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# DUAL ORGANIZATION OF THE EXTEROCEPTIVE COMPONENTS OF THE CAT'S GRACILE NUCLEUS

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The internal organization of the gracile nucleus may be partly described in terms of the well-known somatotopic arrangement found in its transverse planes: distal body parts are represented dorsally and medially, and proximal parts ventrally and laterally (Kuhn, 1949; Johnson, 1952; Gordon & Paine, 1960; Kruger, Siminoff & Witlowsky, 1961). The organization may also be considered in terms of the different kinds of receptor contributing to the afferent supply: cells responding to bending hairs and those responding to light touch or pressure on skin, for example, can be separately recognized in the nucleus (Johnson, 1952; Kruger *et al.* 1961; Perl, Whitlock & Gentry, 1962). Gordon & Paine (1960), drawing attention to a different aspect of its organization, showed that cells at the rostral and caudal ends had, on the average, much larger receptive fields than those in the middle of the long axis, and that the latter were commonly affected by afferent inhibition from the surrounds of their receptive fields. This was taken as evidence of an underlying functional differentiation.

The present paper describes an attempt to elucidate further this latter aspect of the organization. This has involved a more detailed study than before of the sizes and positions of receptive fields and of inhibitory and facilitatory effects from the surrounds of these fields. It was also necessary to pay closer attention to the possibility of distinguishing cells on the basis of the type of receptor supplying them: the importance of doing so is exemplified by the conclusion of Perl *et al.* (1962), with which we agree, that in contrast to many cells supplied by hair receptors, cells supplied by 'touch-pressure' receptors escape the influence of afferent inhibition. Lastly, we have made extensive use of antidromic stimulation from the mid-brain to identify as far as possible those cells contributing to the output of the nucleus, extending the work of Gordon & Seed (1961); and have investigated the question raised by the recent anatomical work of Busch (1961) that different parts of the nucleus may have different paths of projection within the mid-brain. Information of all these kinds was available for many of the cells considered here. The following paper

(Gordon & Jukes, 1964) gives an account of synaptic actions on this nucleus produced by stimulating in the mid-brain and cerebral cortex.

A preliminary account of some of this work has already been published (Gordon & Jukes, 1962).

## METHODS

The data were derived from experiments on seventy-three cats. The great majority were anaesthetized with sodium pentobarbitone, the initial dose given intraperitoneally (38 mg/kg) and subsequent doses of about 10 mg given by intravenous cannula. The remaining cats were given α-chloralose (Hopkin & Williams Ltd, 80 mg/kg) after induction of anaesthesia with ethyl chloride and ether. The level of anaesthesia was always such as to prevent spontaneous movement of the animal or movement in response to any stimulation used.

External records were made from single cells in the gracile nucleus, usually with glass micropipettes filled with 3 M-KCl and with a resistance at 50 c/s of 3·5–6 MΩ, and sometimes with tungsten electrodes of similar resistance made in the way described by Hubel (1957). Other parts of the technique, for instance the methods for exposing the nucleus, holding the animals and inserting the electrodes, have been described previously (Gordon & Paine, 1960). This earlier paper also stressed the difficulties caused by vascular and respiratory pulsation of the spinal cord, which may make impossible stable recording from single cells and often leads to their destruction by the electrode. In place of the earlier method of stabilizing the surface with a small Perspex plate, we now prefer to fill the wound, after inserting the electrode, with paraffin wax (m.p. 45° C) introduced in a just-molten condition. This sets firmly enough to stabilize the surface considerably; it does not interfere with vertical movement of the electrode; and it does not appear to injure the most superficial neurones. We are indebted to Dr P. D. Wall for introducing us to this technique. The cats were warmed by radiant heat, and close attention was paid to the rectal temperature, which was maintained between 37 and 39° C. In experiments in which paraffin wax was not used, it was found that the temperature of the fluid deep in the wound did not differ from the rectal temperature by more than about 1° C.

*Receptive properties of cells.* The assessment of the size and position of receptive field and the most effective stimulus for each cell was made by using light stimuli applied with a camel-hair brush, wisp of cotton-wool, or blunt wooden probe pressed against the skin. The rate of adaptation of the cell to a steady stimulus was roughly assessed. Brusquely applied stimuli capable of giving rise to mechanical effects transmitted to a distance through skin, bone or other tissues were either avoided or used advisedly (see Armett & Hunsperger, 1961; Perl *et al.* 1962). Where there was any doubt of the receptive field being cutaneous, a fold of skin was lifted and the skin itself explored with weak electrical stimuli: shifting of the receptive field *pari passu* with sliding the skin over the underlying tissues was also helpful in identifying fields as cutaneous. If doubt still remained, the field was usually found to be subcutaneous; and this could be confirmed by pushing insulated needle electrodes through the skin and exciting the cell at lower threshold from beneath.

*Peripheral conditioning effects.* In most experiments, each cell whose activity could be observed for any length of time was tested for conditioning effects by stimuli applied outside the physiological receptive field (i.e. in the 'surround'). Most cells (77 %) had a resting discharge in the absence of stimulation; and in these, inhibitory conditioning effects, if present, usually showed up very clearly as a lessening or cessation of discharge when merely a few hairs were brushed. In some cases electrical stimuli, applied to the skin through a pair of needles about 1 mm apart, were used to augment the information obtained by more natural conditioning stimuli. Latency and duration of inhibition could then be conveniently studied by using resting or randomly evoked activity of the cell as a test background and superimposing a number of sweeps, each with a conditioning stimulus locked to the time-

base, on a storage oscilloscope (Gordon & Jukes, 1963). Electrical stimuli were also used in demonstrating facilitatory effects from the surround of the receptive field.

*Antidromic stimulation.* The technique used for antidromic stimulation of cells in the gracile nucleus whose axons projected into the mid-brain was a simplified version of that described by Gordon & Seed (1961). The stimulating electrodes were steel needles of about 0·6 mm *d.*, ground down for the terminal 15 mm or so until they were reasonably thin (0·3–0·4 mm *d*), and sharp at the tip. They were insulated except for about 0·25 mm at their tips. Six, or occasionally seven, of these were mounted with their shafts parallel and about 1·2 mm apart by sticking them to a glass plate with Araldite (Ciba), in such a way that the tips projected 30 mm or more beyond the edge of the plate.

The plate carrying the electrodes was mounted on a manipulator aligned on Horsley–Clarke co-ordinates. The electrodes were inserted, in a selected frontal plane, so as to form a transverse row in the mid-brain. Stimuli (rectangular pulses of 0·06 msec duration, isolated from earth by transformer coupling) could be applied between any two adjacent electrodes, with reversible polarity. The initial depth of the array of electrodes was decided by lowering them in small steps until massive antidromic firing at low threshold could be recorded from the middle region of the gracile nucleus when stimuli were delivered through an appropriate pair of electrodes: subsequent adjustments of depth were made for particular purposes during the experiment. For some experiments the electrodes were of equal length: for others the array was constructed with the electrodes progressively longer from the lateral to the medial end of the row (see Results).

The positions of the electrodes were afterwards found histologically. The brain was fixed, without moving the head from its stereotaxic holder, by perfusion with 0·9 % sodium chloride followed by 5 % formaldehyde-saline. On the next day the relevant block of brain was removed, using a knife-blade moving transversely and operated by the manipulator which had held the stimulating electrodes. This block of tissue was embedded in low-viscosity nitrocellulose and serial sections cut, 50 $\mu$ thick, parallel to its cut faces. By these means it was usually possible to include the entire set of electrode tracks in about six adjacent sections. Alternate sections were stained with Heidenhain's iron-haematoxylin and with Klüver's luxol-blue and cresyl-violet.

*Notation and measurement.* In this and the following paper, the area of surface from which a particular cell could be excited to discharge impulses by 'natural' stimuli of the kinds specified is called the *receptive field.* Inhibitory or facilitatory effects on a cell might be produced by stimuli applied outside this excitatory receptive field; and this further outlying region is called the *surround.* In this we follow an accepted convention with regard to cutaneous fields; but it should be noted that this differs from the convention used for the visual system, where 'receptive field' is held to include all areas making functional connexions with the cell whether these are excitatory or inhibitory (see Kuffler, 1953).

In dealing with the sizes of receptive fields we have used the method described by Gordon & Seed (1961): the fields are distributed over a very wide range, and are conveniently classified into groups with limits successively doubling ($< 0{\cdot}5$ cm$^2$, 0·5–1 cm$^2$, 1–2 cm$^2$, 2–4 cm$^2$, etc.).

The positions of responses in the rostro-caudal dimension of the gracile nucleus are given, as in previous papers (Gordon & Paine, 1960; Gordon & Seed, 1961), in a scale of millimetres, with zero as the rostral border of the nucleus. The actual measurement to which all other measurements were referred was that of the position of the obex, which lies approximately 2·2 mm caudal to the rostral border. The region between zero and 4 mm is referred to as the 'rostral' part, and that between 4 and 7 mm as the 'middle' part of the nucleus. Beyond 7 mm, positions are described as 'caudal'.

We noted the depth in each electrode penetration at which the activity of each cell was recorded, thus finding the depths of the cells relative to each other: we also took a reading of the position of the surface, from which the actual depth of each cell could be found

provided that the surface was not subsequently indented by the electrode. Such indentation was common, however, and estimates of the depth of cells were consequently unreliable in many cases.

