J. Physiol. (1964), **171**, *pp.* 339–360
With 2 plates and 9 text-figures
Printed in Great Britain

CORTICAL PROJECTIONS OF THALAMIC NEURONES EXCITED BY MECHANICAL STIMULATION OF THE FACE OF THE CAT

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(*Received* 25 *November* 1963)

Most neurones within the brain-stem trigeminal nuclei which are activated by light mechanical stimulation of the skin of the face or tongue and which have an axon projection to the contralateral thalamus, have very circumscribed excitatory receptive fields (Gordon, Landgren & Seed, 1961; Darian-Smith, Phillips & Ryan, 1963; Eisenman, Landgren & Novin, 1963). Neurones with similar small receptive fields have also been identified within the medial component of the ventrobasal complex of the thalamus (Gaze & Gordon, 1954; Appelberg & Landgren, 1958) and within the specific somatic sensory cortex, both in Areas I and II (Patton & Amassian, 1952; Cohen, Landgren, Ström & Zotterman, 1957; Mountcastle, 1957; Carreras & Andersson, 1963).

Recently, additional thalamic regions activated by somatic stimulation have been identified in the posterior nuclear region of the thalamus (Poggio & Mountcastle, 1960; Perl & Whitlock, 1961) and also in the nucleus centrum medianum (Albe-Fessard & Kruger, 1962). Neurones within these regions have different functional characteristics; in particular, their cutaneous receptive fields are very extensive, often discontinuous, and many of the units can be fired not only by somatic stimulation but also by auditory stimuli.

The purpose of the present experiments was to examine the functional characteristics of neurones in the posterior thalamus activated by tactile stimulation of the face. In addition to observing cells within the ventrobasal complex and the posterior nuclear region of the thalamus, the subthalamus was also examined for evoked activity. This search was prompted by the detailed description by Nauta & Kuypers (1957) and Anderson & Berry (1959) of a pathway ascending from the brain stem to the subthalamus, corresponding to Forel's (1877) tractus fasciculorum tegmenti. This appeared to be a composite thalamic projection from the brain-stem trigeminal nuclei and the medial part of the brain-stem reticular formation. The medial part of the posterior thalamus was not systematically

explored, although a few neurones within the nucleus centrum medianum were examined.

For each thalamic neurone activated by tactile stimulation of the face, identification of a direct axon projection to the specific somatic sensory cortex was attempted, by antidromic excitation of the cell caused by electrical stimulation of the cortex. It was then possible to determine the contribution of each of the thalamic nuclear regions examined to the specific somatic thalamo-cortical projection.

METHODS

Preparation of the animal. Cats weighing 2·4–3·9 kg were used for all experiments. Anaesthesia was induced with ether and sustained with intravenous chloralose (55–65 mg/kg body weight) a dose sufficient to maintain light surgical anaesthesia throughout the experiment. Respiration was spontaneous and the inspired gas contained approximately 30 % O_2 in N_2. Body temperature was maintained at 37–38° C by means of a d.c. electric blanket. The cat's head was mounted in a stereotaxic instrument, and after the evisceration of one eye a parietal and frontal craniotomy was performed, extending laterally to expose the greater part of the anterior ectosylvian gyrus and all the coronal gyrus. The exposed cerebral cortex was protected during the experiment with a 2–3 mm layer of 2 % agar in physiological saline solution. A small hole was left in the posterior part of this agar helmet and sealed with liquid paraffin. This prevented compression of the brain, which was observed in some early experiments when a complete agar covering of the cerebrum was used. In experiments where detailed mapping of evoked cortical potentials was done, a paraffin pool, maintained at 37–38° C, covered the exposed brain.

During the operative period the systemic arterial pressure was continuously recorded with a Grass polygraph and Statham 23AC strain gauge. During the recording period intermittent recordings were made. If the mean arterial blood pressure fell below 100 mm Hg during this period the experiment was discarded. The range of mean pressures for the sixteen animals at the commencement of recording was 100–120 mm Hg, usually rising 5–10 mm Hg during the remaining part of the experiment.

Recording. Evoked cortical potentials were recorded at the surface by means of a platinum-wire electrode. Extracellular single-cell recordings were made in the thalamus with tungsten micro-electrodes prepared as described by Hubel (1957). A capacity coupled amplifier preceding a Tektronix 535 oscilloscope was used for amplification. For unitary recording the working frequency range was 80–10,000 c/s. Permanent records of the responses of all units were made with a Grass kymograph camera attached to a minotor oscilloscope.

Identification of the recording site. In each experiment the arcuate nucleus (VPM) was first found with the help of stereotaxic co-ordinates. This nucleus was usually identified readily by observing the functional characteristics of the units observed in the first electrode penetration. Serial electrode penetrations were then made in transverse or para-sagittal planes at 0·5 mm intervals, the units in each penetration examined and the limits of activity in the plane defined. All records in an experiment were made with one micro-electrode. The co-ordinates of the recording site for each unit were then known and hence its position relative to the other units examined in the plane. Serial paraffin sections of the posterior thalamus, 20 μ thick, were cut after each experiment, all sections mounted, and every second slide Nissl stained (Einarson's gallocyanin method, 1932). All electrode tracks for the series were identified, which established the lateral and antero-posterior position for each unit. Vertical positions were less accurately determined, except when small

electrolytic lesions (Hubel, 1959) were identified. By following the electrode track in serial sections it was possible to establish the lower limit of the penetration to within 250 μ. Shrinkage of sections was estimated by measurement of the distances between the separate penetrations.

Stimulation procedures

Neurones were initially identified by their discharges evoked by electrical stimulation of the skin of the face or tongue (bipolar, interpole distance 2–4 mm; duration of square pulse 50 μsec). By using the uniselector switch previously described (Darian-Smith, Proctor & Ryan, 1963) the electrical pulse could be passed successively between 10 pairs of electrodes distributed over the contralateral and ipsilateral face and contralateral tongue. If the cell responded to light mechanical stimulation of the skin, its excitatory receptive field was mapped out by means of a brush. The auditory stimulus used was a click presented by means of two small loudspeakers suitably mounted at approximately 15 cm from each ear. The electrical pulse used to activate the loudspeaker was 1 msec in duration.

Having mapped the potentials evoked by electrical stimulation of the contralateral upper lip two sets of bipolar stimulating electrodes were placed on the cortical surface over the regions where maximal initial positive potentials had been observed. One group of 6 pairs of electrodes (polar distance 2 mm; intervals between electrode pairs 2 mm) was placed over the anterior ectosylvian and coronal gyri, and the second set of three pairs of electrodes over the region of activity in the anterior suprasylvian gyrus. A manually operated switch enabled a stimulating pulse (50 μsec duration) to be switched from one pair of electrodes to the next. This arrangement allowed the rapid identification of any axon projection of the neurone being observed, to the cortical region being stimulated.

The differentiation between an antidromic response and a trans-synaptic response in a thalamic cell following stimulation of the cerebral cortex was made by the 'collision' technique previously described (Darian-Smith, Phillips *et al.* 1963; Darian-Smith & Phillips, 1963).

