

Organization of the Face Representation in Macaque Motor Cortex

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ABSTRACT We stimulated with microelectrodes the face representation in precentral motor cortex in macaque monkeys. Responses were very discrete; at threshold current levels the usual response was a small focus of movement in part of a muscle. Facial muscles cluster together in the posterior and anterior portions of the precentral gyrus with tongue movements represented in the intervening region and along the lateral extent. Within each cluster there are multiple representations of individual muscle movements. In long penetrations down the anterior wall of the central sulcus we were able to advance the electrode tangentially through cortex. In these penetrations we encountered a series of discrete zones each of which was related to the movement of a particular muscle or part of a muscle in the face. The lowest threshold points were found in the center of each zone, and as the microelectrode progressed toward the edge, thresholds rose until there was a shift to a new muscle movement. Successive stimulation points separated by as little as 50 μ m could yield different responses. These zones could be either roughly cylindrical or take the form of narrow curving bands running mediolaterally across cortex. There is a tendency for adjacent muscles to occur together, and the representation may be roughly topographical within the limits set by the morphological structure of the muscles themselves. The most commonly evoked muscle response was in zygomaticus, which retracts the corners of the mouth in expressions of fear and anger.

The research described here was undertaken as part of a larger program to explore the neural control of the muscles of facial expression in primates. The face region of motor cortex has been extensively studied using surface stimulation. Early studies found a number of contralateral or bilateral movements of the face, some of which involved complex sequences of movements (Beevor and Horsley, 1890, 1894; Vogt and Vogt, '19). Later investigators using improved anesthesia and lower current levels report more simple contralateral and ipsilateral movements and a greater proportion of movements of individual muscles rather than sequences of movements of several muscles (Walker and Green, '38; Hines, '40; Woolsey et al., '50; Lauer et al., '52). Woolsey et al. ('50) concluded on the basis of extensive cortical mapping with surface electrodes that the primary motor area should include all of Brodmann's ('08) cytoarchitectural area 4 and the adjacent portion of area 6. This single primary motor area was considered to contain a single basically topographic representation of the head and body.

There are a number of problems with surface

stimulation. The site of electrical stimulation is quite distant from the major efferent neurons in layer 5. High current levels must be used to produce an observable response in the periphery, and there is considerable current spread (Asanuma et al., '76). This problem is compounded by the considerable dendritic arborization in the superficial cortical layers. In addition much of motor cortex is buried in the walls of the central and arcuate sulci where it is relatively inaccessible to surface electrodes without extensive ablation of neighboring cortical regions.

Microstimulation techniques have made it possible to study the organization of motor cortex in fine detail (Asanuma and Sakata, '67; Asanuma and Rosen, '72). Until recently most research on motor cortex using microelectrodes has been limited to a small portion of the forelimb representation (Asanuma and Rosen, '72; Andersen et al., '75). Asanuma and collaborators (Asanuma and Rosen, '72; Asanuma '73; Asanuma and Arnold, '75) have proposed that motor cortex is organized in fine columns controlling individual peripheral muscles and suggest that the larger movements often re-

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ported with surface stimulation were due to activation of several such columns. Andersen et al. ('75) argued that the basic unit was somewhat larger than Asanuma et al.'s columns but also found small zones embedded in the large "colonies" in which comparatively low currents evoked movements of single muscles. Janowska et al. ('75a) microstimulated in the hind limb representation in the motor cortex and found that pyramidal tract neurons were activated mainly polysynaptically rather than monosynaptically. In a related study Janowska et al. ('75b) stimulated the surface of motor cortex and found when recording intracellularly from spinal cord motor neurons that monosynaptic excitatory postsynaptic potentials could be recorded from these cells when the cortical surface was stimulated over areas of 3 to 7 mm² typically. However the authors point out that these results do not necessarily rule out the presence of columns in motor cortex.

The only research on the face region done with microelectrodes involved only the jaw muscles. Clark and Luschei ('74) used microstimulation but were concerned mainly with determining the type of jaw movements which could be produced with intracortical microstimulation, and did not report on topographical organization. Other research on jaw movements has involved only recording (Luschei et al., '71).