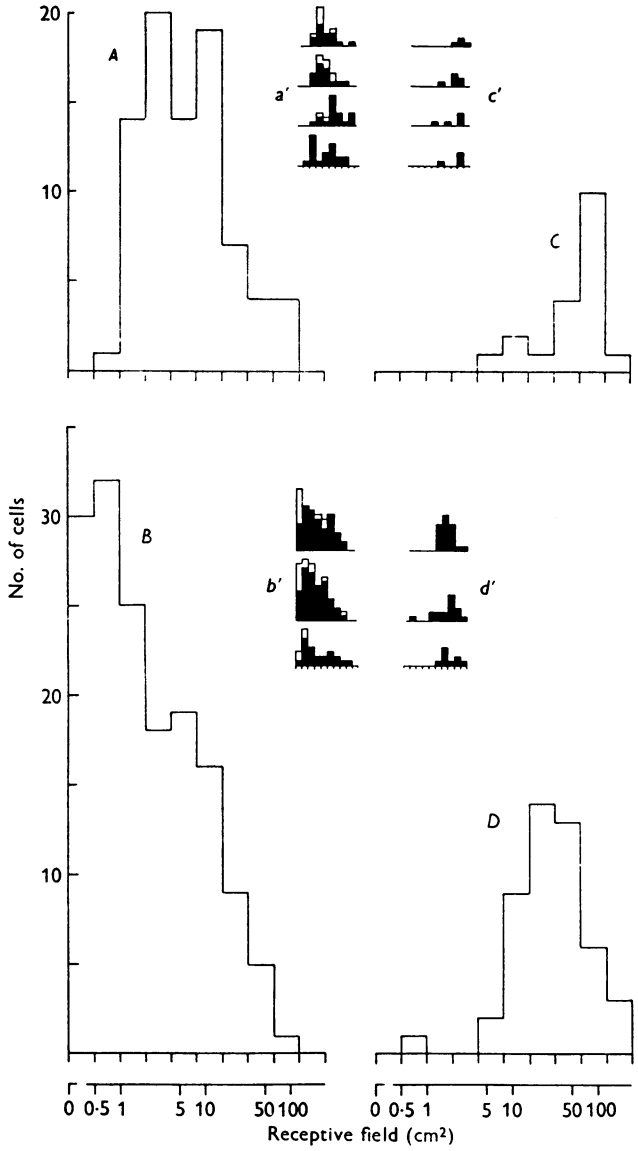



Fig. 1. For legend see opposite page.

## RESULTS

The results to be described are based on a study of single cells in the gracile nucleus, of which 460 were investigated thoroughly enough to provide useful data. All these responded to light superficial stimulation, and for the great majority it was possible to arrive at useful definitions of the type of stimulus to which they were most sensitive and of the sizes and positions of their excitatory receptive fields. We have not included data about cells responding only to deeply applied stimuli or those responding preferentially to movement of joints. We have continuously confirmed the general relation described by Gordon & Paine (1960), in that the mean size of receptive field for cells in the middle of the long axis was much smaller than that for cells lying either rostrally or caudally. The great majority of our observations were in fact made on the rostral and middle parts, rather than the caudal part which has a much lower density of cells. As a first step in resolving this situation more completely, it is necessary to consider separately the groups of cells with different receptive characteristics; and these groups are described below.

### *Groups of cells with different receptive characteristics*

*Cells with high selective sensitivity to displacing cutaneous hairs* (*'hair-sensitive': 209 cells*). This was the largest group. They responded briskly to slight stimuli strictly limited to bending hair; and they had clear-cut

Legend to Fig. 1

Fig. 1. Histograms relating numbers of cells in the gracile nucleus to the sizes of their cutaneous receptive fields. The figure is designed to show this relation for different types of cell and for different positions in the long axis of the nucleus. Ordinates for all graphs represent numbers of cells. Abscissae represent size of receptive field: the lower scales below the bottom graphs (*B* and *D*) have size of field scaled logarithmically, the upper scales showing the limits of receptive field size on which the histograms were constructed. For the latter, note that each successive limit represents a doubling of receptive field range. The two left-hand histograms (*A* and *B*) are for cells with hair-sensitive, pad-sensitive, hair-and-pad-sensitive and claw-sensitive properties. The two on the right (*C* and *D*) are for touch-pressure cells. The upper member of each pair (*A* or *C*) is for cells found in the rostral 4 mm of the nucleus: the lower member (*B* or *D*) is for cells found in the middle 3 mm (4–7 mm from rostral border). The small inset groups of histograms (*a'*, *b'*, *c'*, *d'*; scaled down $\times 4$ from the large histograms), give a more detailed analysis of the larger histograms adjacent to them, the cells in each 1 mm length being here plotted in an individual graph, with the most rostral in each group at the top. In the inset groups on the left (*a'* and *b'*), hair-sensitive cells are plotted in black, and all other groups of cells in the general category appear as white areas. In the middle 3 mm of the nucleus, represented in *b'*, those cells with the smallest receptive fields ($< 0{\cdot}5$ cm$^2$) which are not in black are largely (14 out of 20) made up of claw-sensitive cells.

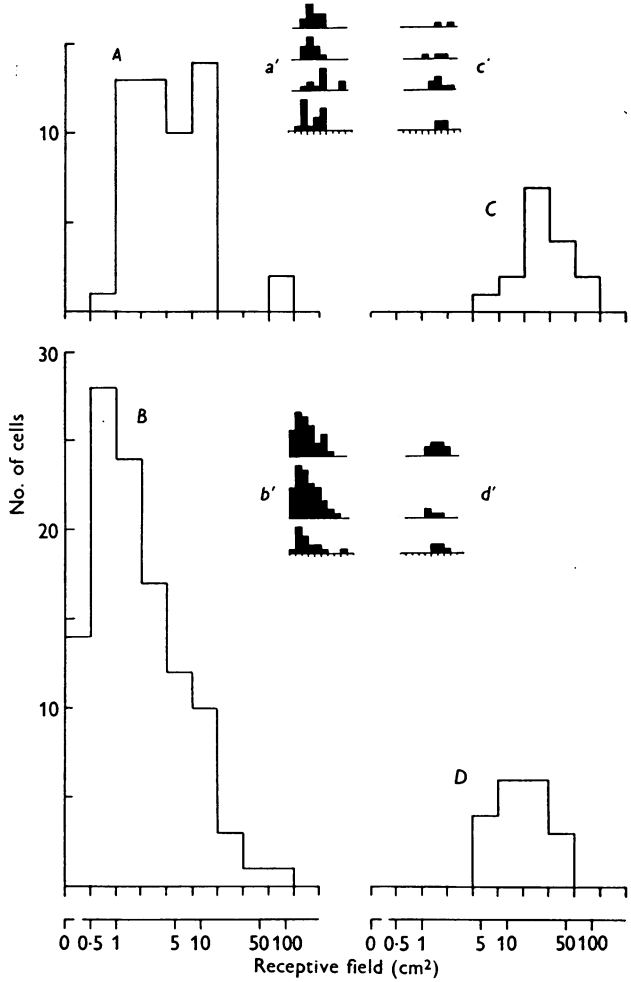



Fig. 2. Histograms relating numbers of cells in the gracile nucleus to the sizes of their cutaneous receptive fields. The figure relates to hair-sensitive cells only, and is designed to show the above relation for different positions in the long axis of the nucleus, comparing cells with proximal fields with those with distal fields. The co-ordinates of the graphs are the same as in Fig. 1. The two left-hand histograms (*A* and *B*) are for cells whose receptive fields included part or the whole of the hind foot ('distal'): the two on the right (*C* and *D*) are for cells whose receptive fields lay proximal to the hind foot, including no part of it ('proximal'). The upper member of each pair (*A*, *C*) is for cells found in the rostral 4 mm of the nucleus: the lower member (*B*, *D*) is for cells found in the middle 3 mm (4–7 mm from rostral border). The small inset groups of histograms, as in Fig. 1, give a more detailed analysis of the larger histograms adjacent to them, the cells in each 1 mm length plotted in an individual graph, the most rostral in each group at the top.

receptive fields. They did not respond to tapping or jarring the limb, a type of stimulus which readily excites vibration receptors, whose existence can be confusing since they will also respond to moving a brush across the skin (Perl *et al.* 1962). The majority of hair-sensitive cells adapted rapidly when the hair was bent and kept steadily bent for some seconds: these clearly correspond to the cells responding to hair movement described by Perl *et al.* (1962). A minority (21 out of 163 adequately tested, or 13%) adapted slowly under these conditions; but since their properties differed from the rest in no other respect we have grouped them in the same category.

Cells of this type were found throughout the length of nucleus investigated. Their receptive fields were distributed over a very wide range, the ratio of the smallest to the largest being of the order of 1:300. Mean size of receptive field varied with position in the long axis of the nucleus. This relation can be seen from Fig. 1, in which histograms are used to show the numbers of cells with different-sized receptive fields which were found in each of the rostral 7 mm. It will be seen from these, for instance (Fig. 1; black areas in inset histograms *a'* and *b'*), that cells with receptive fields of 1 $cm^2$ and less were common 5–6 mm from the rostral border, but almost absent from the rostral 4 mm. Size of field also varied with the position of the receptive field: it is well known that receptive fields tend to be larger when they lie more proximal on the body (Gordon & Paine, 1960; Kruger *et al.* 1961; Perl *et al.* 1962). This relation can be seen clearly in Fig. 4, which also shows the somatotopic arrangement of cells in the middle of the nucleus, deeper-lying cells of this type having progressively more proximal fields. The same relation can be seen in Fig. 2, in which histograms are used to compare the sizes of receptive field of cells with proximal fields and those with distal fields in different parts of the long axis of the nucleus. Proximal fields are significantly larger; but here again a study of the sizes of distal fields—fields including part or the whole of the hind foot—shows the middle of the nucleus to contain the cells with the smallest fields.

