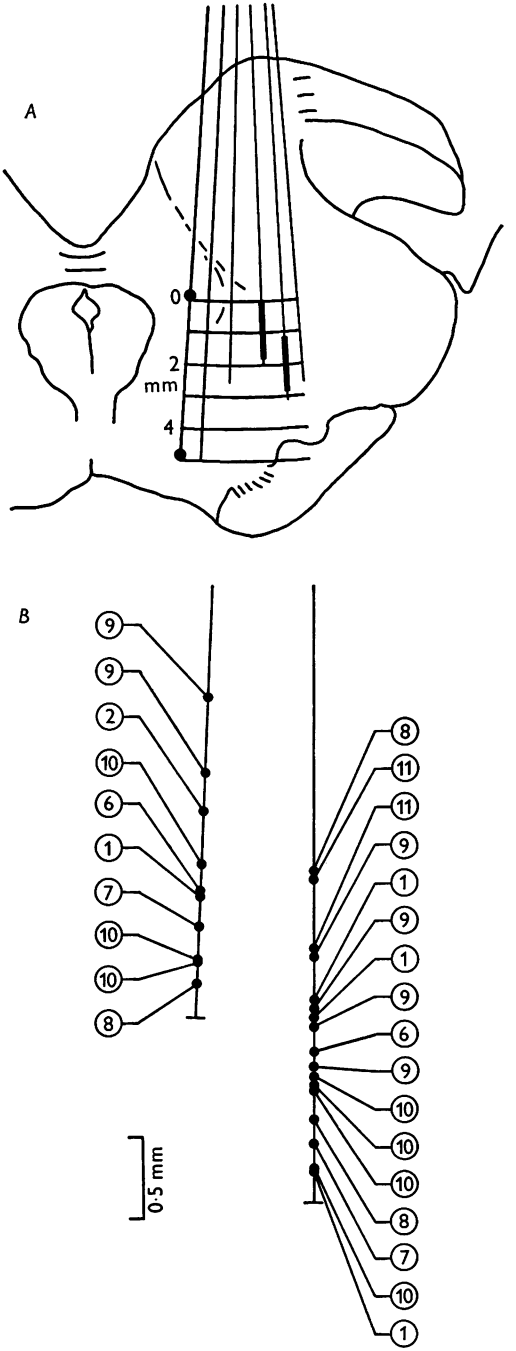
Histological methods. In the last electrode track of each experiment, after all recordings had been made, two electrolytic lesions a known distance apart were made in the mid-brain by passing 20 μA for 20 sec through the micro-electrode with the micro-electrode negative to the indifferent electrode. The head was then fixed by perfusion with 5% formaldehyde-saline after previous washing out of blood with 0·9% sodium chloride. On the next day the relevant block of brain was removed by using a knife blade moving transversely and held in the manipulator previously used to hold the micro-electrode, the head remaining in the stereotaxic frame. After further fixation by immersion the block was embedded in low-viscosity nitrocellulose and serial transverse sections cut, parallel to the cut surfaces of the block, at 50 μm. Alternate sections were stained with Weil's haematoxylin fibre stain and with Klüver's & Barrera's cresyl violet and luxol blue stain for both cells and fibres. The electrode tracks were identified in these sections and the experiment reconstructed spatially by plotting the positions of unit recording sites on large scale diagrams, after making due allowance for shrinkage during fixation which was calculated from the distance apart of the two electrolytic lesions.

RESULTS

Recording from single axons in the medial lemniscus was remarkably successful. In some initial experiments in which vertical electrode tracks were used great difficulty was experienced in finding the lemniscus; once the method of making the tracks radiate from a single point on the cortical surface was adopted, good yields of lemniscal axons were obtained (up to 40 in a single experiment). It can be seen from Pl. 1 and Text-fig. 1 that lemniscal axons were found clustered together within single tracks, and they were usually all within one or two adjacent tracks with few or no units outside the main cluster, in a position which accurately coincided with the site of the lemniscus as determined histologically. In one experiment a group of units was found in a ventromedial position outside the main body of the lemniscus and this contained a high proportion responding to movement of joints or displacement of subcutaneous or deep tissue (see below). Recording conditions for single lemniscal axons in the present experiments were much more stable than those for cells in the exposed pulsating medulla (cf. Gordon & Jukes, 1964). Single units could usually be held long enough to allow receptive field analysis and often for upwards of 30 min.

Receptive properties of lemniscal fibres

Recordings were made from 165 single axons and all but thirty of these were typed according to their excitatory input although *complete* receptor identification was not possible for all of the 135 classified as 'identified'.



Text-fig. 1. For legend see facing page.

It was often extremely difficult to determine which kind of hair excited a particular unit, either because of lack of time or because of inaccessibility of the receptive field for detailed study. Several types of unit were found, however, which under the barbiturate anaesthesia we used were excited by stimulating only a single type of receptor. Other kinds of lemniscal units had well-defined convergences from more than one sort of receptor. The vast majority of units isolated of whatever group had a resting or 'spontaneous' discharge.

(1) *Units responding to movement of tylotrich hairs (fifteen units).* This group of fibres was the largest in which activation was confined to a single type of receptor. The units were excited by movement of tylotrichs within the receptive field but not by movement of guard or down hairs between the tylotrichs. Their receptive fields were small (Text-fig. 2*A*, *B*), usually of only a few mm^2, and in one instance an excitatory receptive field consisted of only two tylotrichs. A characteristic feature of these units was the presence of an adjacent or surround inhibitory receptive field, as shown in Text-fig. 2*A*, *B*. Inhibition of both the resting and evoked discharges was easy to elicit by moving a few hairs in the inhibitory field. It was not possible, however, to determine whether movement of only one particular type of hair was responsible for the inhibition. When the surface of the dorsal columns at C2 was stimulated electrically with single shocks, the initial evoked discharge in these units was followed by a period of silence lasting up to about 150 msec, and it was sometimes possible with low strengths of shock to the dorsal column to produce this inhibition with no preceding excitation.