In exploring the face region of motor cortex with microelectrodes we felt two things were particularly important. In penetrations down sulcal walls in which the electrode travels perpendicular to the radial fibers and would presumably cross columns, stimulation sites should be closely spaced to assess accurately how large a zone is devoted to any one response, to determine if there is overlap of responses, and if so, how much. In addition a large region of cortex should be covered in each animal to determine if the overall pattern of organization is basically as described in studies using surface stimulation, or if it is more complex.

This work has been reported in an abstract (McGuinness and Allman '77).

METHODS

Chronic procedure

A chronic preparation similar to that developed by Evarts ('66) was used for two reasons. First, since there is a certain amount of variability among animals in the location of landmarks such as sulci, if one is studying a large region of cortex, the fine-grained pattern of or-

ganization can be masked by combining data from several animals in composite figures. By using a chronic preparation we were able to obtain data from a large portion of the face region of motor cortex in fine detail from each animal. By comparing detailed maps from several animals it is possible to obtain a much better picture of the overall structure than would otherwise be possible. Second, in addition to better data, the chronic preparation allows one to obtain a large volume of data from fewer animals than would be required using acute procedures. The latter has become increasingly important with the current scarcity of many species of primates.

Our experiments were done on six macaque monkeys (four *Macaca mulatta*, two *Macaca fascicularis*).

Surgery and initial preparation

Monkeys were anesthetized for initial surgery with 15 mg/kg ketamine hydrochloride supplemented with 8 mg/kg ketamine every 20 minutes. A bone flap was removed from over the face region of precentral motor cortex and a 20 mm inside diameter, stainless steel chamber was attached to the skull with dental cement (Grip). The dura was left intact. An additional stainless steel bolt to immobilize the head was attached to the skull posterior to the chamber. All surgery was carried out using aseptic procedures. Following surgery the animal was returned to its cage and allowed several days for recovery.

We carried out experiments on each animal two to three times per week. Typically an experiment lasted from 10 to 12 hours. For an experiment the animal was initially anesthetized with ketamine and placed in a primate chair with its head restrained. The chamber was opened, filled with sterile mineral oil and fitted with a polar coordinate system for plotting electrode penetrations. The chamber was then sealed to prevent brain movement and the electrode lowered into the brain. Either a hydraulic microdrive modified for use with the chamber or a stepping motor microdrive was used to advance the electrode. In most cases the electrode was advanced in either 50 or 100 μ m steps; in one case (PR-1) the electrode was usually advanced in 500 μ m steps, and in a preliminary experiment (CM-1) only 1 response per penetration was studied. After each advance of the microelectrode, except in early experiments CM-1 and D-19, we waited at least two minutes before stimulating to allow the brain to stabilize. We introduced this delay

following electrode advancement because we noted in early experiments that the response would sometimes change after the initial stimulation. We attributed these changes to small movements of the brain relative to the electrode following electrode advance. The responses were stable over time after the two-minute delay was introduced.

During stimulation the minimal dose of ketamine necessary to decrease spontaneous movement and keep the animal from resisting responses was used. This varied but was usually in the range of 2–4 mg/kg every 20–30 minutes. The fact that our thresholds are similar to those obtained by other investigators studying the forelimb region in awake (Kwan et al., '78) or sedated (Asanuma and Rosen, '72) animals suggests that the ketamine-anesthetized animal is appropriate for microstimulation. At the end of each experimental session the monkey was returned to its cage.

Microstimulation

The intracortical microstimulation technique we used was similar to that developed by Asanuma and Sakata ('67). We employed glass-insulated platinum-iridium microelectrodes with an exposed length of less than 20 μ m and stimulated with a 50 msec train of 0.2 msec pulses cathodal current with an interpulse interval of 3 msec (312.5 Hz). Pulse trains were produced by a Neurolog modular system with a constant current stimulus isolation unit (Medical Systems Corporation). Output was calibrated to 0.1 μ A intervals and current levels were read off the dial of the apparatus. Batteries were checked at the beginning and end of each experiment and the equipment was periodically monitored for possible fluctuation. No fluctuation was found.