Cells lying superficially in the middle part of the nucleus—of which hair-sensitive cells make up the great majority—often seemed to be associated in small groups such that careful positioning of the electrode was needed if the activity of one cell was to be studied in reasonable isolation from the three or so other cells of the group. This grouping was not conspicuous in other parts of the nucleus.

*Cells selectively sensitive to light touch of pads ('pad-sensitive': 7 cells).* Cells in this small group could be excited by very light touch, with a wisp of cotton-wool for instance, on the surface of a pad, but not by bending hairs or other form of stimulation. Of those for which adaptation to a maintained stimulus was satisfactorily studied, three adapted rapidly and

one slowly. All cells of this type were found in the middle part of the nucleus. Their receptive fields were all confined to part or the whole of a single pad.

*Cells with both 'hair-sensitive' and 'pad-sensitive' properties* (19 *cells*). These cells, as well as being sensitive to light touch on one or more pads, responded to bending hairs in an area which, except in one case, was continuous with the pad-sensitive area. This one exception had a discontinuous receptive field, with two sensitive pads separated by an area where hair stimuli were ineffective (see Fig. 3*c*, third cell from the top). Of ten such cells whose adaptive properties were adequately studied, eight adapted rapidly and two slowly.

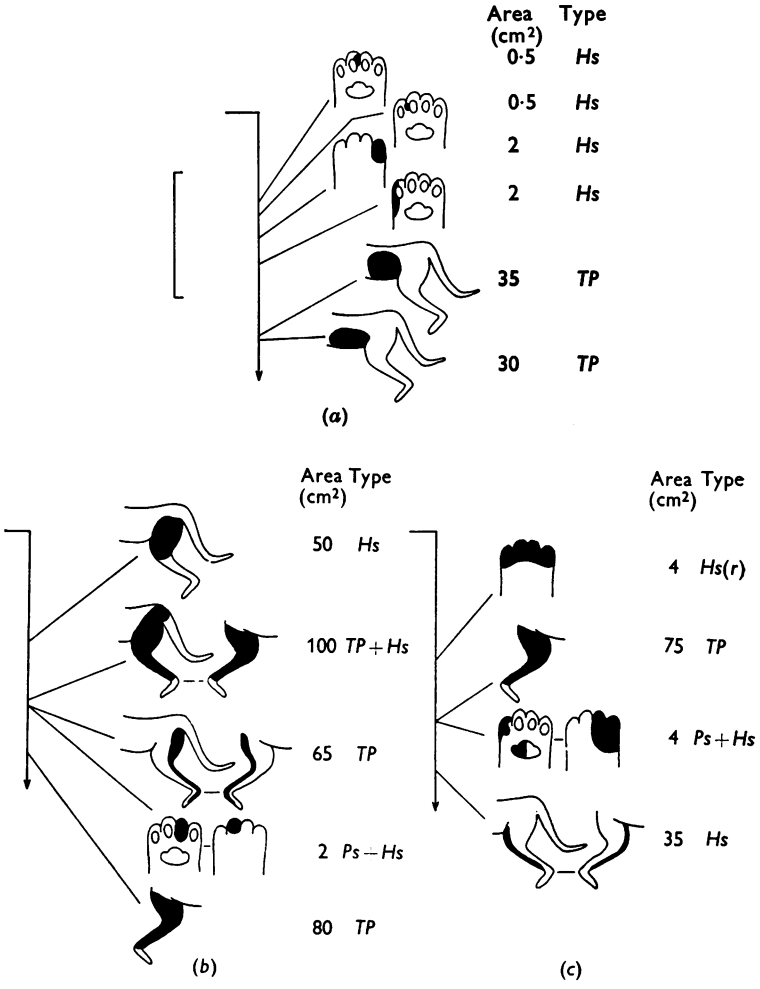



Fig. 3. For legend see opposite page.

Of these 19 cells, 14 were found in the rostral 4 mm of the nucleus, the remaining 5 in the middle part. An example of a second rostral cell of this type is seen in Fig. 3*b*. Their receptive fields had sizes between about 1 and 50 $cm^2$, commonly occupying large parts of the foot: one extended beyond the foot on to the lower leg.

*Cells responding to stimulation of claws* (*'claw-sensitive': 15 cells*). From time to time in the earlier part of this investigation, cells were found which responded with a slowly adapting discharge to firm pressure or other manipulation of distal parts of the foot, and these responses were attributed to stimulation of receptors lying deep in the tissues of the foot. Later it became clear that cells with these properties often responded at extremely low mechanical threshold to pressure on a minute well-defined spot on the soft tissues at the side of the base of a claw. Once this fact was recognized, such cells could be easily and precisely identified. Their response to a steadily maintained stimulus always adapted slowly: a discharge at about 50 impulses/sec could be maintained for many seconds. They responded not only to pressure on the 'receptive spot', which would be rather inaccessible to normal external stimuli, but also to the slightest touch, movement, or steady displacement—particularly plantar flexion—of the appropriate claw. It seems likely, in fact, that it is their function to signal such stimuli received by the claw, and that the receptors themselves lie in the soft tissues at the base of the claw, a mechanically favourable position. Fourteen of these cells were found in the middle region of the nucleus (5–7 mm), and the remaining cell 1 mm caudal to this. Their receptive fields, defined in terms of the sensitive area at the base of the claw, were always confined to a single spot on a single claw.

*Cells responding to light touch or pressure on skin* (*'touch-pressure': 70 cells*). These cells all responded to light touch or pressure on the skin

Legend to Fig. 3

Fig. 3. Scheme to show the sequence of cells encountered, and their receptive characteristics, in three representative electrode penetrations in the gracile nucleus. The dorso-ventral movement of the electrode in each penetration is shown by the vertical arrow, and the receptive fields of the cells are shown in black on the inset diagrams. Lines connect these diagrams to the arrow giving the positions along the penetration at which the cells were encountered: the scale on the left = 1 mm. This expresses fairly accurately the depths of the cells relative to each other. For each cell, the adjoining table on the right gives the respective area of receptive field, and also the type of cell (see text). (*a*) An electrode penetration into the middle part of the nucleus, 5 mm from the rostral border. (*b*) A penetration into the rostral part of the nucleus, 1·7 mm from the rostral border, in another experiment. (*c*) A penetration into the rostral part of the nucleus in the same experiment as in (*b*), 1·4 mm from the rostral border. Abbreviations: *Hs*, hair-sensitive; *Ps*, pad-sensitive; *TP*, touch-pressure; *r*, cell with 'refractory' properties. For definitions see text.

itself. They were relatively very insensitive to stimuli applied to the hairs, but occasionally a discharge could be evoked in this way. They all adapted very slowly to maintained light pressure on the skin. For these, and for other reasons which will be mentioned below, it seems clear that these are

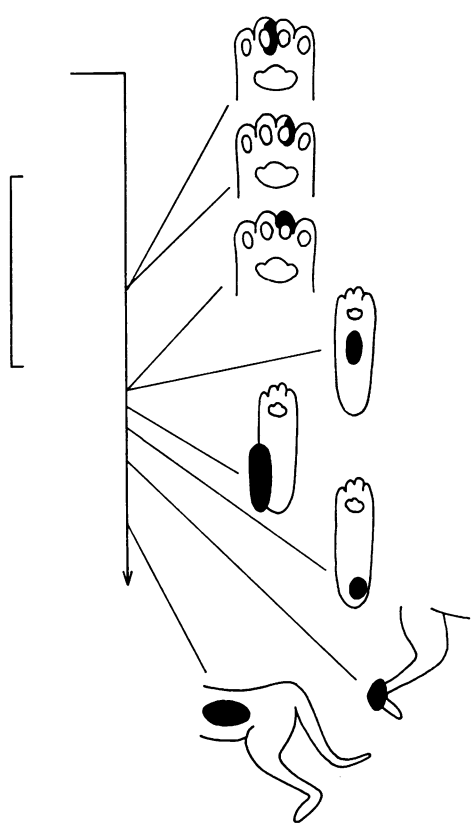



Fig. 4. Scheme to show the sequence of cells encountered, and their receptive fields, in an electrode penetration in the middle part of the gracile nucleus (5·1 mm from rostral border): only cells of the hair-sensitive type (*Hs*) were found in this penetration. The figure is constructed in the same way as Fig. 3. The scale on the left = 1 mm. In addition, the table on the right gives any conditioning effects observed from stimulating the skin in the surround of the receptive field. Abbreviations: *inhib.*, clear inhibition of resting or evoked discharge; *n.t.*, not tested because cell was 'lost'.

the 'touch units' of Perl *et al.* (1962), and that their afferent supply comes mainly or wholly from cutaneous touch receptors of the kind whose properties were described by Frankenhaeuser (1949) and Hunt & McIntyre (1960), and which are associated with a special type of 'touch corpuscle' (Iggo, 1963).

These cells were found throughout the length of nucleus investigated, but their distribution was nevertheless not uniform. In the rostral part, they appeared from our data to lie interspersed with cells of other kinds in a seemingly random way (see Fig. 3*b*, *c*); but in the middle part they were characteristically deep-lying, overlaid by cells of other types—hair-, pad-, or claw-sensitive (see Fig. 3*a*; and Fig. 5 of the following paper, Gordon & Jukes, 1964). Their receptive fields were on average very much bigger than those of the other types described above. This can be seen by comparing the right- and left-hand histograms in Fig. 1: like the hair-sensitive cells already described, it is seen that their fields were on average bigger in the rostral than in the middle part of the nucleus. The fields of most, but not all, the touch-pressure cells we have recognized were rather proximal, on the leg or trunk.