When single tylotrichs were moved with a mechanical stimulator these units responded only to the movement of the hair and not to its static displacement. In this respect they behaved just like the hair follicle

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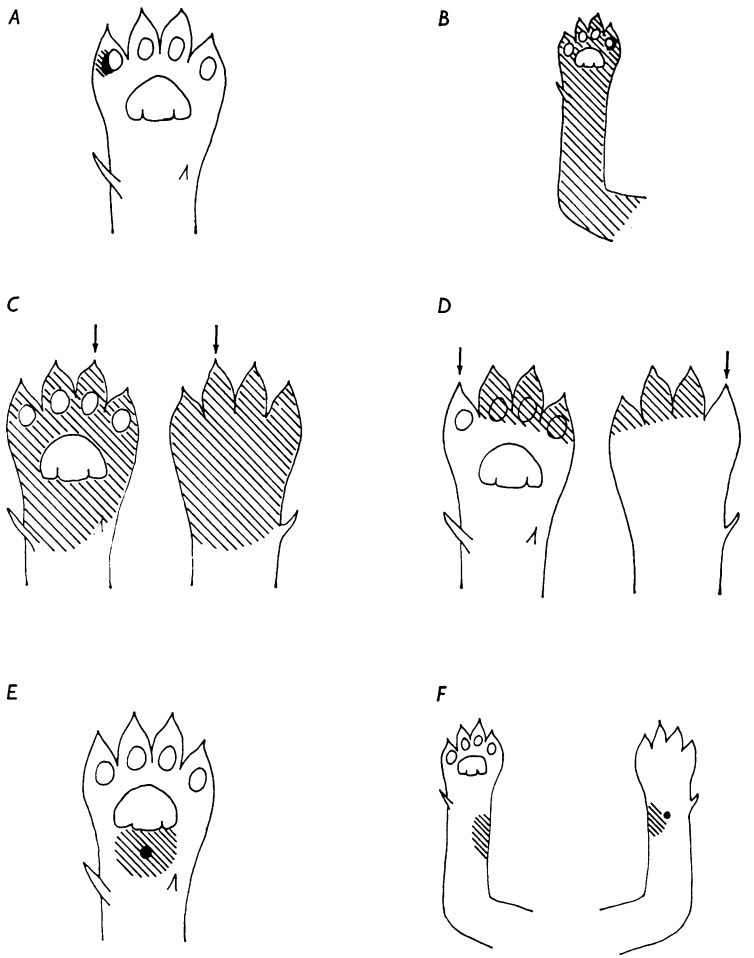
Text-fig. 1. Representation of micro-electrode tracks and of lemniscal axons identified in one experiment.

A tracing of transverse section of upper mid-brain at the site of recording, based on four adjacent 50 μm sections. Six tracks were made, of which only the fourth and fifth (reading from the left or medial side) passed through the lemniscus. The thickened parts of the lines in these latter tracks represent the regions in which responding axons were found. The filled circles in the first (medial) track represent two electrolytic lesions made 5 mm apart in the living brain.

The greater parts of tracks 1–4 are seen in Pl. 1 *A*, and of tracks 5 and 6 in Pl. 1 *B*.

B, reconstruction on a larger scale of the responsive parts of tracks 4 and 5, based on measurements made during the experiment. Each axon is marked by a filled circle, and is given a number which refers to the corresponding category in the text.

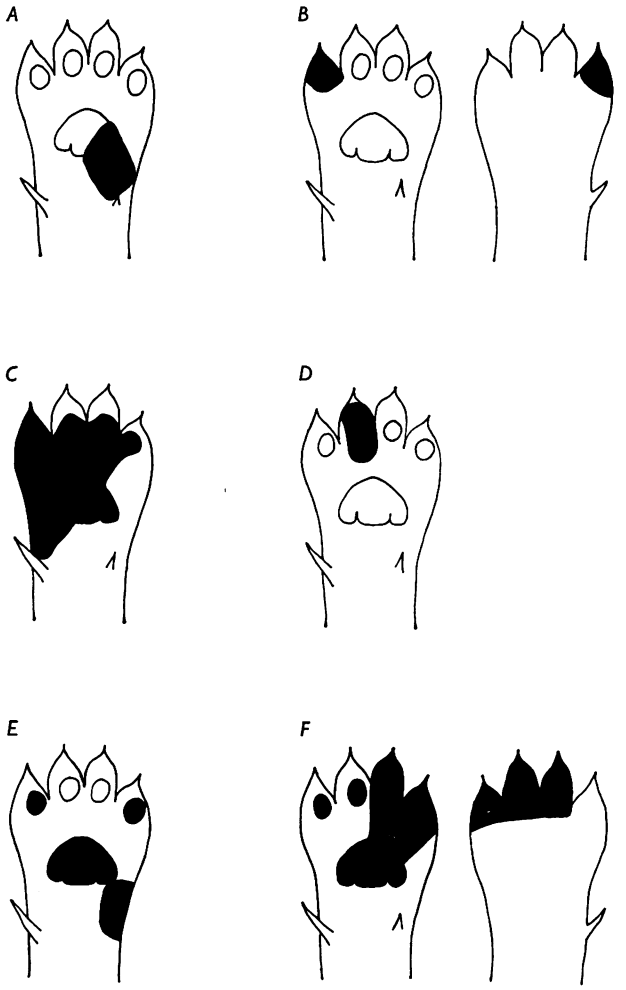
primary afferent units excited by tylotrichs (Type T units; Brown & Iggo, 1967), and showed similar stimulus–response (displacement velocity impulse frequency) relationships as seen in Text-figs. 4*A–D*, and 5. The only difference between the stimulus–response relations of the primary afferent units and these lemniscal units was a small increase in the slope of the power function (see below), which also occurs in the responses of spino-