During experiments the constant current unit was attached to the chair near the chamber. The negative output lead was connected to the electrode contact and the positive lead grounded to the chamber. When current levels were checked a 1 k Ω resistor was connected in series to the ground lead and current across the resistor monitored on an oscilloscope. A second lead from the stimulator triggered an audio amplifier producing a low buzz which signaled the onset of a pulse train. To avoid damaging cortex current levels above 25 μ A were not used.

Determination of Responses

When the electrode was initially advanced in the brain we stimulated at 20 μ A until we en-

countered the first response. The current was then turned down until the response could no longer be seen and was slowly increased until the response reappeared. At subsequent stimulation sites in the same penetration we first stimulated at the same current level as had been used at the previous site. If a response was still present we again lowered the current until the response disappeared and then gradually raised the current until it reappeared. If no response occurred at a new site using the previous threshold we increased the current until a response was encountered or until we reached 25 μ A. After both observers agreed on the muscle movement elicited at a site, one person made the threshold determination while the other controlled current levels. The person making the threshold determination did not know what currents were being used. Threshold was considered the lowest current level at which a response could be consistently elicited.

The response was determined by watching the face. Two observers were always present. The face muscles are particularly easily visualized since except for the jaw muscles they are not involved in movement of joints. Instead they move skin or act against each other. The mimetic muscles have evolved to be readily visible; thus very small movement can be easily seen. The observed response at threshold was often not an entire muscle but rather a small part of a muscle. Stimulating at suprathreshold currents usually recruited the entire muscle. Since many muscles are overlapping and some, such as nasolabials and levator labii superioris proprius, are also roughly parallel, it was sometimes necessary to stimulate with higher-than-threshold current and compare the direction of the recruited response with the pattern of muscle innervation (Huber, '33).

Each response was identified in two ways. The name of the muscle and a written description of the movement was written in the protocol. In addition large photographic prints of the monkey's face were made and the movement drawn on the print with a marking pen. When there was ambiguity about the identification of a muscle response location was confirmed by dissections of the face after perfusion.

Histology and reconstruction

After experiments on an animal were completed, it was deeply anesthetized with pentobarbital, perfused, its brain sectioned, and the electrode tracks reconstructed. Three animals were perfused with 10% formal-saline. The remaining three animals were perfused with

1.5% glutaraldehyde and 1% paraformaldehyde in either phosphate or cacodylate buffer. All brains were frozen and cut in 40 μ m sections in a plane parallel to the angle of electrode penetrations.

During the course of experiments electrolytic lesions at 20 μ A current for 20 seconds were made through the stimulating electrode in selected penetrations at the conclusion of the penetration. Although individual animals were studied for varying lengths of time ranging from three weeks to five months, we preferred to limit our experiments to less than three months duration since we experienced considerable difficulty in reconstructing electrode tracks after longer time periods.

In addition to lesions as an aid to histological reconstruction, in several cases marker electrodes were placed in the brain after perfusion in rows parallel to rows of electrode penetrations and the brain photographed with the marker electrodes in place. Since it is difficult to determine the depth in the brain of a stimulating site while doing electrophysiology in a chronic preparation, we felt it important to know whether shrinkage occurred during processing and to be able to calculate any alteration in sulcal wall angles which occurred in mounting sections. We therefore photographed the frozen brain on the microtome stage during cutting. Every 12th section through the relevant region of tissue was photographed in this manner. We consider careful reconstruction of electrode penetrations and stimulation sites particularly important since it was sometimes possible to elicit responses from microstimulation in the white matter with current levels of less than 10 μ A.

RESULTS

We have studied 2022 responsive sites in six macaque monkeys. Table 1 gives a breakdown of number of penetrations and sites by animal. The majority of the data illustrated comes from

F-4, PR-1, and Herc, since for these animals we have the most complete maps with histological localization of penetration sites.

Muscle responses

Responses were extremely discrete. The usual response we obtained was a discrete focus of movement in part of a muscle. A slight increase in current would usually cause recruitment of a larger region of the same muscle or the entire muscle. Particularly in the case of the most superficial muscles, we would observe a small twitch in the muscle with threshold-level current. A slight increase in current resulted in a directional pull in muscle fibers. Because it is difficult to visualize the muscle activation from a drawing showing only the small twitch, in illustrating results we usually drew in the larger response and the direction of movement. We seldom saw movement of more than one muscle when stimulating at threshold-level currents. In all we saw seven mixed responses which were elicited at 48 stimulation sites. On one occasion we encountered the same two responses from 16 stimulation sites over a distance of 800 μ m.