*Cells combining 'hair-sensitive' and 'touch-pressure' properties* (8 *cells*). Cells in this small group had the properties of touch-pressure cells, at least in the outlying parts of their receptive fields, but within a smaller and roughly central area they responded with great sensitivity to bending hairs. The response to pressure adapted slowly, and the response to hair bending adapted quickly, when the appropriate stimulus was maintained. The recognition of this kind of cell as a distinct class would probably not be clear-cut if the two types of receptive field for a given cell were co-extensive, but we have no evidence of this occurring.

These cells were distributed throughout the length of nucleus investigated. They had rather large pressure-receptive fields, characteristic in size and position of those of touch-pressure cells.

*Cells responding to light touch or pressure, whose receptors lay deep to the skin* ('*subcutaneous*': 6 *cells*). These cells, though responding to light touch or pressure on the skin, were shown to get their afferent supply from receptors in subcutaneous tissues. The techniques used for establishing the cutaneous or subcutaneous origin of the afferent supply have already been described (see Methods). For five of these six cells, this subcutaneous origin was specially emphasized because their activity could be inhibited by weak electrical stimuli given to the skin overlying the receptive field: this will be considered further, in relation to inhibitory effects on other cells, later in this paper. Of four of these cells whose adaptation to steady stimuli was adequately examined, three adapted slowly and one rapidly.

All these cells were found in the middle part of the nucleus. The receptive fields for two of them were confined to the foot: the others were larger, three extending into the lower leg, and one lying on the thigh. These fields were considerably larger on average than those of hair-sensitive cells in this part of the nucleus, ranging between about 5 and 30 $cm^2$.

*Cells sensitive to vibration* (22 *cells*). We have not made a special study of these cells, which have been considered in more detail by Perl *et al.* (1962), though we have been continually aware of their existence. They responded with great sensitivity to sinusoidal vibration, applied, for instance, with a 100 c/s tuning fork to skin or some bony point. These properties naturally preclude any finite size or position being given for receptive field, and we are not in a position, without further analysis, to show where the receptors lie. They came to our attention because it is common, in a restricted region of the nucleus 5–8 mm from the rostral border, to find groups of cells, bounded both superficially and deeply by cutaneous cells, responding rhythmically with the vascular pulse. Each cell fired up to seven impulses with each pulse, the sensitivity of the cell to the vascular pulse being increased by applying steady pressure to the abdomen. The cells could be excited by tapping or applying a tuning fork to the abdominal wall, but not by gently brushing or pressing on the skin there. The pulsatile discharge was not affected by manually compressing the femoral artery; and we are inclined to believe, like Perl *et al.* (1962), that the receptors for these particular cells were Pacinian corpuscles in the abdominal cavity.

Seven of these cells also responded to light cutaneous stimuli—five to bending hairs and two to light touch on skin—in areas on the hind foot which extended for some on to the lower leg. The boundaries of these skin areas were clear-cut; and we feel that these cells may have been innervated by more than the one kind of receptor.

*Cells giving inconsistent responses to stimuli* (*'refractory': 22 cells*). These cells, although they undoubtedly responded to light cutaneous stimuli, did so too inconsistently to let us place them confidently in one or other of the above groups. Properly speaking, therefore, they do not constitute a valid group in terms of receptive characteristics. This inconsistency was most obvious for stimuli repeated at short intervals, the responses usually becoming repeatable if a few seconds were allowed to elapse between stimuli. This sort of 'refractory' behaviour was noticed by Gordon & Paine (1960) in some cells in the rostral part of the gracile nucleus; and the cells of this kind we have seen were all in the rostral 4 mm also. Responses with this character could result from weak afferent convergence from the area stimulated, from polysynaptic activation or from both. We have found, as in earlier work (Gordon & Paine, 1960), that activity in the rostral part deteriorates earliest during an experiment, especially under pentobarbitone anaesthesia. It was relatively more active under chloralose, and 'refractory' responses were not then seen.

*Cells needing bigger mechanical stimuli* (*'insensitive' cells*). A substantial number of cells were found which responded, in our hands, only to stimuli like squeezing or tapping some part of the hind limb. We have deliberately

excluded such cells from this analysis, because we have no confidence that all or any of them were genuinely innervated from mechanoceptors of low sensitivity. It is equally likely that more detailed study would have revealed some more appropriate way of exciting them, with small mechanical or possibly thermal stimuli. The experience we have reported with claw-sensitive cells illustrates this particular hazard in interpretation.

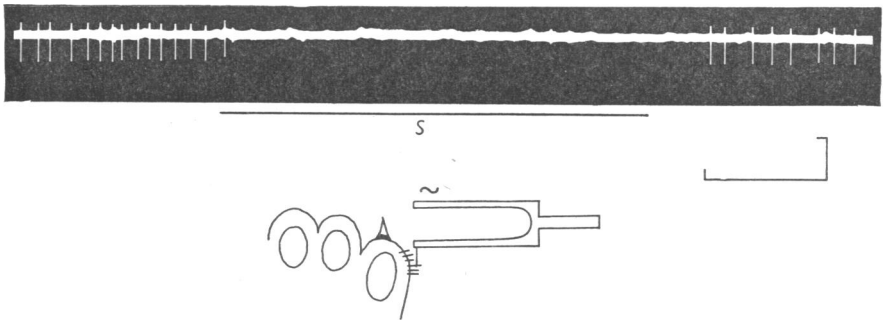



Fig. 5. Inhibition of the resting discharge of a cell in the middle part of the gracile nucleus (6·0 mm). This was a claw-sensitive cell, whose receptive field (see Text) was a small spot within the black area at the base of the claw in the inset diagram. It could be inhibited by light mechanical stimuli in a large part of the ipsilateral body-surface. The figure illustrates its inhibition by a vibrating stimulus (provided by a bristle attached to a 100 c/s tuning fork) applied to hairs about 5 mm from the base of the claw (see diagram). Calibrations: 0·5 sec and 5 mV (negativity upwards). Duration of inhibiting stimulation marked by horizontal line (*S*), accurate to *ca.* 0·2 sec.

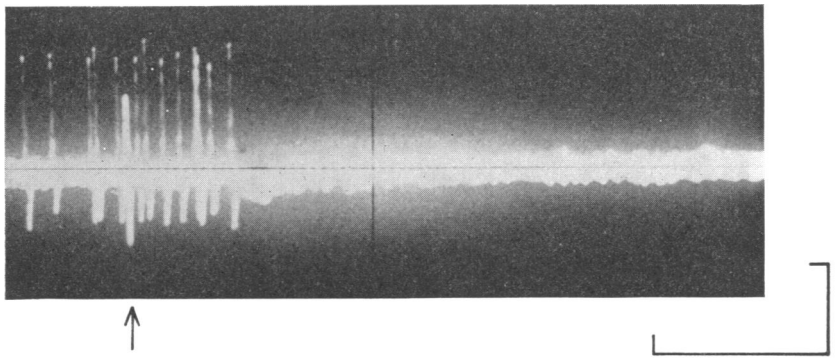
### *Effects of stimuli applied outside the physiological receptive field*

The analysis of the population of cells in terms of their receptive characteristics, which has just been described, now allows a more critical investigation than before of the incidence of afferent inhibitory and facilitatory effects on different types of cell. From this point of view 134 cells of a variety of types have been tested with some care.

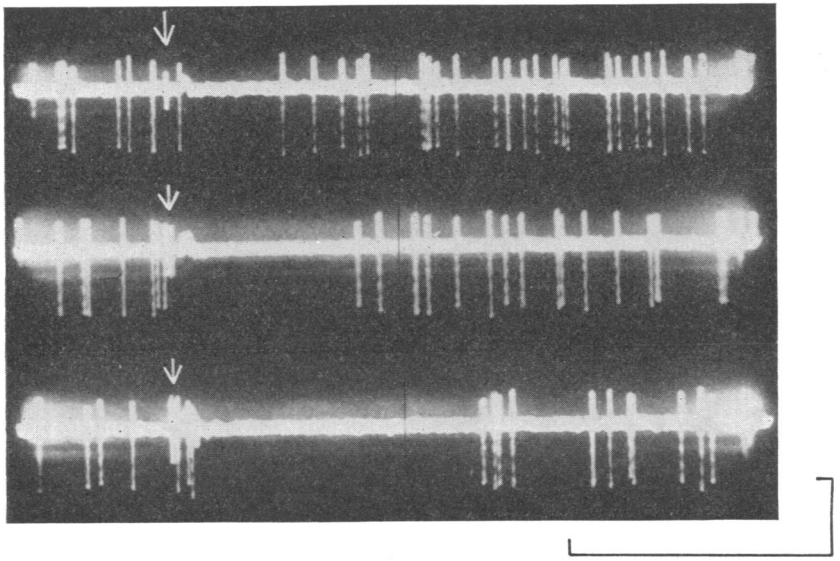
*Inhibition.* Inhibition of the 'surround' type was shown by Gordon & Paine (1960) to be common in the gracile nucleus, especially among cells with rather small receptive fields in its middle region. It has also been observed in the dorsal column nuclei of the rat by Dawson, Podachin & Schatz (1963), and by McComas (1963) who confirmed its high incidence in the middle region of the gracile nucleus. Perl *et al.* (1962) found this type of inhibition in cells sensitive to bending hairs, but not in 'touch' cells (corresponding to our 'touch-pressure' group).