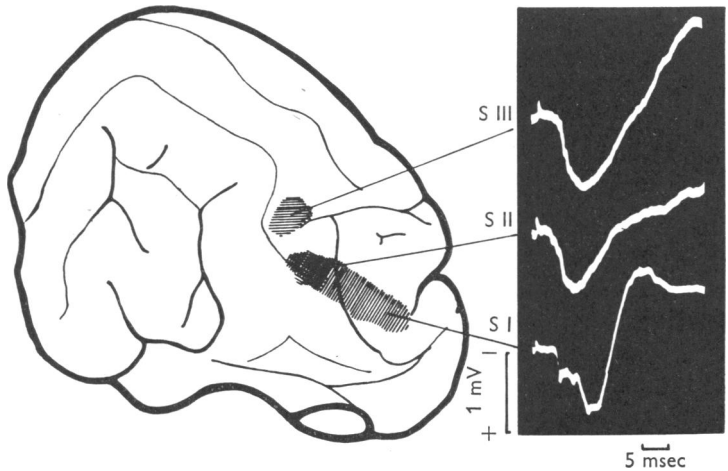
RESULTS

The experimental procedure used was first to map the regions of evoked activity at the surface of the cerebral cortex caused by electrical stimulation of the skin of the upper lip. 9–10 pairs of bipolar stimulating electrodes were then positioned in such a way that the regions of short-latency, high-amplitude, evoked potentials were straddled by these electrodes. This permitted electrical stimulation of the whole of the primary receiving area of the cortex for the contralateral and ipsilateral face by successively switching the stimulating pulse from one bipolar electrode to the next.

Distribution of cortical potentials evoked by electrical stimulation of the skin of the face

Text-figure 1 illustrates the distribution of initially positive evoked potentials on the surface of the cat's cortex, following stimulation of the contralateral and ipsilateral upper lip respectively. Two regions of short-latency responses were observed in the projection of the contralateral upper lip; one, rather elongated, extended across the more lateral parts of the

coronal, anterior suprasylvian and anterior ectosylvian gyri, with no apparent discontinuity. The second smaller region occurred more dorsomedially in the anterior suprasylvian gyrus (marked S III in Text-fig. 1). When the ipsilateral upper lip was stimulated short-latency, initially-positive potentials were evoked, in two discrete areas of the cortex. One of these coincided with the region of contralateral projection to the anterior suprasylvian gyrus (marked S III in Text-fig. 1). The more lateral region of activity was restricted to a small area in the anterior ectosylvian



Text-fig. 1. Regions of short-latency, initially positive, cortical potentials evoked by electrical stimulation of the upper lip. Contralateral stimulation evoked potentials over the whole hatched area. Ipsilateral stimulation evoked potentials in the region marked S III and in the double hatched area marked S II. On the right are records of the potentials evoked in the different regions by contralateral stimulation. The time and voltage calibrations are indicated by the horizontal and vertical bars respectively.

gyrus and the ventral part of the anterior suprasylvian gyrus (cross-hatched and marked S II in Text-fig. 1); little evoked activity was observed in the region of the coronal gyrus. This observation permitted subdivision of the lateral region of cortical activity into an anterior region with a primary contralateral projection and a more posterior region with bilateral projection; the two regions approximated to somatic sensory Areas I and II respectively. Unlike the S I and S II projections for forelimb and hind limb, there was no discontinuity in the evoked potential map for the face. Similar observations have been made previously (Berman, 1961).

The additional region of short-latency activity in the dorsal part of the anterior suprasylvian gyrus evoked by stimulation of either side of the

face has been reported previously for the limbs (Marshall, Woolsey & Bard, 1941; Marshall, 1949; Malcolm & Darian-Smith, 1958).

The latency of the initial positive component of the evoked cortical potential for the different cortical regions is shown in Table 1.

TABLE 1

Cortical recording site	Latency of initial positive wave of evoked cortical potential (msec)	
	Contralateral stim.	Ipsilateral stim.
S I	3·0–4·0	—
S II	3·0–4·0	6·5–7·5
S III	4·5–5·0	9·0–11·0

S I = somatic sensory Area I; S II = somatic sensory Area II; S III = region of evoked activity in anterior sylvian gyrus.

Neurone activity in the posterior thalamus evoked by stimulation of the skin of the face

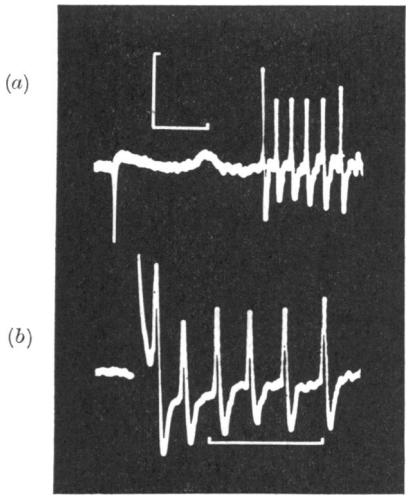
After the initial identification of thalamic neurones by the discharges evoked by electrical stimulation of the skin of the face from one or more of the stimulating sites, their excitatory receptive fields were mapped with a camel-hair brush. Ninety-four per cent of the 536 units fired in response to light mechanical stimulation of the skin. Each neurone was then examined to see if it could be fired by stimulation of the primary receiving cerebral cortex. Finally, any unitary discharge evoked by a 'click' auditory stimulus was examined.

A typical unitary response is shown in Text-fig. 2. Most cells examined were initially negative and their activity could be observed whilst the electrode tip was advanced 150 μ or more. This is strong presumptive evidence that the discharge pattern recorded was that of cell bodies rather than from axons.

The pattern of firing of thalamic units following electrical stimulation of the skin was typically a repetitive discharge with 2–10 spikes in the train. No marked differences in the discharge patterns of individual cells isolated in different parts of the posterior thalamus were observed.

The application of the 'collision' technique (Darian-Smith, Phillips *et al.* 1963; Darian-Smith & Phillips, 1964) to thalamic units to differentiate antidromic from transynaptic activation following cortical excitation was more difficult than in the case of trigeminal units isolated in the brain stem, because of the fluctuations in the latency of the synaptically evoked discharge pattern from the skin. However, it was successfully applied to 19 neurones. Of the cells examined, 12 units with a discharge latency of

2 msec or less following cortical stimulation were antidromically excited. Those cells with longer discharge latencies were found to be synaptically activated. Although this series was small, the findings were identical with our previous observations on the discharge latencies of brain stem trigeminal neurones antidromically activated by stimulation of the contralateral posterior thalamus and also the anterior cerebellar lobe. It seems likely that thalamic cells firing with a latency of 2 msec or less following cortical stimulation were antidromically activated, and that those cells



Text-fig. 2. Records of the discharge of a neurone within the zona incerta. Electrical stimulus of 50 μsec duration applied in *a* to contralateral upper lip, and in *b* to Area S II of somatic sensory cortex. A positive potential is indicated by a downward deflexion. Voltage (1 mV) and time calibrations (5 msec) indicated by the vertical and horizontal bars respectively.