Figure 1 shows the facial musculature of the macaque monkey. The degree of overlap of the muscles themselves ensures that the face region of motor cortex will not contain a straightforward topographic representation. We obtained responses of 12 different facial muscles in addition to those involved in jaw and tongue movements, which we did not attempt to identify according to the specific muscles involved. The facial muscles seen are as follows: zygomaticus, orbicularis oris, buccinator, platysma, orbicularis oculi, levator labii superioris proprius, mentalis, triangularis, depressor supercilii, caninus, nasolabialis, and auricularis anterior and superior. We also obtained shoulder and forearm movements, to demarcate the medial boundary of the face. We did not see any forehead movements; frontalis and cor-

rugator supercilii were not encountered in any animal we studied.

Fine organization

The fine organization of motor cortex was best visualized in penetrations down the wall of the central, and in one animal (Herc), the ar-

uate sulcus where the electrode traversed cortex perpendicular to the radial fibers. In such penetrations we encountered small zones of cortex, usually 300–800 μ m across, in which microstimulation produced one muscle movement. Advancing the electrode in 50- μ m intervals we would obtain the same response at a

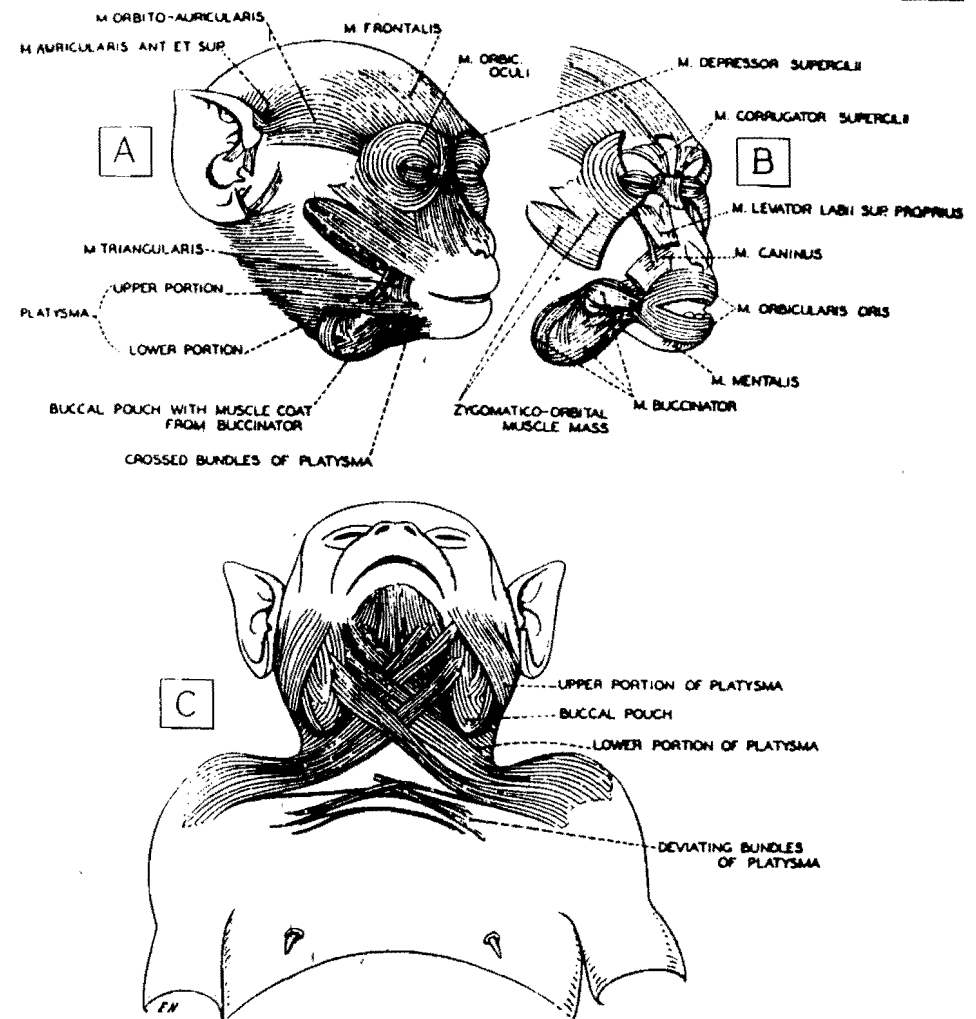


Fig. 1. The facial muscles of *Macaca mulatta* from Huber ('33). The intact superficial facial muscles are shown in drawings A and C. In B some of the surface muscles have been cut away to show underlying muscles. The unlabeled thin sheet of muscle which extends over the nose and medial face in A is nasolabialis. The underlying levator labii superioris proprius is partially shown in B; the inferior portion of this muscle, which is not included, attaches in the upper lip. Figure reproduced from Huber ('33) "The Facial Musculature and its Innervation," in *Anatomy of the Rhesus Monkey* (Hartman, C.G., and Straus, W.L., Eds.). Courtesy of Williams and Wilkins.

TABLE 1. Description of experimental animals and number of response sites

Animal	Species, Sex, Age	Number of penetrations	Number of responsive stimulation sites
CM-1	fuscicularis, male, juvenile	17	17
D-19	mulatta, female, adult	37	506
F-5	mulatta, male, adult	5	134
Herc	fuscicularis, male, juvenile	12	438
F-4	mulatta, male, adult	34	786
PR-1	mulatta, male, juvenile	26	141
Total	6 macaques	131	2022

number of sites. After encountering a movement we saw a drop in threshold as we advanced toward the center of each zone; threshold then began to climb, peaking at the point where the response changed. Typically threshold was lowest at the center of the zone and highest at the edges. Figures 2, 3, 4, and 5 show two such penetrations from one animal, one from the central sulcus and one from the arcuate. We observed this same pattern even when the response changed from one portion of a muscle to another movement of the same muscle. We have a total of 37 penetrations from which two or more different responses were elicited with more than 10 responsive sites 50 μ m or 100 μ m apart.¹ In these penetrations 87% of the changes from one response to another coincided with a threshold peak, and 75% of the peaks were at a point where the response changed. The calculations are based on 214 peaks and 186 response changes. The two coincided 161 times.