Afferent inhibition was studied by methods which have already been described. In almost every case in which electrical stimuli were used for

conditioning, the inhibitory effect of a 'natural' conditioning stimulus had already been observed. Inhibitory effects from the surround were very clear-cut: this was especially so close to the receptive field, the effect



(a)



(b)

Fig. 6. For legend see opposite page.

diminishing with distance. Figure 5 shows the inhibitory effect of stimulating hairs 5 mm from the receptive spot on the resting discharge of a claw-sensitive cell: the discharge was abolished for the duration of the stimulus (1·7 sec). For sixteen cells, the *latency* of the inhibitory effect from the surround was studied by a method involving superimposition of sweeps on a storage oscilloscope (see Methods), using an electrical pulse for conditioning. A record of such an observation is shown in Fig. 6*a*. Stimuli were adjusted to give the minimal latency under these conditions. Latencies for different cells ranged between 7·2 and 18·6 msec, with a mean at 10·5 msec (time from peripheral stimulus to observed inhibition of cell). In four of these cases, a small wave which was attributable to a response of other cells to the conditioning stimulus (see Fig. 6*a*, *b*) was recorded from the gracile nucleus by the micropipette, and the latency of onset of this wave could be used as an index of excitatory latency of cells in the same part of the nucleus. In each case the excitatory and inhibitory latencies were found to be within 1 msec of each other: intervals shorter than this are probably not within the resolution of the method. *Duration* of inhibitory effect, using a brief (0·25 msec) electrical stimulus, varied with the strength of the shock (see Fig. 6*b*). With inhibitory stimuli strong enough to give maximal effects, durations of total inhibition of about 100 msec were common, the longest observed having been 250 msec. It is clear that any hypothesis dealing with the intranuclear organization underlying these inhibitory effects must take account of this long duration (see Andersen, Eccles & Schmidt, 1962). It must also take account of the

Legend to Fig. 6

Fig. 6. Inhibition of the resting discharges of cells in the middle part of the gracile nucleus by a weak electrical stimulus to the skin outside the receptive field. Each trace is made up of superimposed sweeps on a storage oscilloscope, the stimulus occurring at the same point in each sweep (marked by an arrow and also visible as a shock-escape). (*a*) Inhibition of a hair-sensitive cell with a receptive field of about 0·5 cm$^2$ on one of the toes, by a stimulus given on the sole of the foot about 3 cm from the receptive field. Twenty-five superimposed sweeps. This record was made at a sweep velocity fast enough to allow an estimate of the latency for the onset of complete inhibition (12 msec). The beginning of inhibition almost coincides with the beginning of a small wave representing the response of other cells, more distant from the recording electrode, to the stimulus: see also the waves in (*b*), below. This cell could be excited antidromically from the medial lemniscus. Calibrations: 20 msec and 1 mV (positivity upwards). (*b*) Inhibition of another hair-sensitive cell with a receptive field of about 2 cm$^2$ on a toe (black area on inset diagram), by a stimulus given in the middle of the dorsum of the same foot (see point marked by arrow in diagram). Five superimposed sweeps in each trace. The three traces show, from above downwards, the effect of successively increasing stimulus strength. Note the increasing duration of complete inhibition. Calibrations: 200 msec and 2 mV (positivity upwards).

extreme sensitivity with which the inhibitory mechanism responds to physiological stimuli.

Inhibition was found in 96 of the 134 cells tested with conditioning stimuli. It was found commonly in hair-sensitive cells, especially in the middle region of the nucleus, where 64 out of 69 tested, or 93 %, were inhibited from the surround. In the rostral region, significantly fewer hair-sensitive cells were inhibited—9 out of 17, or 53 %. For this type of cell, the likelihood of inhibition occurring depended on position in the nucleus rather than on size of receptive field: the deeper-lying hair-sensitive cells in the penetration in the middle of the nucleus shown in Fig. 4, for instance, had the larger fields characteristic of more proximal position on the body, but both proximal and distal cells were inhibited. Of three other types of cell which are virtually confined to the middle region of the nucleus, we investigated 4 pad-sensitive, 11 claw-sensitive and 5 subcutaneous cells: all showed afferent inhibition. It has already been mentioned that the inhibitory field for subcutaneous cells included the skin overlying the excitatory receptive field. Of 5 pad- and-hair-sensitive cells, a type mainly found by us in the rostral region, 2 out of 3 rostral cells were inhibited, and 2 in the middle region were not.

The only type of cell which appeared to escape entirely the influence of afferent inhibition, whether in the rostral or the middle region, was the touch-pressure cell, of which we tested 19. This agrees with the observations of Perl *et al.* (1962). On the other hand, 1 out of 4 cells combining hair-sensitive with touch-pressure properties was inhibited, this one lying in the middle region.

*Facilitation.* Facilitation of cells in the gracile nucleus by single stimuli applied outside their receptive fields was seen by Gordon & Paine (1960), who used a test stimulus to a nerve supplying the receptive field and a conditioning stimulus to a neighbouring nerve whose stimulation alone did not excite the cell. Perl *et al.* (1962) found that certain cells ('touch units') could often be excited by electrical stimuli applied to the skin, beyond the receptive field where tactile stimuli were effective. They pointed out that this effect must depend on the existence of excitatory connexions from fibres supplying regions outside the tactile field, which are subthreshold for the cell unless a number are synchronously activated, as by an electrical stimulus. The 'facilitatory' phenomena we have seen were mainly of this kind, though facilitation was also observed under conventional conditions with test and conditioning stimuli. Electrical stimuli applied at considerable distances (up to 10 cm) from the receptive field were often effective, at thresholds low enough to discount the possibility of the effect being caused by physical spread of stimulus. It would appear that such cells have a facilitatory surround to their receptive field.

Facilitation of this kind was seen in 22 cells. Of the hair-sensitive cells which did not have inhibitory surrounds, all 5 in the middle region were facilitated, and 6 out of 8 in the rostral region. Two pad-and-hair-sensitive cells, of 5 tested, were facilitated (2 of the rest being inhibited); and also 8 touch-pressure cells—all those we tested. We noted the absence of inhibitory effect on 11 further touch-pressure cells which were not specifically tested for facilitation.

So far as our experience went with these tests for afferent conditioning, the distribution of facilitatory effects from the surround of the receptive field was complementary to that for inhibitory effects, cells usually showing either one or the other.

*Projection of axons into the mid-brain: responses to antidromic stimulation*

Antidromic excitation of cells in the gracile nucleus by stimulating in the upper mid-brain gives evidence about the paths by which the cells project (Gordon & Seed, 1961). In most of our experiments we inserted a transverse row of stimulating electrodes in the mid-brain, and for many cells excited antidromically we determined the voltage threshold for such excitation, with each electrode in turn as the stimulating cathode. This allowed a graph to be plotted for each of these cells, relating transverse position to voltage threshold. It can be seen from Fig. 7 that thresholds passed through a well-defined minimum, which must correspond to the position of the projecting fibre in the transverse axis. This technique does not resolve the position of the fibre so precisely in the dorso-ventral axis. On the other hand we have found, while adjusting the depth of the electrodes in each experiment, that when optimum depth and transverse position have been found for any cell, the threshold, for the stimulating conditions we used, lay between 0·5 and 1 V; and that this threshold rose by 5 to 20 times for 1 mm of vertical movement away from the optimum position. This allows some estimate of the vertical error involved in our assessment of the position of each projecting fibre.

In those experiments involving stimulation in the mid-brain, 126 cells of a variety of receptive types was excited in a way strongly suggesting antidromic activation: a single spike were fired at constant threshold and latency. Where time allowed, we applied additional and more stringent tests which are now described.

We arbitrarily classified responses as antidromic when a single spike occurred at constant threshold and latency, and the cell *either* followed the first five of a train of twice-threshold shocks of frequency 750/sec or more, *or* responded to a second single twice-threshold shock at a shock interval of 0·6 msec or less—both these latter tests were used if practicable. These criteria are stringent enough to make it virtually certain that the cells in question were responding antidromically rather than trans-synaptically. Unfortunately this stringency excludes many cells whose responses were probably antidromic nevertheless; and complete

proof of the antidromic nature of a response must rest on another type of argument which we have applied to only two cells in the present study.

The argument is one that has been used previously (e.g. by Darian-Smith, Phillips & Ryan, 1963). If the cell fires an orthodromic impulse along its axon, then it will not subsequently be able to fire an impulse in response to antidromic stimulation until a minimum time has elapsed equal to twice the conduction time between the cell and the antidromic stimulating electrodes *plus* the refractory period of the axon at the point of stimulation. But it can respond to trans-synaptic stimulation after a time that is presumably much shorter (the refractory period of the cell). Figure 10*c* shows that of the refractory period of a cell in the gracile nucleus was short ($< 1{\cdot}5$ msec). The fact that the response of this