Text-fig. 2. Receptive fields of lemniscal units excited by a single receptor type. Excitatory fields are shown as filled areas (except in *C* and *D*, see below) and inhibitory fields as cross-hatched areas. *A*, *B* units responding to movement of tylotrichs; *C*, *D* units responding to slowly adapting claw receptors, the excitatory receptive field being indicated by an arrow pointing to the claw, movement of which excited the units; *E*, *F* units responding to displacement of cutaneous touch corpuscles (Type I slowly adapting units). Inhibition in all of these units was elicited by moving hairs.

cervical tract neurones excited by movement of tylotrichs (Brown & Franz, 1969).

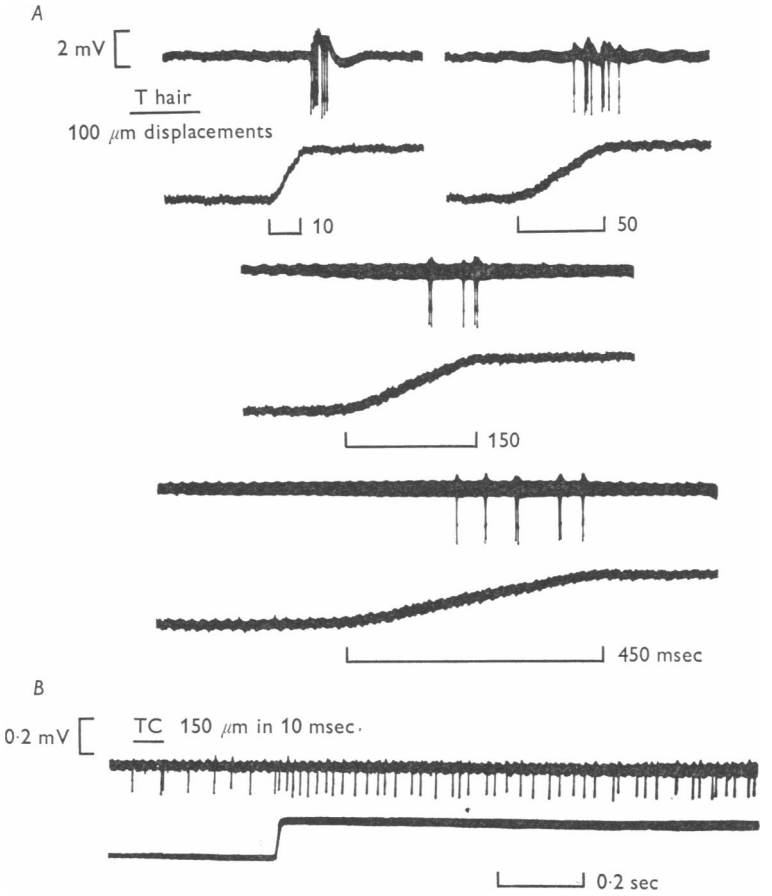
For two units in this group for which a satisfactory range of quantitative data was obtained, the stimulus–response relation was tested by linear/linear, linear/logarithmic, logarithmic/linear and logarithmic/logarithmic best fit. For both of these, and for another unit referred to below which



Text-fig. 3. Excitatory receptive fields of lemniscal units excited from hairs and pads. *A*, *B*, *C*, units excited by rapidly adapting receptors associated with hairs and in the foot pads. The strip-like excitatory field of the unit shown in *A* was typical for this group. *D*, *E*, *F*, units excited by hair and pad displacement and with a slowly adapting component in the response. The unit shown in *D* had the usual continuous type of excitatory field. Two units shown in *E* and *F* had discontinuous excitatory fields.

responded to movement of all types of hairs, the log/log relationship showed the best correlation coefficient and lowest standard error of the line of best fit. For the two units in the present group the log/log slopes were 0·83 ± 0·02 and 0·70 ± 0·02 (see Text-fig. 5).

(2) *Units responding to touching glabrous foot-pad skin (4 units).* These units responded with a rapidly adapting discharge during movement of a