In penetrations roughly parallel to the radial fibers, thresholds were highest in the superficial lamina and became lower in the deeper layers until they began to rise in layer 6 as we approached the white matter. Figures 6 and 7 illustrate such a penetration. Although we attempted to have our electrode parallel to the radial fibers, in practice there was always a slight angle causing the changes in responses shown in Figure 6. In this penetration there was a progression of three responses across the eyelid beginning at the lateral corner and ending in the medial corner. Responses A and C were both small muscle twitches at threshold. Microstimulation at B caused a downward flicker of the upper eyelid. Current levels slightly above threshold at sites for all three responses resulted in closure of the eyelid.

Macro-organization

The fine organization of the narrow columnar zones is embedded in a larger macro-organization. Figure 8 shows data from the two animals from which we have the most complete maps. The mimetic muscles cluster in the posterior and anterior portions of the face region with tongue movements represented in the central portion and along the lateral extent. Eyelid movements are represented at the medial edge of the face region adjoining the shoulder and neck muscles. Within each cluster, individual muscles or parts of muscles are often represented several times. The clusters cannot be characterized as distinct topographical representations of the entire face on the basis of the

data we have now. There is a tendency for adjacent muscles to occur together, and the representation may be roughly topographical within the limits set by the morphological structure of the muscles themselves. The region we are calling tongue is comprised of a number of fine movements of individual muscles in the tongue. Such movements can also be seen interspersed with the mimetic responses, particularly at the lateral extent of the central sulcus penetrations. Topographical detail can best be seen in the wall of the central sulcus where electrode penetrations were tangential to the radial fibers. By stimulating every 50 or 100 μ m, one could cover a region of cortex in much finer details than was possible in separate penetrations across the surface of the gyrus. Figure 9 shows a series of sections taken at approximately 1 mm intervals which illustrate a series of penetrations down the anterior wall of the central sulcus in one monkey, F-4. The penetrations shown in Figure 9 correspond to the eight most posterior penetrations in F-4 shown in Figure 8.