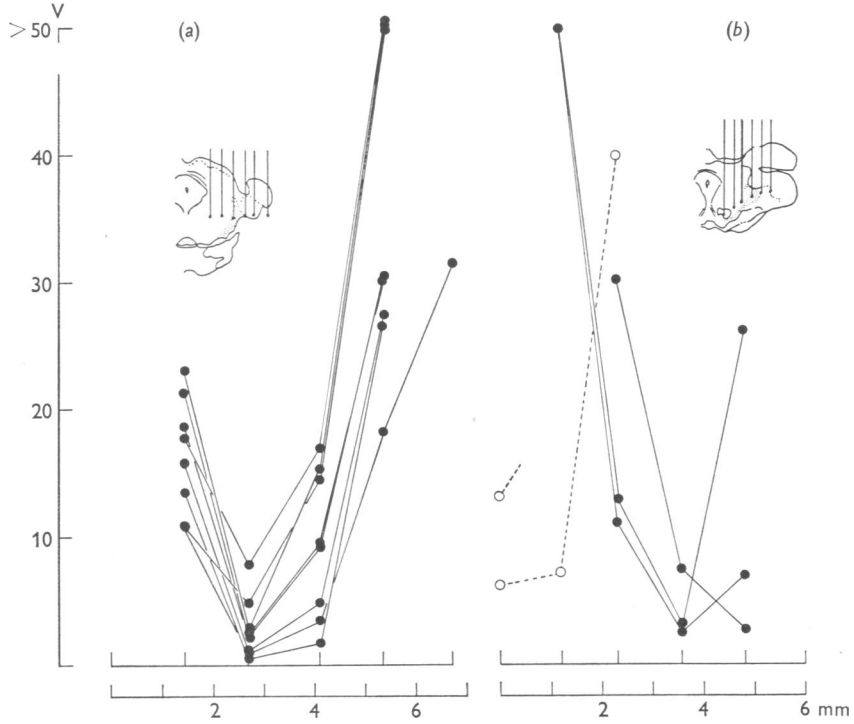



Fig. 7. Graphs relating the threshold (ordinate) for antidromic excitation of cells in the gracile nucleus to the transverse position of the stimulating cathode in the contralateral mid-brain (abscissa). The upper abscissal scale gives the transverse positions of the electrode tips: the lower scale is in mm, referring to the brain before fixation. Each set of points connected by lines refers to a single cell. The positions of the stimulating electrodes and their non-insulated tips in the mid-brain are shown on inset tracings from histological sections: the approximate position of the medial lemniscus is shown in these tracings as a dotted area. (*a*) Graphs for antidromic excitation of eight cutaneous cells in the middle part of the nucleus. The six electrodes for this experiment were all inserted to about the same depth. (*b*) Graphs for antidromic excitation of cutaneous cells in the rostral (open circles and interrupted lines) and middle (filled circles and solid lines) parts of the nucleus. The electrode tips lay successively deeper from the lateral to the medial end of the row in this experiment.

cell to mid-brain stimulation (Fig. 10*a*) was blocked by a 'spontaneous' impulse fired by the cell as much as 5·8 msec beforehand (Fig. 10*b*) now shows that this response was antidromic.

Judged by these criteria, 74 cells were excited antidromically in our experiments, and for all but 8 of these the receptive characteristics were investigated thoroughly enough to let them be placed in one or other of the groups we have already specified. Thirty-nine were hair-sensitive, 2 pad-sensitive, 1 pad-and-hair-sensitive, 6 claw-sensitive, 9 touch-pressure, 1 touch-pressure-and-hair-sensitive, 3 subcutaneous, 3 vibration-sensitive, and 2 'refractory'. The other 8 were identified as cutaneous but were not investigated in detail. It is clear, then, that some members of each category of cell project in the contralateral mid-brain.

Of the cells giving antidromic responses whose receptive characteristics were known, the great majority (51) were in the middle region of the nucleus. Gordon & Seed (1961) found that most of the cells they investigated in the middle region could be excited antidromically from the lemniscal region of the contralateral mid-brain. We can now be more specific: provided that the stimulating electrodes were suitably placed for stimulating the main (dorso-lateral) body of the lemniscus, we found that 42 out of 48 (or 88 %) of cells tested in this part of the nucleus were antidromically excited—excluding the touch-pressure cells, of which only 8 out of 26 (31 %) were excited. Of the cells showing afferent inhibition, most of which, as we have said above, lay in the middle region of the nucleus, virtually all those tested (37 out of 38) were fired antidromically from the main body of the medial lemniscus. These inhibited cells were of the following kinds: 23 hair-sensitive, 2 pad-sensitive, 6 claw-sensitive, 3 subcutaneous, 1 touch-pressure-and-hair-sensitive, and 2 others responding to light pressure on pads.

This very dense projection of cells showing afferent inhibition into the main body of the lemniscus in the rostral mid-brain strongly suggests that the axons of these cells form a quantitatively important element in the input to the ventrobasal complex of the thalamus. It is relevant here that in one experiment in which the stimulating electrodes were inserted much more rostrally, three cells were excited antidromically with the most effective electrode lying in the ventrobasal complex: these were all hair-sensitive cells showing afferent inhibition.

Judged by the same criteria, only 10 of 31 rostral cells which we tested projected into the main body of the lemniscus. Gordon & Seed (1961) also found a considerable deficit in the projection of this part of the nucleus, and showed that it could be partly attributed to some of the cells projecting to the cerebellum. The existence of such a projection has been confirmed by Holmqvist, Oscarsson & Rosén (1963). The possibility remains that some rostral cells project towards the thalamus by paths outside the main body of the lemniscus. The anatomical work of Busch (1961), for example, has shown degenerated fibres in a ventromedial

position in the upper mid-brain, ventral to the red nucleus, after lesions involving the rostral parts of the dorsal column nuclei. In a number of experiments we arranged the stimulating electrodes in the way shown in Fig. 7*b* (inset), so that the medial electrode lay deep enough to excite fibres in the region indicated by Busch's work. Some rostral cutaneous cells were shown to respond antidromically to stimuli delivered in this

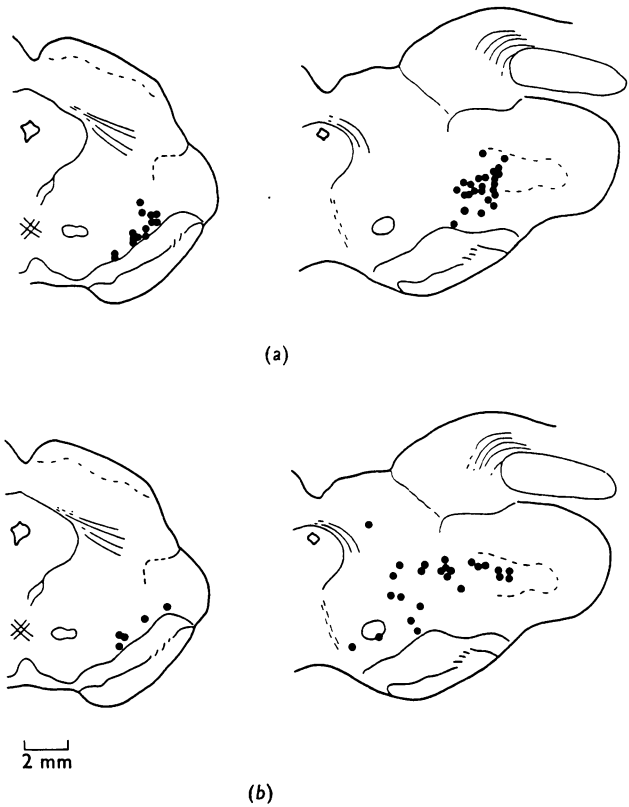



Fig. 8. Tracings of transverse sections of the cat's brain stem, showing the electrode-tip positions from which cells in the gracile nucleus could be excited antidromically at lowest threshold (always 6 V or less). Each filled circle refers to the stimulation of a single cell. The data used for these figures were derived from a number of experiments; and each point was plotted on the more appropriate of the two representative tracings (those on the left being approximately in frontal plane 3, those on the right in plane 5), using the relation of the points in each individual brain to obvious anatomical landmarks as a guide in plotting. The scale refers to the brain before fixation, allowance having been made for shrinkage. (*a*) Points for antidromic excitation of 38 cutaneous cells in the middle part of the gracile nucleus (14 from plane 3, 24 from plane 5), derived from 23 experiments. (*b*) Points for antidromic excitation of 30 cells in the rostral part of the nucleus (5 from plane 3, 25 from plane 5), derived from 12 experiments.

position (see e.g. Fig. 7*b*; and Fig. 8*b*, right-hand tracing), and so also were two cells sensitive to joint rotation which are not considered further in this paper. But comparing our results in these particular experiments with those of Gordon & Seed (1961), who used a row of stimulating

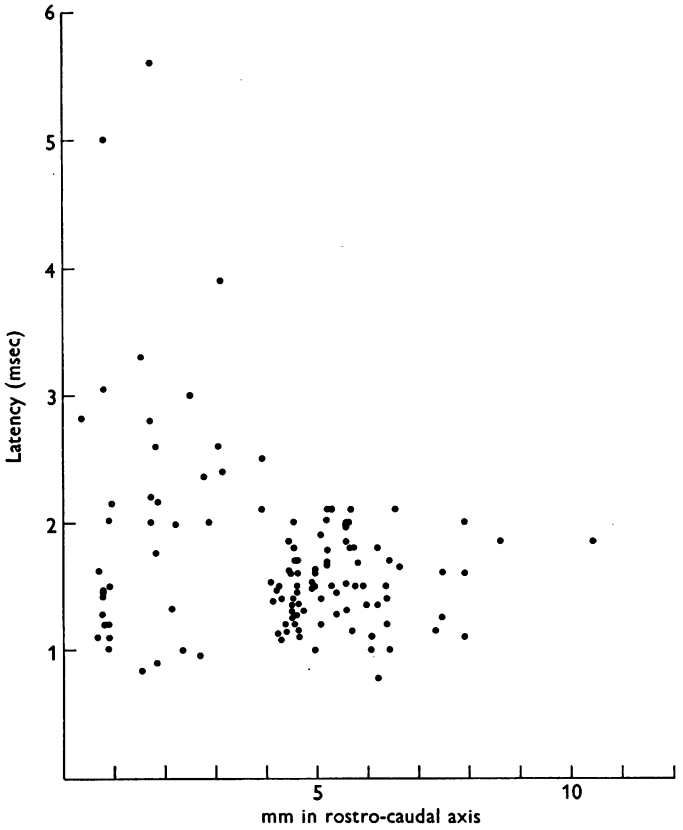



Fig. 9. Graph showing the latencies of antidromic response (ordinate) of cutaneous cells in the cat's gracile nucleus to twice-threshold shocks applied in the contralateral mid-brain (frontal planes 3 to 5), expressed as a function of their position in the rostro-caudal dimension of the nucleus (abscissa, on which zero is the rostral border). Each point refers to a single cell: 124 points are plotted. The graph includes data obtained by Gordon & Seed (1961) but not fully reported in their paper.