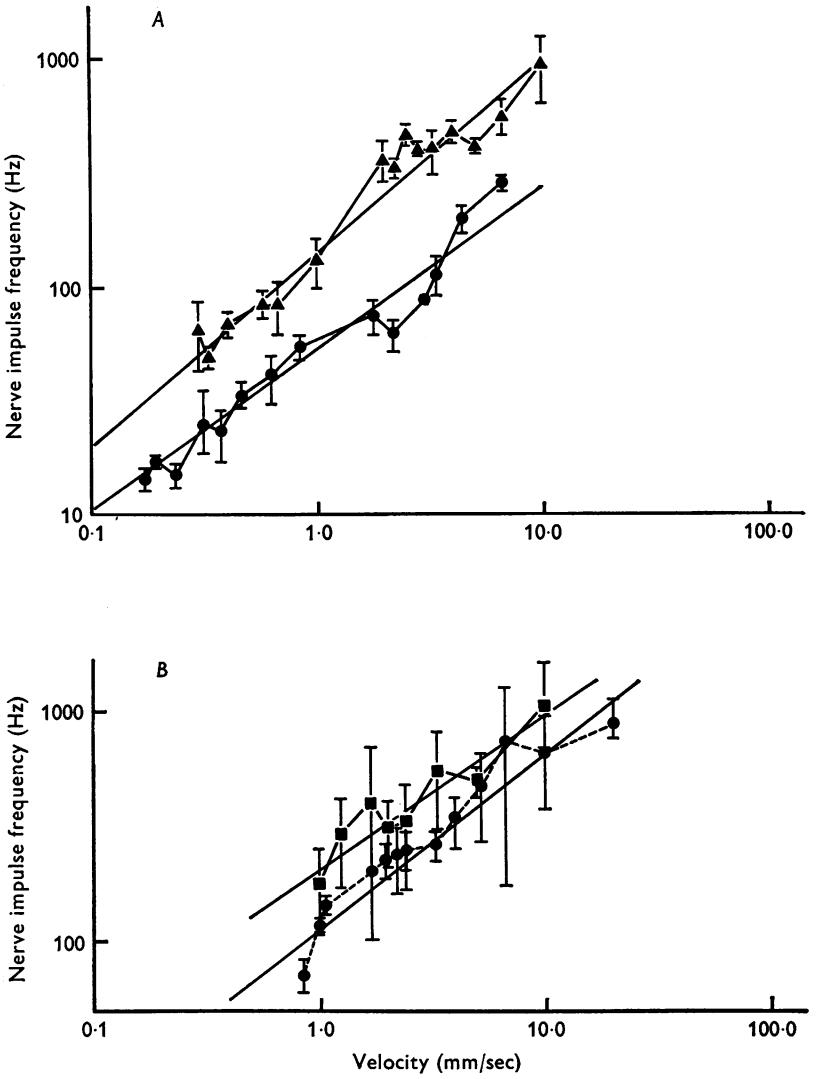


Text-fig. 4. Responses of lemniscal units to mechanical stimulation of skin receptors.

A, unit responding to linearly rising ramp displacements of a tylotrich hair at four different velocities and a constant displacement amplitude. The rise time of the ramp stimulus is given in each case by the scale below.

B, unit responding to displacement applied to a touch corpuscle at the velocity and amplitude indicated.

In all records the upper trace represents the discharges of the unit (positive downwards) and the lower trace the displacement of the stimulating probe.



Text-fig. 5. Stimulus-response relationships for three units. Ordinates: log nerve impulse frequency in lemniscal axon. Abscissae: log velocity of movement of stimulating probe.

A, two units (▲ and ●), responding to movement of tylotrich hairs, with slopes 0·83 ± 0·02 (▲) and 0·70 ± 0·02 (●).

B, unit responding to movement of all types of hair, to illustrate that the response law of these rapidly adapting units is little affected by stimulus amplitude. Responses measured at different velocities but always with total amplitude 50 μm (■, slope 0·70 ± 0·05). The same with total amplitude 100 μm (●, slope 0·77 ± 0·03).

In all cases the vertical bars indicate ± 1 S.E.

stimulator on the foot-pads. Three had excitatory receptive fields restricted to one pad or part of a pad and one had a larger field comprising two toe-pads and part of the central pad. Adjacent inhibitory receptive fields were present for two of three units tested and inhibition could be evoked by the dorsal column stimulus in three of the four units. They were therefore essentially similar to the rapidly adapting pad-sensitive cells in the gracile nucleus described by Gordon & Jukes (1964).

(3) *Units responding to movement of claws (two units).* These units corresponded to the claw-sensitive cells described by Gordon & Jukes (1964). Each had a single spot-like receptive field in the soft tissue at the base of a claw and adapted slowly to maintained displacement of the claw or of the skin over the spot (see Text-fig. 2*C*, *D*). Both units had adjacent inhibitory receptive fields, as shown in Text-fig. 2*C*, *D*.

(4) *Units responding to displacement of cutaneous touch corpuscles (two units).* Both units of this kind had receptive fields on the forelimb, each excitatory field comprising four cutaneous touch corpuscles (Type I slowly adapting receptors, Brown & Iggo, 1967) and the units responded to their displacement in the way characteristic for these receptors, with a dynamic component during movement and an irregular slowly adapting discharge during maintained displacement (see Text-fig. 4*E*). Inhibitory fields were present for both units. For one unit the inhibitory field was of the surround type but for the other was asymmetric and probably not immediately adjacent to the excitatory field (see Text-fig. 2*E*, *F*). Inhibition was produced by movement of hairs for both of these units. Particular care was taken to classify these units correctly because of the controversy concerning the central projection of Type I units (Brown, 1968; Petit & Burgess, 1968; Whitsel, Petrucelli & Sapiro, 1969; Harrington & Merzenich, 1970).

(5) *Units with properties similar to Type II slowly adapting receptors (three units).* All these units had receptive fields confined to a single spot, pressure upon which evoked a slowly adapting discharge which was more regular than that of the units last described above. They all had a regular background discharge and could be excited by stretching the skin containing the receptive spot. It may be assumed, because of these properties, that their receptors were the Type II slowly adapting kind (Chambers & Iggo, 1967; Brown & Iggo, 1967; Chambers, Andres, Duering & Iggo, 1972), and since each receptive field contained only a single spot there must have been a one-to-one excitatory relation between the pre- and post-synaptic neurones concerned. Furthermore, no inhibitory receptive field could be found for any of these units nor was inhibition evoked by electrical stimulation of the cervical dorsal columns.