Muscles are either represented in a number of non-contiguous zones or form continuous bands running mediolaterally across motor cortex. The evidence for bands rather than non-contiguous representations is best seen in the series of penetrations shown in Figure 9. For example zygomaticus (F2 and F3 in the figure) first appeared near the fundus of the central sulcus in the most lateral section, 96, and subsequently was found slightly higher up the sulcal wall in sections 134 and 151. Its most medial extent was the posterior penetration in section 167, where zygomaticus was elicited concurrently with two branches of levator labii superioris proprius (F9 and F10 in Fig. 3) in a mixed response. This response occurred at four stimulation sites 100 μ m apart, all with thresholds of 18 μ A or higher, which suggests the electrode was moving between columns in this region. In the most medial section, 200, zygomaticus had dropped out but the two branches of levator labii were still seen adjacent to protrusion of the corner of the mouth (orbicularis oris, F8 in Fig. 3). Such a pattern could result from the intersection of narrow bands at different points or from stimulation of repeated small non-contiguous zones devoted to the same muscle.

¹This analysis is based on data from F-5, Herc, and F-4. Only one response per penetration was elicited in the preliminary experiment CM-1. Another early experiment (D-19) was excluded since we stimulated immediately following electrode advancement, which may give erroneous results since the brain may not have stabilized (see Methods). In PR-1 we advanced in 500 μ m steps.