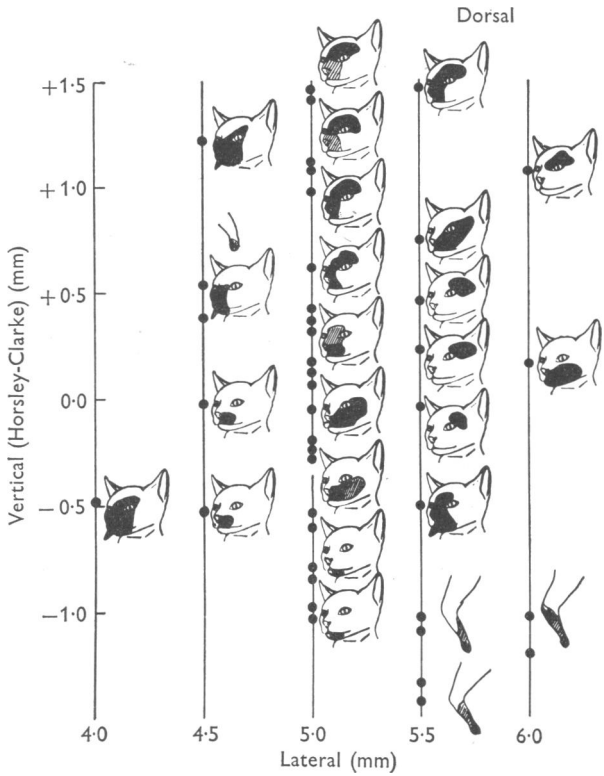
discharging with a longer latency were synaptically discharged from the cortex. This criterion of antidromic activation is applied to the whole cell population of the present experiments.

As with brain-stem trigeminal units projecting to the thalamus, most thalamic cells in the present series which fired antidromically following cortical stimulation after an interval of 1–4 msec, fired repetitively also via a synaptic pathway (see Text-fig. 2).

Distribution of neurone activity in the posterior thalamus

Neurones discharged as a result of mechanical stimulation of the face or tongue were observed in four nuclear regions within the posterior thalamus. The cell population in each region had specific functional characteristics which are outlined below.

Ventrobasal complex. Considerable evoked unitary activity was encountered when the electrode tip entered the medial component of the ventrobasal complex, the nucleus ventralis posteromedialis (VPM) as defined by Jimenez-Castellanos (1949) and Rose & Mountcastle (1952). Of the 329 cells isolated within VPM, 93 % had discrete excitatory cutaneous

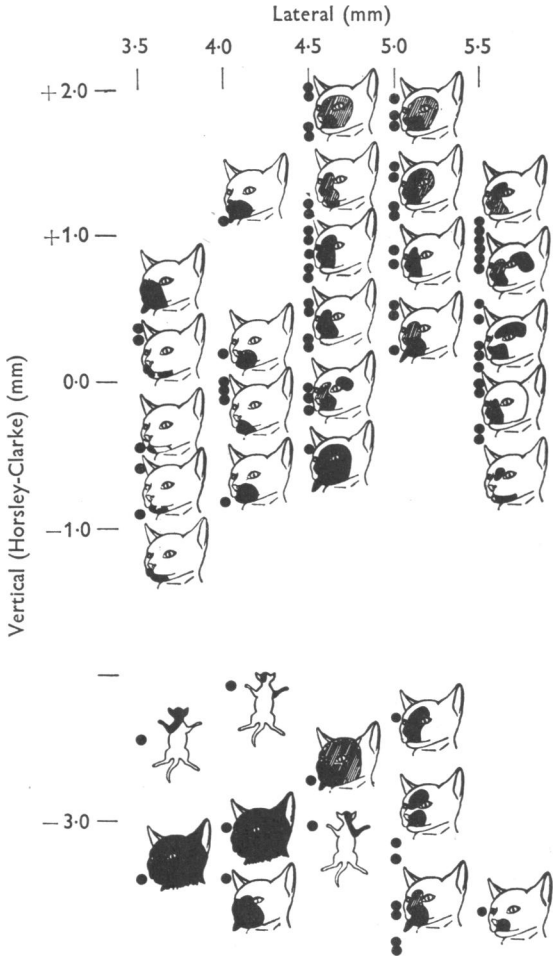


Text-fig. 3. The relative positions of neurones isolated in the oral third of VPM. Five electrode penetrations were made with the one electrode at 0·5 mm intervals. The cutaneous receptive field of each unit is shown in the adjacent diagram. Forelimb receptive fields are contralateral. The recording site is shown in Text-fig. 6*a*. Horsley-Clarke ordinates are indicated. Recording in right side of the thalamus.

receptive fields for light mechanical stimulation of the type found by Poggio & Mountcastle (1960) in the lateral component (VPL) of the ventrobasal complex. The appropriate stimulus for activation of the remaining units was not identified.

Topographical organization. In any transverse plane through the ventrobasal complex of the thalamus there was a distinctive distribution of neurones in terms of their cutaneous excitatory receptive fields. This is

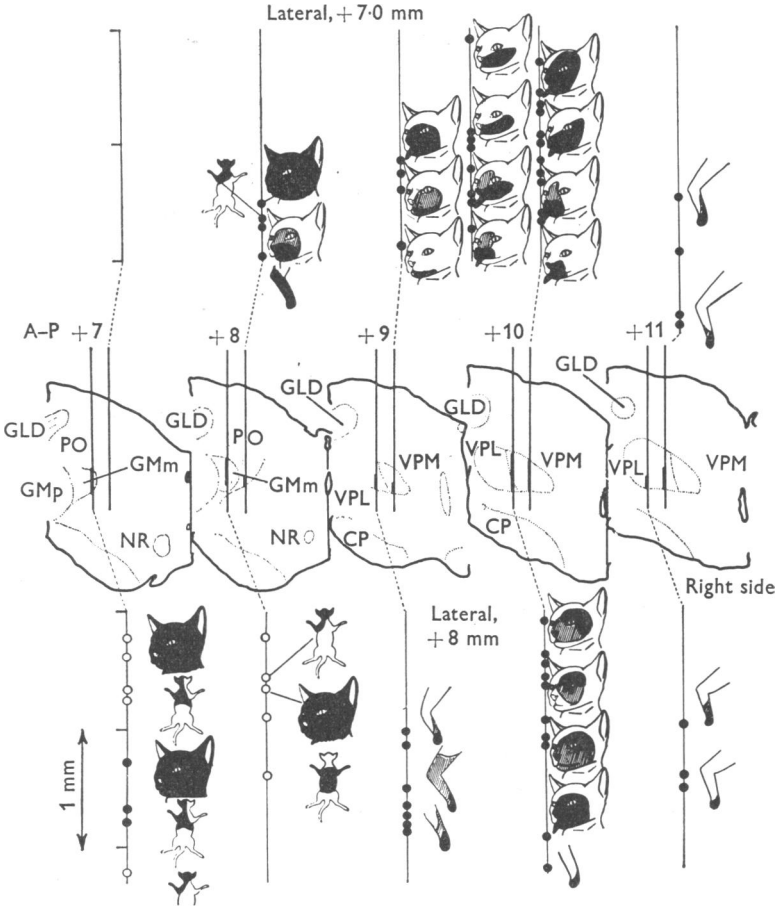
seen in Text-figs. 3 and 4, which passed respectively through the rostral third and caudal third of VPM. Neurones with receptive fields in the perioral region were in the most medial part of VPM. Those units with receptive fields restricted to the lower jaw lay in the more ventral position. Perioral receptive fields often extended on to the ipsilateral side of the