(6) *Units responding to movement of all types of hair* (*five units*). In addition to the units only excited by tylotrichs there was another clear category excited only by hair movement, but this group was excited by movement of all the hairs within the receptive field, i.e. down hairs, guard hairs and tylotrichs. In most respects they were similar to the units excited only by tylotrichs, having similar stimulus–response relations with a rapidly adapting discharge in which the frequency was determined by the velocity but not by the amplitude of hair movement (Text-fig. 5*B*). The slopes of the log/log plots of stimulus velocity-impulse frequency relations for the unit illustrated in Fig. 5 were 0·70 ± 0·05 at 50 μm and 0·77 ± 0·03 at 100 μm displacement amplitude, suggesting independence of slope value from stimulus amplitude. Stimulation by electrodes on the cervical dorsal columns elicited inhibition in three of these units but not in the other two. For one of the units inhibited by dorsal column stimulation, hairs in the natural inhibitory receptive field were moved with a mechanical stimulator to condition a test response evoked by an independent mechanical stimulator in the excitatory field. Very effective reduction of the number of impulses in the test response was produced up to conditioning-testing intervals of about 70 msec, but after testing at this delay the unit was lost. The inhibitory conditioning also markedly increased the latency of the first impulse but the fewer impulses in the conditioned response were at a higher frequency than in the unconditioned situation.

(7) *Units responding to movement of hairs and to displacement of the skin of the toe-pads* (*twelve units*). This appeared to be a well defined category of units although there were similarities between this and the next group (units excited by hair movement and skin displacement). For five of these units there was no slowly adapting component in response to pressure on the hairy skin or on the pads and their receptive fields were continuous (Text-fig. 3*A*,*B*,*C*). Cells with similar receptive properties were found in the gracile nucleus by Gordon & Jukes (1964). The shapes of the excitatory fields of these units tended to be strip-like with the edges of the strip clearly defined and sometimes running across part of a pad (see Text-fig. 3*A*). For the other seven units there was a slowly adapting component in the response in addition to the rapidly adapting response to hair or pad movement. Five of these had excitatory receptive fields similar to those with no slowly adapting component (Text-fig. 3*D*) but the other two had discontinuous excitatory receptive fields (Text-fig. 3*E*, *F*) with some part or parts of the field separated from the rest by an area of skin from which neither excitation nor inhibition could be elicited. The two latter units, together with one responding to pad stimulation and described above in section 2, were the only units in the present sample with discontinuous excitatory fields.

Eight units in this group were tested for inhibition, either by exploring the skin near the excitatory field or by electrical stimulation at the surface of the dorsal columns. Inhibition was seen in seven of them.

(8) *Units responding to hair movement and to maintained displacement of hairy skin* (*nine units*). These units responded with a rapidly adapting discharge to movement of hairs in the excitatory field and in addition with a slowly adapting discharge to maintained displacement of the skin in the same area. The slowly adapting component had a low threshold to natural stimulation in some units and in one of these displacement of touch corpuscles was effective in evoking the slowly adapting discharge. Other units required strong pressure to evoke the slowly adapting discharge. Inhibition was observed in three of five units tested.

(9) *Other units responding to hair movement* (*forty-one units*). This group of units had a rapidly adapting discharge to hair movement and no slowly adapting component. No further information is available on the type of hair follicle afferent units which excited, because some had inaccessible receptive fields and others were lost before the field could be adequately typed. A few needed spatially summating stimuli to fire more than one or two impulses and in this respect they were similar to some primary hair follicle units excited by movement of guard hairs (Type G units, Brown & Iggo, 1967).

(10) *Units responding to joint movement or with receptors deep to the skin* (*forty-two units*). This group contained some units responding exclusively to extension or flexion of a particular joint and also units which, though many also responded to joint movement, had receptive sites that did not lie in a joint capsule. Some in this latter group, for example, needed heavy pressure over a bony point or kneading of a muscle to excite them. They all adapted slowly to maintained displacement. They have been placed here in a single group because of the difficulty in defining their receptive properties more precisely. It was characteristic of this group that they almost all required a much higher strength of shock applied to the surface of the dorsal columns to fire them, possibly indicating that their afferent axons at this upper cervical level were further away, perhaps deeper or more lateral, from the surface of the columns than those of the other groups of units. For twenty-nine units tested with such stimuli, twenty-four responded at latencies less than 2·5 msec and 14 responded with only a single impulse. As mentioned below, this group of units was strongly represented in the ventromedial portion of the lemniscus.

(11) *Unidentified units* (*thirty units*). These could not be classified into any of the types described above, usually because of the position of the receptive field or because of inadequate time. For many of them, however,

the position of the excitatory field was determined accurately enough to be of help in studying somatotopic organization within the lemniscus.

Organization of the medial lemniscus

This investigation was not primarily designed for somatotopic analysis of the medial lemniscus. Although the method we evolved could well be used for that purpose we did not space our recording tracks closely enough to achieve high spatial resolution, except in one experiment in which both the dorsolateral and the ventromedial components of the lemniscus described by Busch (1961) were investigated. Nine tracks passed through some part of the lemniscus in that instance. In other experiments our whole samples of fibres were taken within one to five tracks. Further considerations in planning an accurate topographical analysis are discussed below (see Discussion).

One striking fact was the large preponderance (88%) of fibres with receptive fields in forelimb and upper trunk over those with fields in lower trunk, hind limb or tail. In the former group, for fibres whose field positions were accurately enough determined (163 of 165 axons), fifty-nine were on the forepaw, fifty-five on some more proximal part of the forelimb, and twenty-eight on neck, shoulder or upper trunk. In the latter group six were on the hind paw, nine on more proximal parts of the hind limb, one on the tail and four on the lower trunk. The forepaw in particular achieves a high proportion of the total representation. Fibres with facial fields were not especially looked for, and in fact only one was found. This emphasizes that our technique for detecting single fibres was largely based on the fibre responding to a shock delivered to the dorsal spinal surface at C2, which excluded units with facial fields from the investigation. In the main dorsolateral mass of the lemniscus fibres with hind limb fields tended to occupy a central or centro-lateral position, but hind limb fibres were sometimes closely flanked dorsally and ventrally by forelimb fibres.