electrodes with all their tips level and much more superficial than our medial electrodes, it was clear that they had succeeded in exciting antidromically a much higher proportion of rostral cells (63 %, of 78 cells). Having ourselves observed antidromic excitation of a rostral cell at very low threshold by stimulating in a dorsomedial position far removed both

from the main body of the lemniscus and from the ventromedial bundle of Busch, we felt it was likely that the projection of the rostral part of the gracile nucleus was quite dispersed at this level of the brain stem, and therefore not amenable to systematic investigation in single experiments by the methods we were using. But the position becomes clearer if the results of a number of experiments are considered together. We identified anatomically the points from which rostral cells had been antidromically excited at low threshold, both in our own experiments and those of Gordon

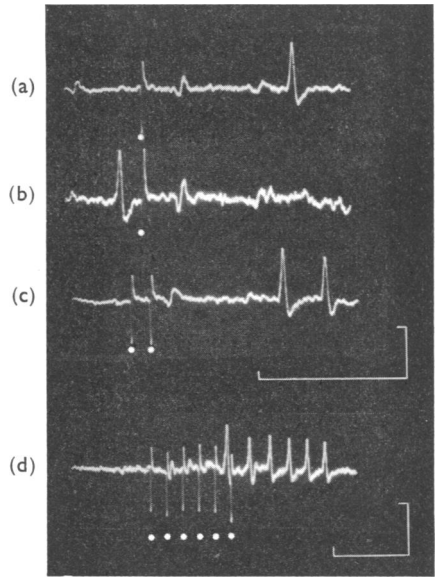



Fig. 10. Antidromic excitation of a touch-pressure cell in the rostral part of the gracile nucleus (0·82 mm). Threshold of response 1·0 V, with the stimulating cathode in the contralateral mid-brain in the position of the most dorsomedial point in Fig. 8*b* (right-hand tracing). Threshold rose sharply superficially and deep to this point. (*a*) Response to a single twice-threshold shock. Latency 5·0 msec. (*b*) Antidromic response blocked by a 'spontaneous' impulse in the same cell occurring 5·8 msec before the expected antidromic response. (*c*) Antidromic responses to a pair of twice-threshold shocks separated by the shortest interval at which the second shock was effective (0·64 msec). (*d*) Antidromic responses to a train of six twice-threshold shocks delivered at a frequency of 940 shocks/sec. This cell had a receptive field of about 100 cm$^2$ on the proximal part of the foot, whole of lower leg, and distal part of the thigh, and was facilitated by stimulation outside this field. Other properties of this cell are mentioned in the legend of Fig. 7 of the following paper (Gordon & Jukes, 1964). Calibrations: 5 msec and 0·5 mV (negativity upwards). Note that the time-scale for (*d*) is different from that for (*a*) to (*c*). Voltage amplification was somewhat increased in (*b*) to compensate for temporary reduction in spike amplitude. The timing of the stimuli is indicated by conspicuous shock-escapes and by white dots in all records.

& Seed, and have plotted these points on a composite map for each of two levels in the brain stem (Fig. 8*b*). For comparison, a number of points are also plotted for cells in the middle of the nucleus (Fig. 8*a*). There is a striking contrast between the distribution of points for the rostral and for the middle regions of the nucleus, for those experiments in which the stimulating electrodes were in about frontal plane 5 (right-hand tracings of Fig. 8). This is not seen for electrodes more caudal in the brain stem (left-hand tracings). It appears that there is a medial dispersion of some fibres projecting from the rostral part of the nucleus, and that it is likely to begin between the two mid-brain levels represented in Fig. 8. The existence of this previously unsuspected dispersion means that our figures and those of Gordon & Seed (1961) probably give a considerable underestimate of the extent of projection of the rostral part of the nucleus.

Another indication of a difference between the projections of rostral and more caudal-lying cells in the nucleus comes from a comparison of the latencies of their responses to antidromic stimulation. Figure 9 shows that although the shortest latencies in the rostral region are similar to the shortest in the middle region, the scatter among the latencies of rostral cells is considerable and the mean latency much longer. Some of these rostral cells had latencies so long (5 msec or more) as to raise the question whether their responses were really antidromic rather than transsynaptic; but it is clear from the proof presented in Fig. 10 that antidromic responses of this order of latency do occur in the rostral region.

## DISCUSSION

It has been shown that there exist in the cat's gracile nucleus a number of types of cell which respond to light mechanical stimulation of the surface of the body; and that each type, recognized by us by the nature of its excitatory afferent input, is represented in the output from the nucleus into the contralateral mid-brain. It is striking that these cells, especially in the middle region of the nucleus, maintain on the whole a clear specificity with regard to peripheral stimuli. Hair-sensitive, pad-sensitive, claw-sensitive and touch-pressure cells, for example, are distinct and easily recognizable entities. This does not mean that each type is necessarily supplied from a unique type of receptor, a matter on which we have strictly no evidence; but it suggests a general functional similarity among its receptors. We feel more definite about the claw-sensitive cells, because it seems likely that the minute and sharply localized sensitive spots at the base of the claws actually represent the sites of receptors placed strategically for responding to stimulation of the claw. We do not know of any existing description of such receptors. Cells whose properties suggest that

they receive excitation from more than one general class of receptor were in the minority: hair-and-pad-sensitive cells with continuous receptive fields were the commonest of these.

The purpose of this paper was to resolve the problems raised by Gordon & Paine's (1960) observation that cells with cutaneous fields in the middle region of the nucleus have a smaller mean size of receptive field than those in the rostral or caudal regions. It is now clear that this was due to the preponderance in this middle region of cells, lying mainly superficially, which have a small average size of field, and which are almost all subject to afferent inhibition. Cells of this kind are found much less commonly in the rostral region. The cells are not all supplied by the same kind of receptor: a large group of them is specifically hair-sensitive, others are pad-sensitive, claw-sensitive or respond to subcutaneous pressure. What unifies them as a major element in the organization of the nucleus is that they receive afferent inhibition and that they virtually all contribute to the output of the nucleus into the main body of the medial lemniscus. The cells of this system are arranged, at least in the middle of the nucleus where they are numerous, in an orderly somatotopic fashion; and size of receptive field increases with more proximal position on the body (e.g. Fig. 4). It has been mentioned that several cells of this kind are often found in a group; and it is very tempting to suggest that this part of the nuclear organization is represented by the superficial cell-clusters, which have a similar distribution in the long axis of the nucleus, and whose component cells, with their large cell-bodies and bushy, densely packed dendrites, have a distinctive morphological appearance (Kuypers, Hoffman & Beasley, 1961; Kuypers & Tuerk, 1964).

The deep-lying touch-pressure cells in the middle region do not belong to the above organization. In fact cells with pure 'touch-pressure' properties are the only kind of cutaneous cells which do not ever appear to receive afferent inhibition (Perl *et al.* 1962; and the present paper). Touch-pressure cells are also found in the rostral region, where they are mixed in an apparently random way with other cutaneous cells having moderate or large receptive fields—mainly those hair-sensitive and other cells which do not receive afferent inhibition and which form a much bigger component in the rostral than in the middle region. Afferent inhibition for these various cells has been replaced by afferent facilitation. These components of the mixed population in the rostral region are also characterized by their lack of somatotopic orderliness, even though all parts of the hinder half of the body surface are apparently represented there, and by the more heterogeneous and diffuse nature of their projection from the nucleus.

It should be noted that these functionally distinct subdivisions of the

nucleus are not characterized primarily by the kind of receptor supplying them. It is true that, in our experience, claw-sensitive and pad-sensitive cells were only found in the first, and touch-pressure cells only in the second system; but hair-sensitive and pad-and-hair-sensitive cells were represented in both. The greater average size of receptive field in the rostral region is not in fact due, as Perl *et al.* (1962) suggested, to a preponderance of touch-pressure cells there, but to the fact that the average size of field for all types of cell is greater. Kruger *et al.* (1961) suggested that the large average size of field reported by Gordon & Paine (1959) in the rostral region might be explained if they had sampled proportionately more cells there with proximal (and therefore larger) fields. We are satisfied that this is not the explanation of the differences we have seen. The sample we have made of 'proximal' hair-sensitive cells, though small, was in fact about the same size in rostral and in middle regions (Fig. 2). Their fields in the middle region tended to be rather smaller, commonly with inhibitory surrounds (Fig. 4).