Text-fig. 4. The relative positions of neurones isolated in a transverse plane through the caudal part of VPM. Five electrode penetrations were made with the one electrode at 0·5 mm intervals. The cutaneous receptive field of each unit is shown in the adjacent diagram. Units isolated within VPM and the subthalamus are shown. Plate 1 is a photograph of the histological section corresponding to this series of penetrations. The section was cut at an angle of approximately 10° to the plane of electrode penetrations. The upper part of the section is posterior to the recording plane of this diagram and the lower part of the section is anterior. Recording in right thalamus.

face. Neurones with receptive fields in the frontal and preauricular areas usually were found in the dorsolateral part of VPM, whilst those with receptive fields near the angle of the jaw were found ventrolaterally in this nucleus.

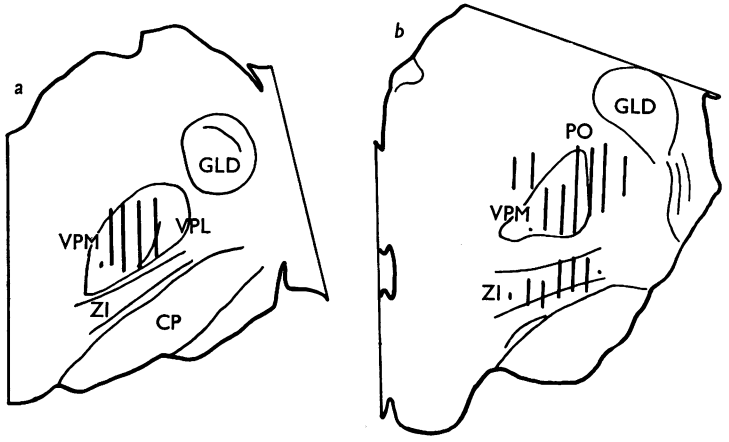
It is seen that for all cells examined in VPM the receptive fields were



Text-fig. 5. The relative positions of neurones isolated in 2 parasaggital planes (lateral position 7 and 8 mm respectively). All penetrations were made with the one electrode and the positions of cells plotted from the ordinates of the recording site. The cutaneous receptive fields are indicated in the adjacent diagrams. Open circles indicate that cell fired also in response to an auditory stimulus. Outline drawings of the appropriate transverse histological sections indicate the anatomical recording sites. VPM = n. ventralis posteromedialis; VPL = n. ventralis posterolateralis; GLD = lateral geniculate body; GMp = principle n. of medial geniculate body; GMm = magno-cellular n. of medial geniculate body; PO = posterior nuclear group of thalamic nuclei; NR = red nucleus; CP = cerebral peduncle.

small, varying from areas of 2–3 mm in diameter to receptive fields with a diameter of 20–25 mm. The somatotopic projection, as is seen in Text-figs. 3, 4 and 9 did involve some overlap in projection. This partly resulted from the variation in the area of separate receptive fields but was exaggerated by the fact that the resolution possible with extracellular recording is limited. This occurs because evoked discharges of thalamic neurones were recorded at distances up to 150 μ from the cell body.

Quite marked structural changes occur in VPM in the rostro-caudal direction. In the anterior third of the nucleus, differentiation from the



Text-fig. 6. *a*, transverse sections of right thalamus corresponding to the planes of penetration in Text-fig. 3 (left); and *b*, to Text-fig. 9 (right) respectively. Abbreviations as for Text-fig. 5. The limits of unitary recordings are indicated by the heavy near-vertical lines.

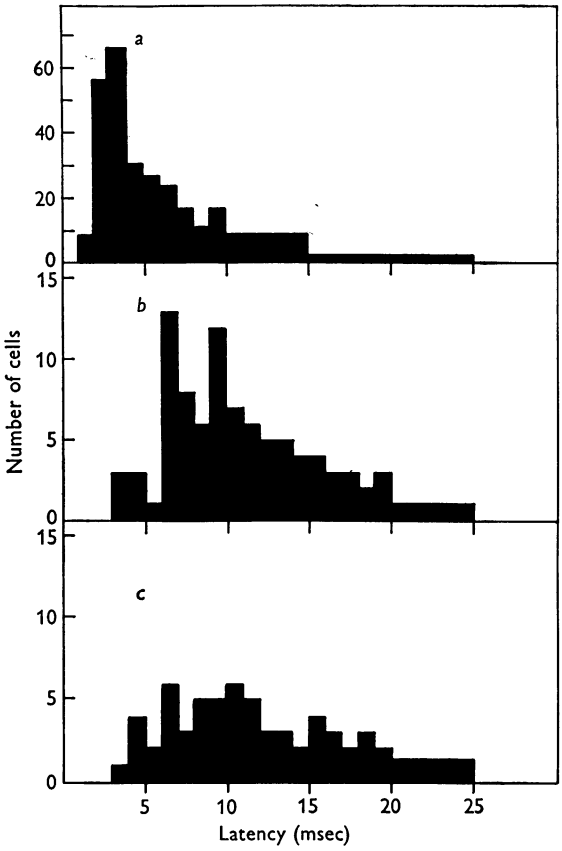
adjacent VPL and ventral and medial structures is quite apparent in Nissl-stained sections (see Pl. 2; fig. 2).

However, we observed no functional differences in the cells isolated at different rostro-caudal levels. The maintained somatotopic organisation is seen in Text-figs. 3 and 4. In Text-fig. 5, where the receptive fields of units isolated in parasaggital sections are illustrated, this absence of antero-posterior functional differentiation is again shown.

Text-fig. 7 illustrates the distribution of the shortest latency of discharge following electrical stimulation of the skin of the contralateral face (duration = 50 μsec). The distribution was unimodal, with a mean value of 7·4 msec (S.D. = 5·4 msec; $n = 329$). Most units discharged repetitively, containing 2–10 spikes/discharge.