Fibres in the same receptive group were quite commonly found close together in pairs or sometimes triplets within a single electrode track. This was striking where the receptive characteristics were especially clear-cut, as for tylotrich hair units (see, for example, Text-fig. 1*B*), for Type II units for which two out of the three recorded were within 0·1 mm of each other, and for units with joint or other deep-lying receptors (Group 10 above) for which examples are seen in both tracks illustrated in Text-fig. 1*B*.

Fibres in the groups with 'pure' receptive characteristics (Groups 1 to 5 above) tended to lie in the central or deep parts of the main dorsolateral lemniscal mass. Units with joint or other deep-lying receptors tended to

be deep in this region (see Text-fig. 1 *B*) and also formed a high proportion of the sample of fibres from the ventromedial bundle of Busch (1961) which was explored in one experiment.

DISCUSSION

We have found that recording from single lemniscal axons is a reliable and productive way of studying the output of the somaesthetic nuclei of the medulla. Recording from lemniscal axons was facilitated by first locating the approximate termination of the axons and then systematically scanning the region immediately caudal to this with a high-impedance microelectrode.

The advantages of recording at a distance from the nuclei themselves were mentioned earlier. One is to avoid disturbing them physically. It is well known, and has recently been emphasized in the case of the gracile nucleus (Cremers, 1971), that the frequency of firing of neurones is readily influenced by the proximity of a recording electrode to their cell bodies and dendrites. In such circumstances it cannot be certain to what extent background discharge in the absence of stimulation is an artifact or even what reliability may be attached to measurements of stimulus–response relations. The present experiments have shown, at least under the anaesthetic conditions used, that the great majority of leminiscal axons and therefore of relay cells in the appropriate nuclei have a background discharge which is not an artifact. The evidence is conclusive for the large number of units which had inhibitory components to their receptive fields, stimulation of which reduced or abolished this resting discharge. The point of view that resting discharge generated in relay nuclei may have a function as a background against which to signal inhibition therefore remains a viable one. The other particular advantage in recording from axons in the mid-brain lay in being able to record from well isolated single units for a period of time long enough to characterize their receptive fields accurately. In addition, when the receptive field was easily accessible, stimulus–response relations could be studied quantitatively. This degree of isolation is only possible in the dorsal column nuclei if pulsatile movement is minimal, and it is quite possible that even under good conditions most successful records have been made from cells at the edge of the cell clusters (Cajal, 1909; Kuypers, Hoffman & Beasley, 1961; Kuypers & Tuerk, 1964) but not from within them where the close packing of cells is very disadvantageous for unitary extracellular recording. This potential bias is presumably absent in a sample of lemniscal axons.

It is likely that the great majority of our lemniscal axons originated from relay cells in the dorsal column nuclei. Leaving aside the trigeminal

system, which was not investigated, these nuclei form the major source of lemniscal axons and contribute to both the main dorsolateral mass and to the ventromedial bundle of the tract (Busch, 1961; confirmed by Gordon & Jukes, 1964). Our cervical stimulating electrodes were on the surface of the dorsal columns, which probably biased the sample of lemniscal axons somewhat in favour of relay cells of the dorsal column-medial lemniscal system. However, since large stimuli were sometimes needed to elicit a response from a unit, especially for units whose receptors were in joints or other deep tissues, we are likely to have excited cells or fibres of other systems such as spinocervical axons or neurones of the lateral cervical nucleus. The spinocervicothalamic system is known to project, by means of axons of cells in the lateral cervical nucleus, into the contralateral medial lemniscus (Morin & Catalano, 1955; Busch, 1961; Gordon & Jukes, 1963; Horrobin, 1966), The need for a large stimulus does not, however, show definitely that the axons in question belonged to the spinocervicothalamic system, because such stimuli are also necessary to excite the deepest fibres of the dorsal columns themselves which lie about 3 mm from the dorsal surface at this level. There is also a contribution from the dorsolateral funiculus which terminates in the rostral parts of the dorsal column nuclei and excites relay cells projecting in the lemniscus (Dart & Gordon, 1973; Gordon & Grant, 1972), and this may also have contributed to our sample. It is not known if the post-synaptic fibres of the dorsal columns (Uddenberg, 1968*b*), which contribute to the input of both dorsal column nuclei (Petit, 1972; Rustioni, 1973), terminate on cells projecting into the lemniscus, so no view can be expressed on their involvement in the present experiments. The presence in our sample of a high proportion of axons with receptive fields containing low-threshold inhibitory components is a particular reason for implicating the central cell-nest regions of the dorsal column nuclei as the origin of such axons, since relay cells with these properties are especially common there (Gordon & Jukes, 1964) and have not been seen in the other systems studied at least with the methods so far employed (Gordon & Jukes, 1963; Horrobin, 1966; Dart & Gordon, 1973).