There are other reasons for believing that the rostral pole is differently organized from the rest of the nucleus. It has been mentioned (Gordon & Paine, 1960; and the present paper) that this region appears to be more sensitive to anaesthesia and deteriorates first during an experiment. After an hour or two, this part may be entirely unresponsive except for the activity of a few proprioceptive cells. It seems possible that this is the reason for Kuhn's (1949) finding that cutaneous stimuli were relatively ineffective in producing evoked potential changes rostral to the obex. We also found a number of rostral-lying cells with inconsistent or 'refractory' properties when excited by peripheral stimuli. It has been mentioned that one possible reason for these differences in the rostral region is that a substantial number of cells there are separated from the periphery by several synapses, a view supported by McComas's (1963) observations on the latency of response to peripheral stimuli of rostral cells in the rat's gracile nucleus. It does seem, however, that cells in this region of the cat's cuneate nucleus receive some primary afferent fibres, because Kuypers & Tuerk (1964) have shown degeneration there after section of dorsal roots. This degeneration, after cutting one or two roots, was more diffuse in the rostral than in the middle region, a fact consistent with the lack of somatotopic orderliness and larger receptive fields of many of the rostral cells. The rostral region differs also in cyto-architecture and dendritic architecture from most of the rest of the nucleus (Kuypers *et al.* 1961; Kuypers & Tuerk, 1964): cell-clusters are much less common, and there is a majority of smaller cells of triangular or multipolar type, many with long radiating dendrites. A similar architecture is found deep in the middle part of the nucleus, where we found many touch-pressure cells.

Our conclusions about the paths of projection of cells in the rostral part of the nucleus, arrived at from the results of antidromic stimulation, agree well with recent anatomical findings. We have confirmed Busch's (1961) conclusion that some of the rostral cells project ventro-medially in the upper brain stem. We have found that the projection path for rostral cells diffuses medially and dorso-medially from the lemniscus at this level. Kuypers & Tuerk have independently reached a similar conclusion from a study of degeneration in the brain stem following a lesion in the rostral parts of the dorsal column nuclei: some degenerating fibres were traced to the area medial to the medial geniculate body and suprageniculate nucleus. From our data, the axons of some of the rostral cells appear to remain in the main body of the medial lemniscus at this level, and may therefore reach the ventrobasal region of the thalamus: but considerable doubt must remain about the termination of many axons from this part of the nucleus.

The long latency for antidromic excitation of many rostral cells is presumably due to slow conduction in the projecting axons, though a circuitous path could add to the delay. Their cell bodies are smaller than those in the cell clusters, as Kuypers & Tuerk (1964) have shown, and may give rise to smaller axons. It is also possible that some axons are reduced in diameter by bifurcation. We have never found more than one low-threshold point in the mid-brain for the antidromic excitation of a single cell—evidence which would have suggested bifurcation—but Gordon & Seed (1961) showed that some rostral cells could be excited antidromically both from the cerebellum and the lemniscus, indicating that the axons of these cells did bifurcate. Further investigation is needed of the extent to which this occurs. Systematic bifurcation would perhaps help to explain the further observation of Kuypers & Tuerk (1964) that retrograde cell changes after section of the contralateral lemniscus, although very severe in the cell-cluster region, as one would expect from our data, were much less severe in the rostral region and deep part of the middle region of the nucleus. Any axon branches projecting to the cerebellum would have remained intact in these experiments, and thus protected the cells concerned against severe retrograde damage.

Further discussion of the evidence presented here will be deferred to the end of the following paper, which deals with synaptic effects on the gracile nucleus from stimulation in cortex and brain stem.

## SUMMARY

1. The properties of single cells of the cat's gracile nucleus which responded to light mechanical stimulation of the body surface were investigated by electrical recording. The investigation included a study of

their receptive characteristics and fields, of inhibitory and facilitatory effects from stimulation in the 'surrounds' of these fields, and of the projection of the cells into the mid-brain as determined by antidromic stimulation.

2. Most of the cells fell into one or other of the following groups: hair-sensitive, pad-and-hair-sensitive, claw-sensitive, skin touch-pressure, subcutaneous pressure, and vibration-sensitive. Hair-sensitive (most adapting rapidly) and skin touch-pressure cells (all adapting slowly) were much the commonest types. Claw-sensitive cells (all adapting slowly) formed a small well-defined group whose properties have not previously been described. All these types were represented in the output of the nucleus into the contralateral mid-brain.

3. The small average size of receptive field found among cells in the middle of the long axis of the nucleus (Gordon & Paine, 1960) was shown to result from the preponderance there of cells receiving afferent inhibition. Such cells were much less common in the rostral region. They lay mainly superficially and were disposed in an accurate somatotopic fashion. They virtually all projected into the main body of the contralateral medial lemniscus, constituting a very large fraction of the output of the nucleus. Such cells were hair-sensitive, pad-sensitive, pad-and-hair-sensitive, claw-sensitive, or responded to subcutaneous pressure.

4. A second type of cell-organization predominated in the rostral region, including cells of the hair-sensitive, pad-and-hair-sensitive and skin touch-pressure groups; and in the deep part of the middle region of the nucleus (skin touch-pressure cells only). Their average size of receptive field was rather large. Such cells were facilitated, not inhibited, from the area surrounding their receptive fields. Somatotopic arrangement was not obvious in the disposition of these cells. Only about a third of them were definitely shown to project into the contralateral mid-brain.

5. Some cells in the rostral part of the nucleus projected into the main body of the lemniscus in the rostral part of the contralateral mid-brain; but antidromic stimulation showed that others deviated medially, ventromedially and dorsomedially from the lemniscus at this level. Mean latency for antidromic response of rostral cells was much longer than for more caudal cells.

6. In a discussion of the results, it was shown that a good correlation exists between the two types of functional organization described here, and the cyto-architectural differentiation of the nucleus described by Kuypers & Tuerk (1964).

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## REFERENCES

ANDERSEN, P., ECCLES, J. C. & SCHMIDT, R. F. (1962). Presynaptic inhibition in the cuneate nucleus. *Nature, Lond.*, **194**, 741–743.

ARMETT, CHRISTINE J. & HUNSPERGER, R. W. (1961). Excitation of receptors in the pad of the cat by single and double mechanical pulses. *J. Physiol.* **158**, 15–38.

BUSCH, H. F. M. (1961). An anatomical analysis of the white matter in the brain stem of the cat. Dissertation for Doctorate of Medicine, Leiden.

DARIAN-SMITH, I., PHILLIPS, G. & RYAN, R. D. (1963). Functional organization in the trigeminal main sensory and rostral spinal nuclei of the cat. *J. Physiol.* **168**, 129–146.

DAWSON, G. D., PODACHIN, V. P. & SCHATZ, S. W. (1963). Facilitation of cortical responses by competing stimuli. *J. Physiol.* **166**, 363–381.

FRANKENHAEUSER, B. (1949). Impulses from a cutaneous receptor with slow adaptation and low mechanical threshold. *Acta physiol. scand.* **18**, 68–74.

GORDON, G. & JUKES, M. G. M. (1962). Correlation of different excitatory and inhibitory influences on cells in the nucleus gracilis of the cat. *Nature, Lond.*, **196**, 1183–1185.

GORDON, G. & JUKES, M. G. M. (1963). Superimposition of sweeps on a storage oscilloscope as a method of studying changes in excitability of single nerve cells. *J. Physiol.* **169**, 64–65*P*.

GORDON, G. & JUKES, M. G. M. (1964). Descending influences on the exteroceptive organizations of the cat's gracile nucleus. *J. Physiol.* **173**, 291–319.

GORDON, G. & PAINE, C. H. (1959). Some features of the physiological organization of nucleus gracilis in the cat. *J. Physiol.* **148**, 34–35*P*.

GORDON, G. & PAINE, C. H. (1960). Functional organization in nucleus gracilis of the cat. *J. Physiol.* **153**, 331–349.

GORDON, G. & SEED, W. A. (1961). An investigation of nucleus gracilis of the cat by antidromic stimulation. *J. Physiol.* **155**, 589–601.

HOLMQVIST, B., OSCARSSON, O. & ROSÉN, I. (1963). Functional organization of the cuneocerebellar tract in the cat. *Acta physiol. scand.* **58**, 216–235.

HUBEL, D. H. (1957). Tungsten microelectrode for recording from single units. *Science*, **125**, 549–550.

HUNT, C. C. & MCINTYRE, A. K. (1960). Properties of cutaneous touch receptors in cat. *J. Physiol.* **153**, 88–98.

IGGO, A. (1963). New specific sensory structures in hairy skin. *Acta neurovegetativa*, **24**, 175–180.

JOHNSON, F. H. (1952). Microelectrode studies on the cuneate and gracile nuclei of the cat. *Amer. J. Physiol.* **171**, 737.

KRUGER, L., SIMINOFF, R. & WITKOWSKY, P. (1961). Single neuron analysis of dorsal column nuclei and spinal nucleus of trigeminal in cat. *J. Neurophysiol.* **24**, 333–349.

KUFFLER, S. W. (1953). Discharge patterns and functional organization of mammalian retina. *J. Neurophysiol.* **16**, 37–68.

KUHN, R. A. (1949). Topographical pattern of cutaneous sensibility in the dorsal column nuclei of the cat. *Trans. amer. neurol. Ass.* **74**, 227–230.

KUYPERS, H. G. J. M., HOFFMAN, A. L. & BEASLEY, R. M. (1961). Distribution of cortical 'feedback' fibres in the nuclei cuneatus and gracilis. *Proc. Soc. exp. Biol. Med.* **108**, 634–637.

KUYPERS, H. G. J. M. & TUERK, J. D. (1964). The distribution of the cortical fibres within the nuclei cuneatus and gracilis in the cat. *J. Anat., Lond.* **98**, 143–162.

MCCOMAS, A. J. (1963). Responses of the rat dorsal column system to mechanical stimulation of the hind paw. *J. Physiol.* **166**, 435–448.

PERL, E. R., WHITLOCK, D. G. & GENTRY, J. R. (1962). Cutaneous projection to second-order neurons of the dorsal column system. *J. Neurophysiol.* **25**, 337–358.