Cortical projection. Identification of the cortical axon projections of these cells in VPM was made by antidromic activation of the cell. Only

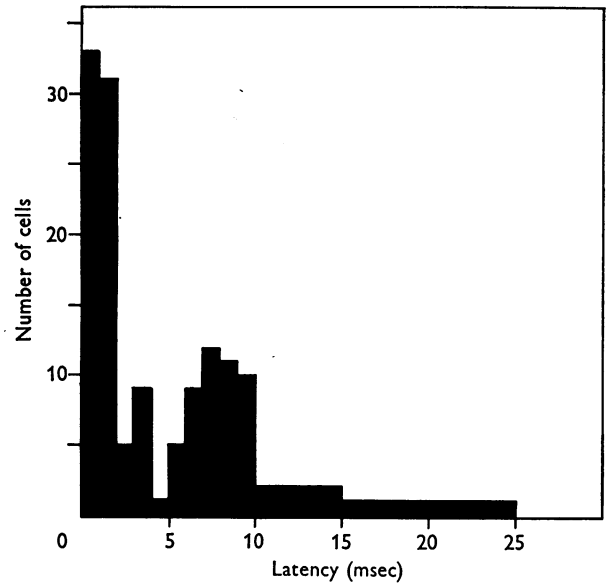
19 % of the cells identified in the nucleus could be antidromically discharged, although another 15 % were trans-synaptically activated. This contrasts with our previous observations on brain-stem trigeminal nuclei, where antidromic excitation of up to 80 % of the main sensory nucleus cells was obtained by electrical stimulation of the contralateral thalamus



Text-fig. 7. Histograms of shortest discharge latencies evoked by electrical stimulation of the face in neurones within (*a*) n. ventralis posteromedialis, (*b*) the posterior nuclear group of the thalamus, and (*c*) sub-thalamus.

in the region of VPM. Whilst the experimental situations for antidromic stimulation of the two cell groups differed it is unlikely that this marked difference in the two findings can be entirely accounted for by inefficiency in the stimulation procedure. More probably these observations reflect true differences in the proportions of the two cell groups projecting to the contralateral thalamus and ipsilateral specific somatic cortex respectively (see Discussion, p. 356).

The distribution of the shortest latency of discharge following cortical stimulation is shown in Text-fig. 8. Many of these cells fired repetitively, all but the first spike being trans-synaptically evoked, as was illustrated by observing the effect of conditioning one cortical stimulus by a preceding cutaneous stimulus. The antidromic pulse followed the test stimulus after a response interval of approximately 1 msec. The later part of the discharge, however, was regularly inhibited for intervals up to 100 msec following the preceding discharge.



Text-fig. 8. Histogram of shortest discharge latencies of neurones within n. ventralis posteromedialis evoked by electrical stimulation of the specific somatic sensory cortex.

For most VPM units with axons projecting to the specific somatic cortex, the cortical region from which the cell could be antidromically discharged was restricted to that excited by 2–3 pairs of adjacent stimulating electrodes. A few units could be discharged from a wider area covered by 4 or 5 electrodes, but these were always adjacent, and the effect may have resulted from stimulus spread. Table 2 shows the distribution of the projection sites of these antidromically activated units. Forty-eight per cent of the 64 cells projected to S I, with only about 15 % projecting to S II and to the third active region in the suprasylvian gyrus respectively. A few cells could be excited by stimulation of more than one region of the specific somatic cortex.

TABLE 2

Recorded site	Total neurone sample	Neurones with axon projection to cortex	Cortical projection area					Neurones synaptically activated from cortex
			S I	S II	S I and S II	S III	S II and S III	
VPM	329	64	31	11	9	10	3	49
PO	97	1					1	24
ZI	70	9	2	4	2	1	9	49

VPM = medial component of ventrobasal complex; PO = posterior nuclear group of thalamus; ZI = zona incerta and 'Field H' of Florel; S I = specific somatic sensory Area I; S II = specific somatic sensory Area II; S III = region of evoked activity in anterior suprasylvian gyrus (see text).

Contrasting with the neurones antidromically discharged by cortical stimulation, those VPM units which fired only trans-synaptically following this stimulus, could commonly be activated from a large part of or all the specific sensory cortex. The discharge was usually repetitive and quite variable both in its latency and in the length of the discharge train. No neurone examined within VPM was discharged in response to an auditory stimulus.

The posterior group of nuclei of the thalamus

When electrode penetrations posterior and dorsolateral to the ventrobasal complex were made a second region of evoked unitary activity was encountered in the regions shown in the sections of Text-figs. 5, 6 and 9 and Pl. 2, fig. 1. This region corresponded accurately to that described by Poggio & Mountcastle (1960) as the posterior group of nuclei of the thalamus (PO) and included (i) anteriorly a narrow region of small cells lying between the dorsolateral margin of the lateral component of the ventrobasal complex and the lateral geniculate body; (ii) the ventral part of the lateral posterior nucleus; and posteriorly (iii) the magno-cellular component of the medial geniculate body. In this region 97 neurones were examined which were activated by electrical and light mechanical stimulation of the skin of the face. This cell sample thus corresponded to only part of the population examined by Poggio & Mountcastle and did not include cells activated only by nociceptive stimulation.

Functionally these neurones differed markedly from cells isolated within the VPM nucleus. The excitatory receptive fields, whilst always including part of the face (by virtue of the method of identification) extended beyond the distribution of the contralateral trigeminal nerve. Many receptive fields extended on to the ipsilateral face and in addition most cells had receptive fields, including one or more forelimbs, the neck and trunk and often the hind limbs. The excitatory receptive fields were commonly discontinuous. Because most neurones had such widespread excitatory receptive fields no topographical projection to the region was apparent.

The distribution of the shortest latency of discharge following electrical stimulation of the skin of the face is shown in Text-fig. 7. The mean value was 12·1 msec (S.D. = 6·2 msec; $n = 97$).

Cortical projection. One neurone only of the PO sample examined was antidromically discharged by electrical stimulation of the specific sensory cortex. This unit, whilst lying beyond the dorsolateral margin of the ventrobasal complex, was atypical of the PO cells since its receptive field was small and perioral in distribution. Twenty-four of the 97 PO neurones fired repetitively when the cortex was stimulated, with latencies

varying between 4 and 20 msec. They had the characteristics of synaptic discharge; the discharge of each cell varied considerably in latency and duration and usually failed to follow stimulus repetition accurately at rates above 5/sec.

As with the sample of PO neurones examined by Poggio & Mountcastle, a number of these cells (34 % of group), in addition to discharging following cutaneous stimulation, also fired in response to an auditory stimulus. Interspersed between these units and often in their immediate neighbourhood, were units which fired only in response to an auditory stimulus.

We were unable to differentiate functionally among neurones isolated within the different anatomical subdivisions of PO, except that within the magno-cellular component of the medial geniculate body neurones responding to both an auditory stimulus and a cutaneous stimulus were much more common than in the lateral posterior nucleus. Two purely auditory units in the magno-cellular component of the medial geniculate body responded antidromically following electrical stimulation of the specific somatic cortex in Area II (S II).