We did not attempt to study closely the somatotopic organization of the lemniscus. The preponderance of forelimb over hind limb, and particularly the dense representation of the forepaw are already familiar in other somaesthetic tracts and nuclei and in the cortex. The topographical grouping of fibres in the same receptive category, and the tendency for fibres with very distinct and unmixed receptive properties to lie in the central and deeper parts of the main lemniscal mass, may reflect features of the lemniscal projection of the central parts of the dorsal column nuclei, referred to above, which occupies this part of the cross-sectional lemniscal

profile (Busch, 1961). The cervicothalmic projection occupies the dorsolateral part of the lemniscus but becomes progressively overlapped by the dorsal column nuclear projection more rostrally (Busch, 1961), so that the two projections are moderately intermixed at the level at which most of our tracks were made (about frontal plane A4·5). It might thus be expected that a dual representation of the body surface, one dorsal and one ventral in the lemniscus, would be distinct at more caudal levels but would become progressively less clear rostrally. Such an arrangement was suggested but not clear-cut in our results. A proper study of this question would require that the sampling was not systematically biased in favour of either path.

Of the fifty-two axons most satisfactorily analysed for receptive properties (see Results, sections 1–8) twenty-six responded as if, under the conditions of these experiments, each could be excited by only a single type of receptor. Two of these types have been recognized previously in cells of the gracile nucleus (those excited by rapidly adapting pad receptors and those excited by slowly adapting claw receptors; Gordon & Jukes, 1964). The largest group, excited only by movement of tylotrich hairs, has not previously been recognized, and with their characteristic adjacent or surround inhibitory fields they were presumably included in the 'hair-sensitive' group by Gordon & Jukes (1964). The response of these post-synaptic axons differed from those of the primary Type T hair follicle afferent units (Brown & Iggo, 1967) only in the existence of a resting discharge and in the presence of an inhibitory component in the receptive field. The inhibition and most of the resting discharge must have been developed in the relay nucleus, most myelinated primary axons, except those from Type II receptors, having little or no resting discharge (Brown & Iggo, 1967; Burgess & Perl, 1967; Burgess, Petit & Warren, 1968). Of the stimulus–response (velocity of hair movement-frequency of discharge) functions tested, the log/log plot of a power law function gave the best fit, as explained earlier, with exponents for two well studied units of 0·70 and 0·83. These values are higher than those found for primary Type T afferent units (Brown & Iggo, 1967) suggesting a change of slope generated at the synaptic relay, although no precise comparison can be made at present between slopes measured pre- and post-synaptically with the small number of data available.

In addition to the tylotrich hair units, the groups of neurones responding exclusively to stimulating Type I or Type II slowly adapting receptors have not previously been recognized separately in central somaesthetic systems. Cells have been described in the gracile nucleus that responded with a slowly adapting discharge to light pressure on hairy skin (Perl, Whitlock & Gentry, 1962; Gordon & Jukes, 1964) and it was emphasized

that they did not have inhibitory components in their receptive fields, thereby differing from the majority of the population which showed rapidly adapting responses to hair or pad displacement with adjacent or surround inhibition. It is most likely, in view of the present findings, that these cells (called 'touch-pressure' cells by Gordon & Jukes, 1964) owed their slowly adapting properties to an input from cutaneous Type II receptors (Chambers & Iggo, 1967; Brown & Iggo, 1967) since lemniscal axons with an input from these receptors did not have an inhibitory component in their receptive fields, whereas those with inputs from Type I receptors did. The observation that units which are only excited by displacement of cutaneous touch corpuscles (Type I receptors) do occur in the medial lemniscus reopens the question what their central role might be. Some of the 'touch units' described by Uddenberg (1968*a*) in the cervical dorsal columns and with receptive fields on the forelimb certainly had properties characteristic for Type I units and the present results show that information from these receptors probably gets at least as far as the thalamus (N. ventralis posterolateralis).

For the two types of slowly adapting units with receptors in hairy skin, for the claw units and for the units excited by tylotrich movement, the degree of excitatory convergence of the primary afferent fibres on to the central neurones must have been severely restricted. As mentioned earlier, for the Type II units it must have been 1:1, but also for the other three classes it cannot have been much greater since, (1) only four touch corpuscles were in the fields of each Type I unit and each corpuscle is innervated by only a single afferent fibre, giving an upper limit to the degree of convergence of 4:1, (2) movement of a single claw or a single spot at the base of a claw excited the claw units, (3) the tylotrich units had very small excitatory receptive fields confined in one case to two hairs. Although one cannot in all cases exclude an influence of anaesthesia or afferent inhibition in limiting field size, for example with tylotrich hairs, limited convergence provides the simplest and most probable explanation. The remarkable receptive 'purity' of the post-synaptic fibres in this part of our lemniscal sample must depend on precision of anatomical connexions. This aspect of transmission in the somaesthetic system is also emphasized by observations on cortical cells in the unanaesthetized monkey, some of which are activated only from Pacinian corpuscles and others only from rapidly adapting receptors in glabrous skin (Mountcastle *et al.* 1969).

The absence from our sample of 'pure' lines of units only excited by movement of guard hairs seems to call for comment. This group (Type G hair units) makes up about 35 % of the fibres in fasciculus gracilis (Brown, 1968) and is the only class of units with dorsal column axons that is not represented as a 'pure' line post-synaptically. It is possible, of course, that

such post-synaptic units do exist in the lemniscus and that we did not record from them because of the size of our sample or because their axons are small, or that we did not recognize them. Certainly, some of the units which responded to hair movement (class 9 in Results) required spatial summation of stimuli to elicit more than one or two impulses as do some of the primary Type G hair follicle units. The only lemniscal units for which Type G hairs made up a recognizable component in their receptive fields had various degrees of convergence from different receptor types, i.e. classes 6, 7 and 8 in the Results.