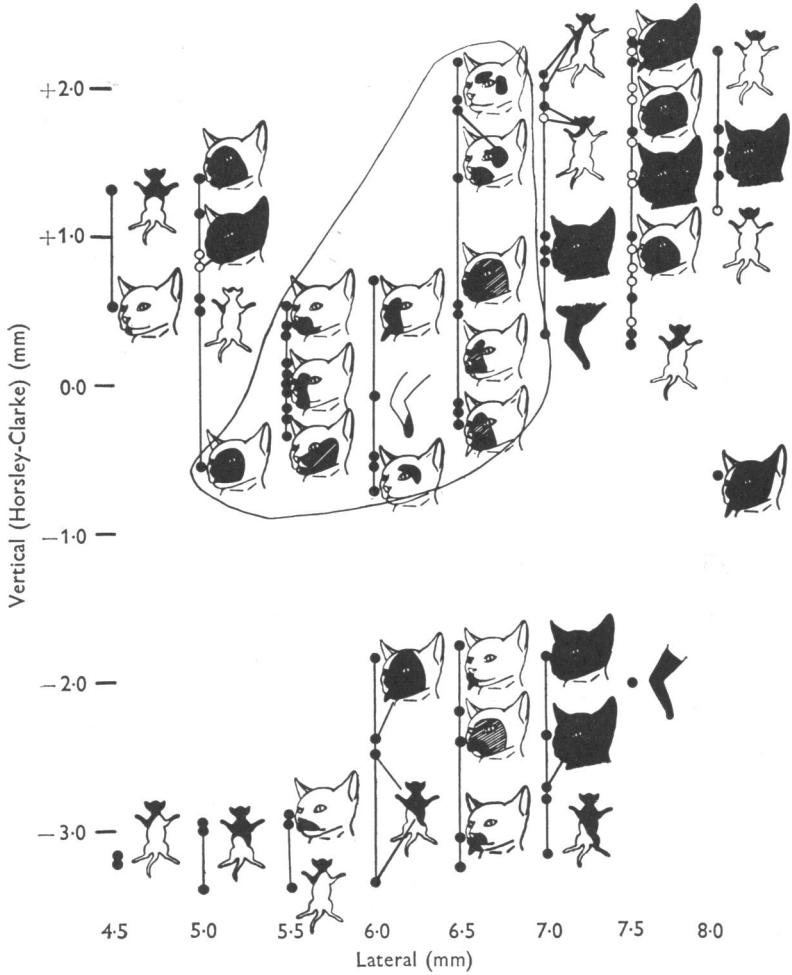
Region of Field H of Forel and of zona incerta

One half to one millimetre ventral to VPM an additional group of 70 neurones activated by light mechanical stimulation of the face was observed. The positions of these cells was restricted mainly to the region of the zona incerta and lateral half of the Field H of Forel (1877). Some of these units appeared also to be within the sub-thalamic nucleus. Caudally we observed no activation of cells in the ventral tegmental area of the mid-brain, and rostrally few units were observed within the most anterior part of the zona incerta and Field of Forel. Localization of these neurones exactly within each of these quite restricted regions of the sub-thalamus was not possible because (as is characteristic of our extracellular recording from cell bodies) the discharge pattern from most units could be recorded whilst the micro-electrode tip was advanced from 100 to 200 μ. No neurones activated by cutaneous stimulation were recorded medially in the hypothalamus nor in the region of the mamillary body.

The shortest latency of discharge following electrical stimulation of the skin of the face was measured for all these units, the mean value being 13·4 msec (S.D. = 5·9 msec; $n = 70$) and the distribution that shown in Text-fig. 7. This mean latency was significantly longer than that for the cell group observed within VPM, but did not differ significantly from the mean latency of cells examined in PO. The discharge pattern observed was typically repetitive, but apart from a longer latency differed in no obvious respect from the evoked discharges observed in VPM and PO.

Many of the neurones examined in this sub-thalamic region had complex

cutaneous receptive fields for tactile stimulation. Forty-one units had extensive receptive fields, which extended well beyond the peripheral distribution of the trigeminal nerve. Most of these cells included in their receptive field both sides of the face and often intraoral structures as well.



Text-fig. 9. The relative positions of neurones isolated in a transverse plane passing through the middle third of n. ventralis posteromedialis (outlined); the posterior nuclear group of the thalamus, dorsolaterally, n. centrum medianum dorsomedially and the zona incerta and Field H of Forel ventrally. Recording in right thalamus. A series of 8 electrode penetrations with the one electrode were made at 0·5 mm intervals. The cutaneous receptive field of each cell is shown on the adjacent diagram. Receptive fields indicated on an isolated forelimb are contralateral. Text-figure 6 *b* is the appropriate transverse section of the thalamus corresponding to this series of penetrations.

In addition, one or more limbs were commonly included. Like the receptive fields of many PO units, discontinuities were observed in the receptive fields of some cells, the excitatory regions being separated by an unresponsive area of skin. The remaining neurones in this region excited by tactile stimulation had circumscribed receptive fields, very similar to those of VPM units. Usually cells with small receptive fields lay in the lateral part of the sub-thalamic active region (within the zona incerta) whilst those with extensive receptives were more medial within the nucleus of the Field of Forel. This, however, was not invariable. Typical distributions of such neurones within the sub-thalamus are shown in Text-figs. 4 and 9. The corresponding histological sections are shown in Pl. 1 and Text-fig. 5. Plate 2, fig. 2 also illustrates a penetration passing through the rostral part of the zona incerta, with the sites of recording of evoked unitary discharges.

As is shown in Table 2, 9 units were antidromically activated by electrical stimulation of the specific somatic sensory cortex. All these neurones had very widespread cutaneous receptive fields. As with VPM units, the cortical region from which each neurone could be antidromically fired was usually quite restricted, being most common in somic sensory Area II.

As can be seen in Table 2, 49 of the 70 units examined in this region fired trans-synaptically following cortical stimulation. The characteristics of this discharge were similar to those observed in VPM and PO, being repetitive, with a variable latency between 3 and 25 msec. Again, most of these units fired following electrical stimulation of all parts of the specific somatic sensory cortex.

Nucleus centrum medianum

This region was not systematically explored. However, 18 units were examined within this nucleus, which were excited by light mechanical stimulation of the face. Some of these are seen in Text-fig. 9. Their receptive fields were complex, as shown. Three of these cells fired in response to an auditory stimulus. Two units of this small sample were antidromically discharged by electrical stimulation of the specific somatic sensory cortex.

DISCUSSION

The widespread but organized activation of the cerebral cortex following cutaneous stimulation, which was observed in the present experiments, has been frequently reported in animals anaesthetized with chloralose (Albe-Fessard & Rougeul, 1958; Malcolm & Darian-Smith, 1958). The cortical potentials evoked in the region of specific somatic sensory Areas I and II by stimulation of the contralateral face could not be differentiated into two discrete regions, either in terms of amplitude of the initial

posterior wave or of its latency. We observed no discontinuity in these parameters. In the more caudal region in the ventral part of the anterior suprasylvian and ectosylvian gyri, however, bilateral projection of the face was observed, in agreement with Berman's findings (1961). This region of bilateral representation of the face corresponds to the region designated S II by Woolsey (1947) and the more anterior region with a contralateral projection only corresponds to the S I projection of the face described by him. We have not observed the bilateral representation of the face within the S I projection described by Hamuy, Bromiley & Woolsey (1956) in the dog, nor the similar bilateral representation of the tongue of the cat reported by Cohen *et al.* (1957).

The additional region of evoked activity in the dorsal part of the anterior suprasylvian gyrus was first reported by Marshall *et al.* (1941) and later by Marshall (1949) and Malcolm & Darian-Smith (1958). Our finding that a significant projection of VPM cells to this cortical area occurs in the cat supplement these earlier observations and suggest that this third region also forms part of the specific somatic sensory cortex.

The neurone populations which we observed, both in VPM and in PO, to be excited by light mechanical stimulation of the skin of the face had receptive field and somatotopic characteristics essentially similar to those described previously (Rose & Mountcastle, 1954; Gaze & Gordon, 1954; Appelberg & Landgren, 1958; Poggio & Mountcastle, 1960; Perl & Whitlock, 1961).

Direct examination of thalamocortical axon projections, by means of antidromic excitation of the neurone, demonstrated the large-fibre projection of VPM neurones to somatic sensory Area I already well recognized (see Macchi, Angeleri & Guazzi, 1959) and a smaller projection to somatic sensory Area II. In our experiments no differential projection from the anterior and posterior parts of VPM to somatic Areas I and II respectively was observed. Axon projections to both S I and S II occurred from all parts of the nucleus, in contrast to the observations of Knighton (1950), who described a projection to S II from the posterior part of the nucleus only. The present findings agree well with those of Macchi *et al.* (1959) who studied retrograde degeneration in the ventrobasal complex following localized cortical ablations.

The low yield (19 %) of antidromically-activated neurones in VPM following electrical stimulation of the specific somatic sensory cortex differed from previous experimental series (Darian-Smith, Phillips *et al.* 1963; Darian-Smith & Phillips, 1964), where antidromic activation of brain-stem trigeminal cells was obtained by electrical stimulation of the posterior thalamus and anterior cerebellum respectively. Up to 80 % of the sample in these experiments was antidromically fired, demonstrating that

in suitable circumstances the method allows the identification of a large proportion of the cells with axon projections to the region stimulated. Whilst the experimental situations differ considerably, it would appear likely from them that the present findings do not result simply from ineffectual stimulation of the cerebral cortex, but rather reflect the fact that a significant proportion of the VPM population excited by cutaneous stimulation of the face does not project to this region of cortex. Comparable observations have been made following cortical lesions involving the specific somatic sensory cortex (Walker, 1938; Le Gros Clark, 1949; Macchi *et al.* 1959). Even after widespread decortication a significant proportion of neurones within the ventrobasal complex did not degenerate.

Unlike the VPM cell population, neurones isolated within the posterior nuclear group of the thalamus, in the present experiments, were not excited antidromically by electrical stimulation of the specific somatic sensory cortex. Our negative findings demonstrate that PO neurones did not have axon projections to the cortex functionally similar to those of the VPM cells. If the PO units *did* have a projection to the specific somatic sensory cortex the threshold for discharge by cortical stimulation was much higher than for VPM cells. This might occur if the diameter of the thalamo-cortical fibres was considerably smaller for PO cells than for VPM units. A second possible explanation for our negative findings is that our criteria for the identification of antidromic activation of thalamic units are too rigid and that some units with a discharge latency greater than 2 msec were in fact antidromically activated. This appears unlikely, however, because the discharge pattern of PO neurones that was evoked by cortical stimulation, in addition to having a long latency, had the other characteristics of synaptic excitation, including a fluctuating latency and inability to follow high-frequency repetitive stimulation. The 'collision' technique was applied to only 2 PO units, both of which were shown to be synaptically discharged.

Such evidence as has been advanced to support a thalamo-cortical projection from the PO region has been based either on the distribution of retrograde degeneration following cortical lesions (Rose & Woolsey, 1958), on the distribution of cortical potentials evoked by localized thalamic stimulation (Knighton, 1950) or on the comparison of the functional characteristics of neurones examined within this thalamic region and within somatic sensory Area II of the cortex (Carreras & Andersson, 1963). None of these methods provide direct evidence for an axonal projection of PO neurones excited by somatic stimulation.

Neurones activated in the subthalamus by tactile stimulation of the skin of the face were localized mainly to the region of the zona incerta and the region of the nucleus of the Field H of Forel. In the more lateral

zona incerta most units had small receptive fields very similar to those of VPM cells. Neurones within the Field H of Forel had complex, often discontinuous and widespread, receptive fields. Nauta & Kuypers (1957) have provided a full description of a diffuse ascending pathway from the brain stem which terminates, in part, in the region of evoked activity we have observed in the sub-thalamus. This tractus fasciculorum tegmenti of Forel (1877) would appear the likely anatomical pathway which activates these cells. It has a composite origin, arising partly from the trigeminal spinal nuclei and partly from the adjacent reticular formation, a factor which may well account for our finding of the two cell types with distinctive receptive fields.

Nine neurones with large cutaneous receptive fields were activated antidromically by electrical stimulation of the specific sensory cortex. They mostly projected to a localized region in Area S II and could possibly account for the units observed in this area by Carreras & Andersson (1963) which had similar receptive fields. However, unlike the cortical cells described by Carreras & Andersson, these thalamic units did not fire to auditory stimuli.

SUMMARY

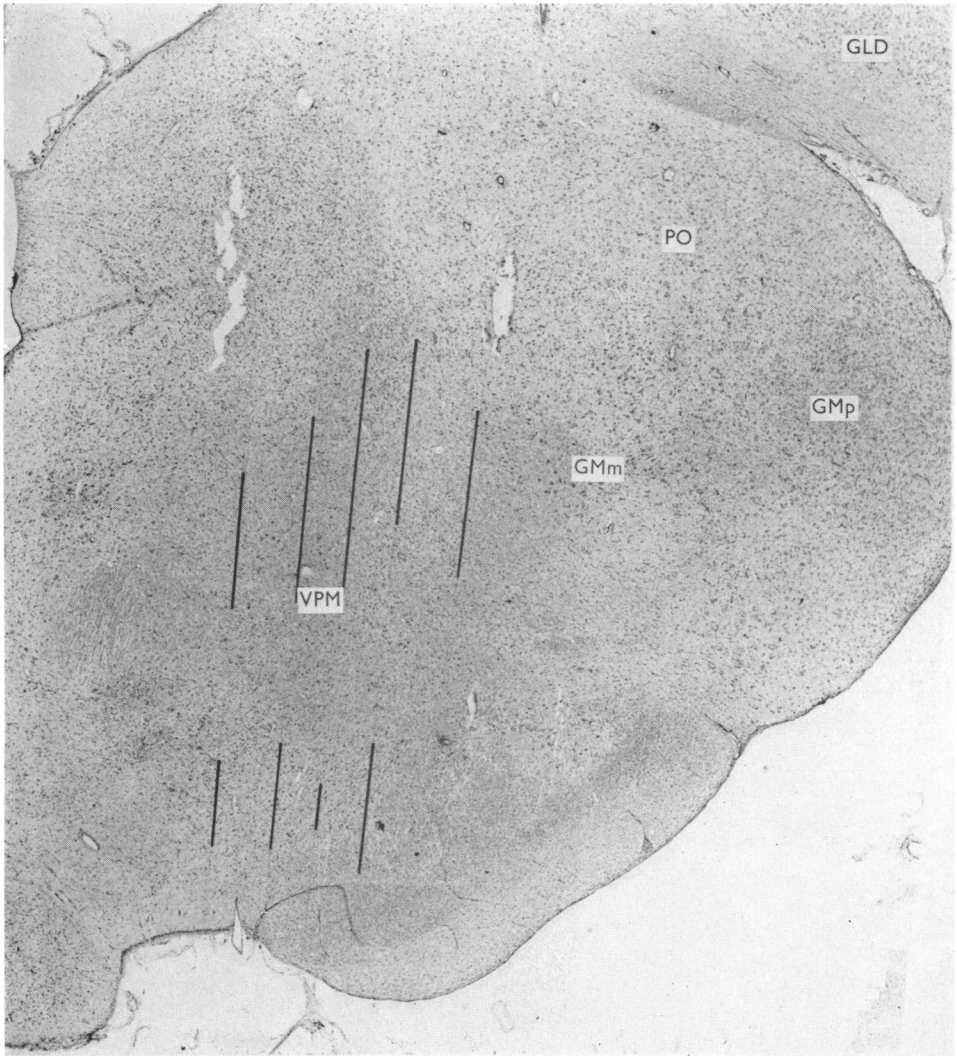
1. Discharges evoked in neurones within the posterior thalamus by mechanical stimulation of the skin of the face were recorded in anaesthetized cats with tungsten micro-electrodes.