The other twenty-six units in our sample of axons with thoroughly analysed receptive properties showed various degrees of inter-receptive excitatory convergence. Some received convergence from all types of hair receptor, some from low-threshold rapidly adapting receptors in pads and hair follicles, and others from hair receptors combined with a variety of slowly adapting receptors in skin or deeper tissues with the threshold for the slowly adapting component ranging from light contact to noxious pressure. Relay cells have previously been recognized in the gracile nucleus with continuous excitatory fields from hair and pad receptors (Gordon & Jukes, 1964), but the other types have not been previously characterized at a lemniscal level. The existence of these heterogeneous forms of convergence upon cells projecting into the medial lemniscus, in addition to the 'pure' lines already mentioned, reminds one that the medial lemniscus, like other tracts or indeed nerves, is an anatomical entity and connects (in this instance) various medullary and upper spinal nuclei with various nuclei or subnuclei of the thalamus. The medial lemniscus is not a functionally homogeneous system of fibres and we feel, therefore, that the term 'lemniscal' should be reserved to specify solely the anatomical location of fibres in the medial lemniscus and should not be assumed to define any particular function within the somaesthetic system.

We have left largely unresolved the exact identity of lemniscal axons excited by movements of the limbs. We worked by choice on animals with limbs and trunk in an intact state so as to be able to observe the full range of functional activation of lemniscal axons. Under these circumstances one can recognize that certain axons respond to rate of change or maintained alteration in the position of a joint, but one cannot with certainty identify the receptors as articular, muscular, tendinous or belonging to any other particular deep structure. The lemniscus clearly contains a substantial proportion of fibres responding to such positional stimuli, but other types of experiment will be necessary to characterize them correctly.

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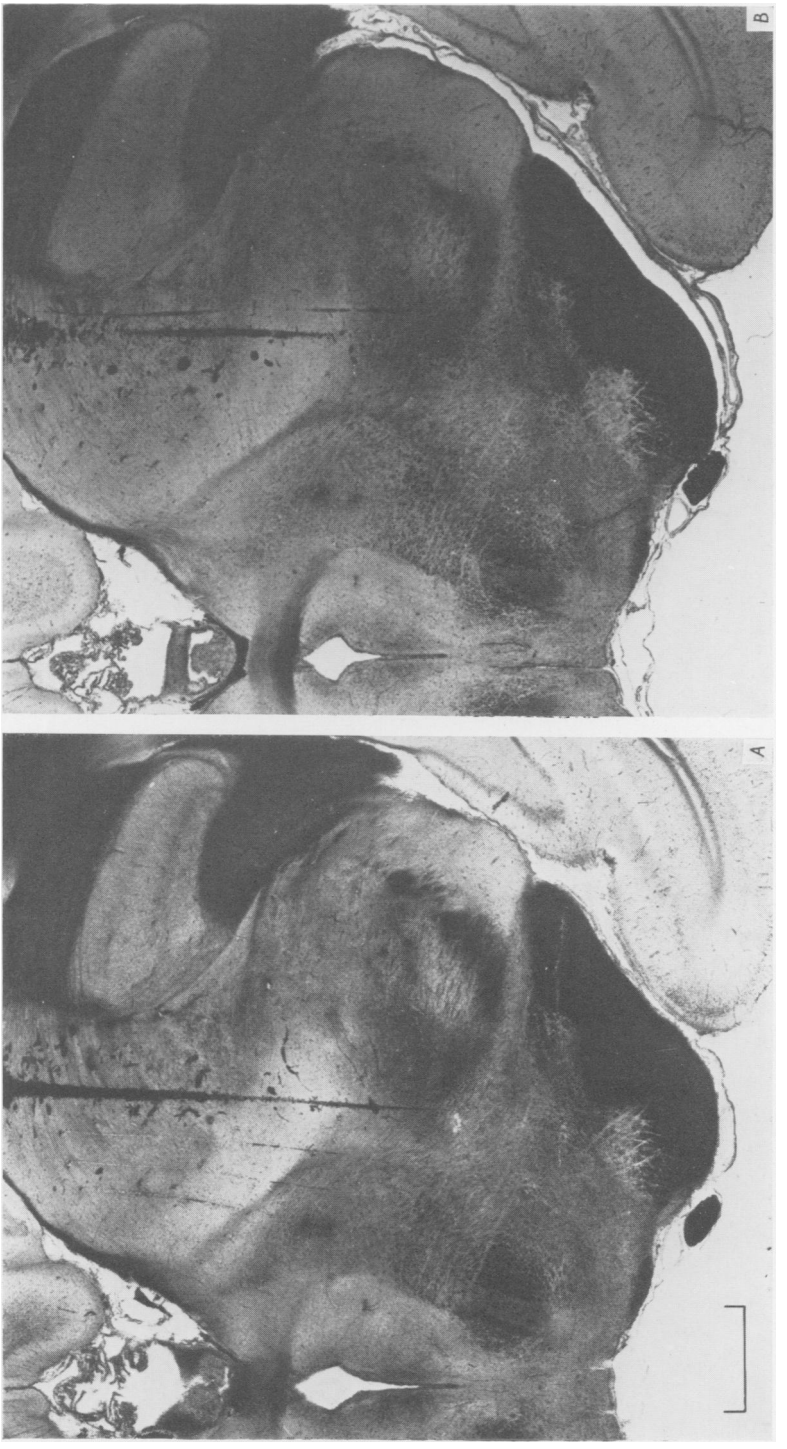
EXPLANATION OF PLATE

Transverse sections of upper mid-brain from the same experiment as that illustrated in Text-fig. 1. The sections are 50 μm thick and are separated by 50 μm in the antero-posterior plane. *A* shows tracks 1–4 (reading from the left or medial side), and *B* shows tracks 5 and 6.

Stain: Weil's haematoxylin. Scale: 2 mm (in brain before fixation).


B
A