2. The cell bodies of neurones activated by this stimulus lay within (*a*) the medial part of the ventrobasal complex (VPM); (*b*) the posterior nuclear group of the thalamus, including part of the posterior lateral nucleus and the magno-cellular division of the medial geniculate body; (*c*) the sub-thalamus in the region of zona incerta and the nucleus of the Field H of Forel (Z I); and (*d*) in nucleus centrum medianum (CM).

3. In VPM neurones activated by tactile cutaneous stimulation had small receptive fields and demonstrated somatotopic organization. 19% of these units had discrete axon projections to the specific somatic sensory cortex, including a restricted area in the anterior suprasylvian gyrus.

4. In PO no topographical organization was apparent, most cells having very large, often discontinuous, cutaneous receptive fields. In addition to firing in response to tactile stimulation, many of these units responded to an auditory stimulus. No axon projection to the cerebral cortex was demonstrated.

5. In Z I most activated neurones had widespread cutaneous receptive fields, but a few had quite small fields; no topographical projection was evident. Approximately 10% of this neurone sample had a direct axon projection to the somatic sensory cortex.



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6. It is suggested that Forel's tractus fasciculorum tegmenti, a composite ascending pathway, is the projection to the sub-thalamus activated by tactile cutaneous stimulation.

This work was supported by a grant from the National Health and Medical Research Council, Australia. I wish to thank Mrs P. Curtis for much help with these experiments.

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EXPLANATION OF PLATES

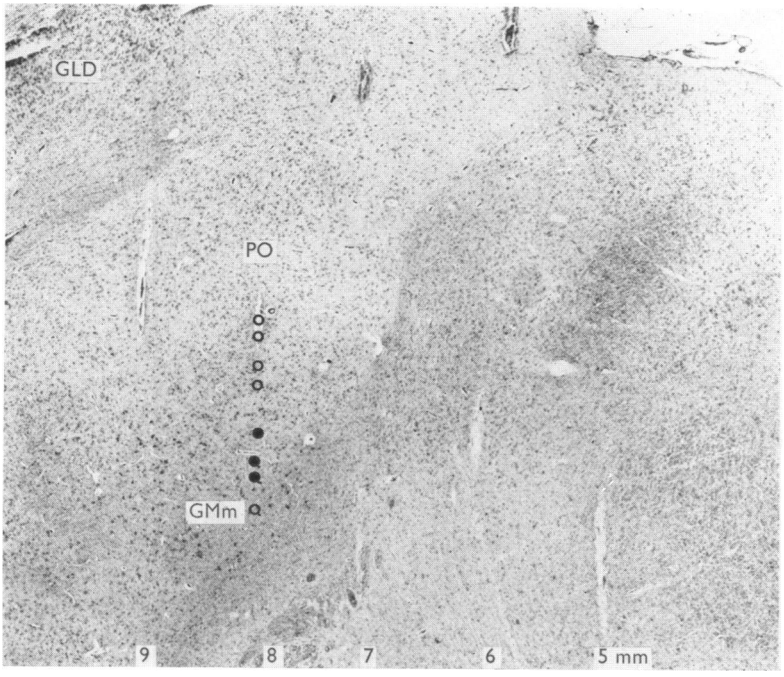
PLATE 1

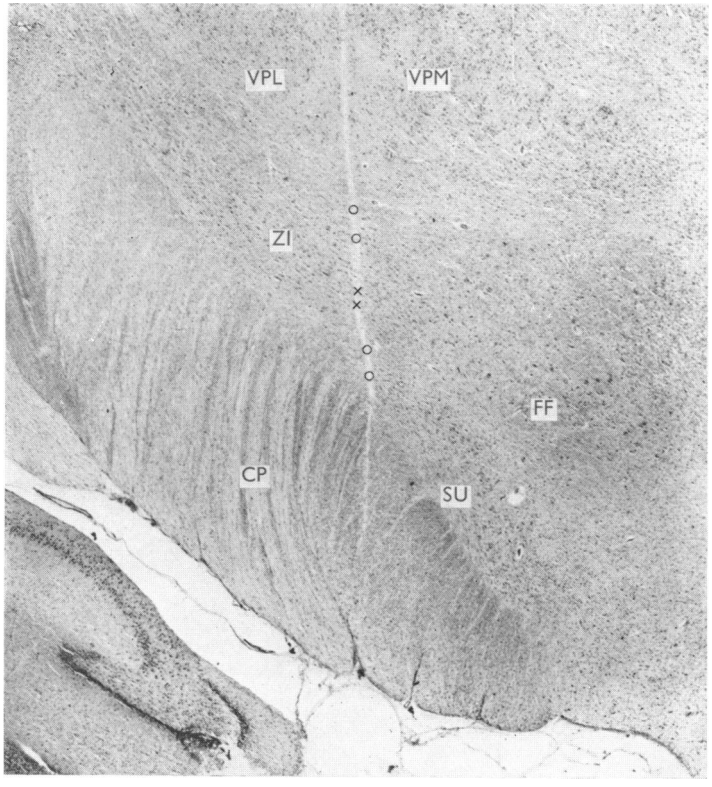
Transverse section through the posterior thalamus corresponding to the plane of electrode penetrations shown in Text-fig. 4. Part of each electrode track is seen in the region of VPM. Abbreviations as in Text-fig. 5. Einarson's gallocyanin method; thickness = 20 μ.

PLATE 2

Fig. 1. Transverse section corresponding to plane 7 in Text-fig. 5. A series of penetrations are seen; the heavy vertical line indicates the region of unitary recording. Open circles indicate units which responded to both somatic and auditory stimulation; black circles indicate positions of cells firing to somatic stimulation only. Abbreviations as in Text-fig. 5.

Fig. 2. Transverse section at the level of the rostral third of n. ventralis posteromedialis. A single electrode track passing into the subthalamus is seen and the recording sites for single units. Open circles indicate neurones with widespread receptive fields; crosses indicate cells with small receptive fields restricted to the contralateral face. Abbreviations as in Text-fig. 5. S.U. = subthalamic nucleus; F.F. = Field H of Forel.





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