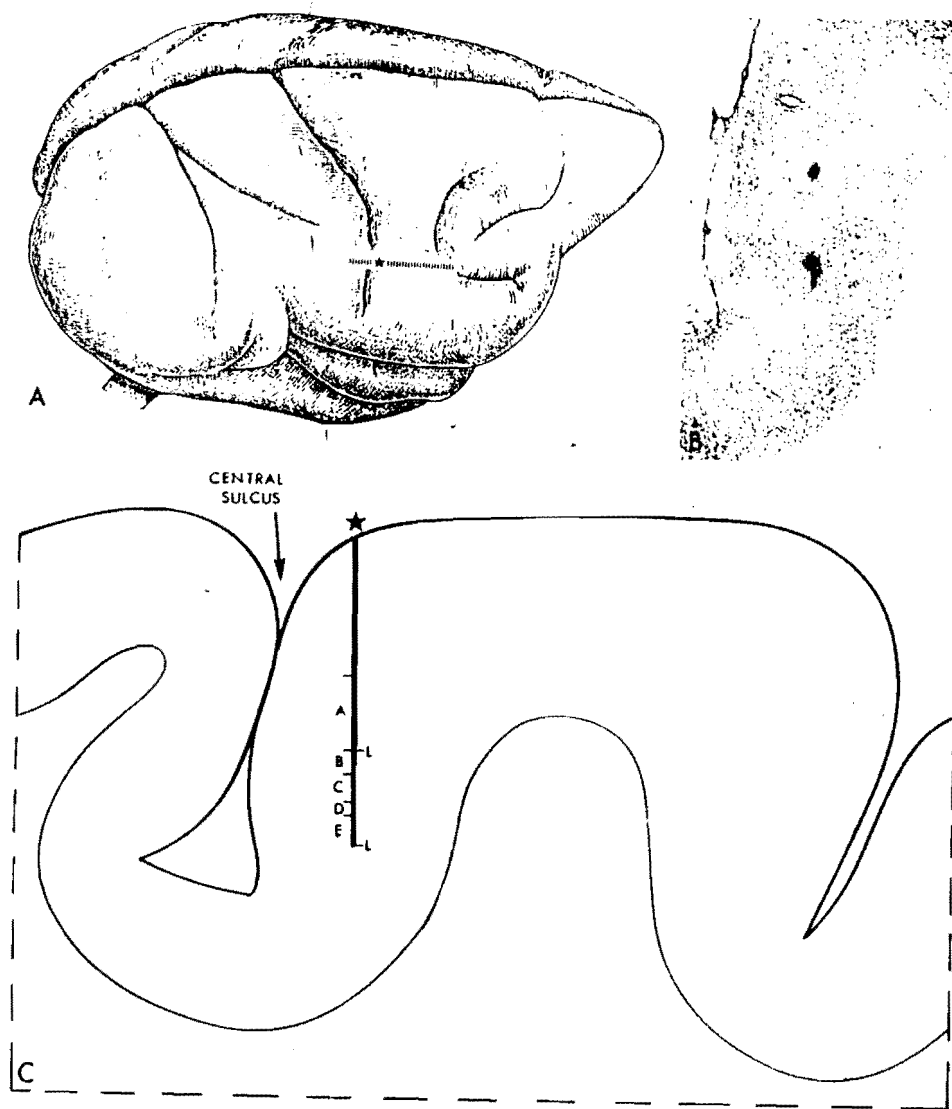


Fig. 2. The histological reconstruction of a central sulcus penetration from Herc. The line across precentral motor cortex shows the location from which the section was taken, the star indicates the site of the electrode penetration. Letters on the left of the penetration in the line drawing of a brain section correspond to responses shown in Figure 3. The L's on the right indicate the locations of lesions which can also be seen in the photomicrograph of the same section in the upper right hand corner.

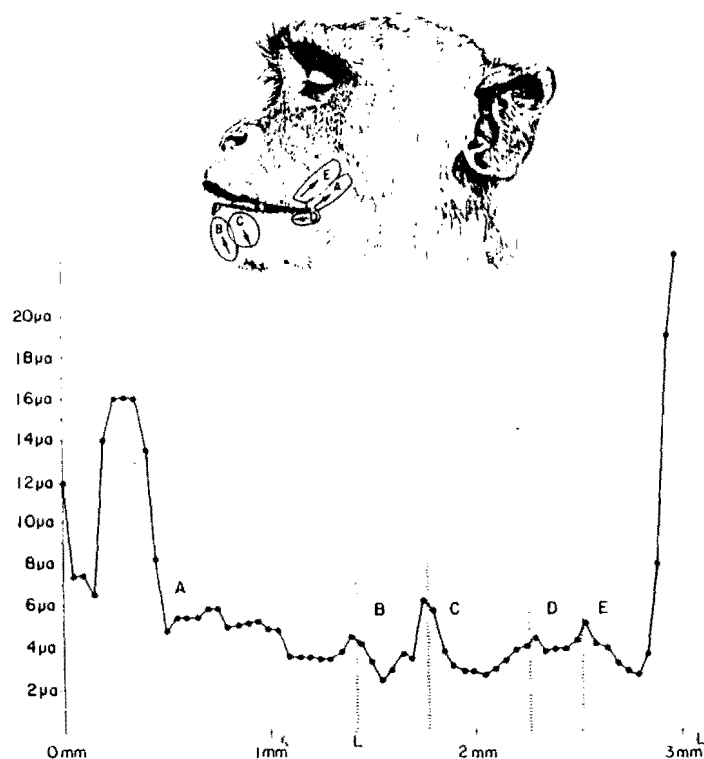


Fig. 3. A response-by-depth curve for the penetration shown in Figure 2. Each filled circle indicates a responsive site. The abscissa is current threshold in microamperes. The lettered responses drawn on the face correspond to the letters above the line in the graph. Hatched lines were used to indicate the point at which the response changed.

There was a diagonal band of jaw responses which began at the lateral extent of the central sulcus penetrations and cut across the surface of the gyrus in the anterior medial direction. This is best seen in the map for F-4 in Figure 8. Again the pattern could result from either long narrow bands or non-contiguous sites.

Threshold by muscles

Figure 10 shows the thresholds for responses of the three major muscle groups in the face. The number of responses by thresholds of individual mimetic muscles are shown in Figure 11. There are considerable differences in frequency with which different muscles were encountered. Two muscles, zygomaticus and orbicularis oris, accounted for more than half of the mimetic responses and comprised 29% of all

responses reported in these tables. Although threshold distributions varied for the different mimetic muscles, in only one case, caninus, were more than half of the responses over 10 μ A.

Motor cortex boundaries

The motor-somatosensory boundary was readily defined physiologically in several animals. In both F-5 and Herc in penetrations down the anterior wall of the central sulcus, we reached a point beyond which microstimulation at current levels under 25 μ A would no longer elicit an observable movement of the face. In two such penetrations in each animal lesions were made at this point, and we were able to verify histologically that the electrodes were still in the gray matter. One of these

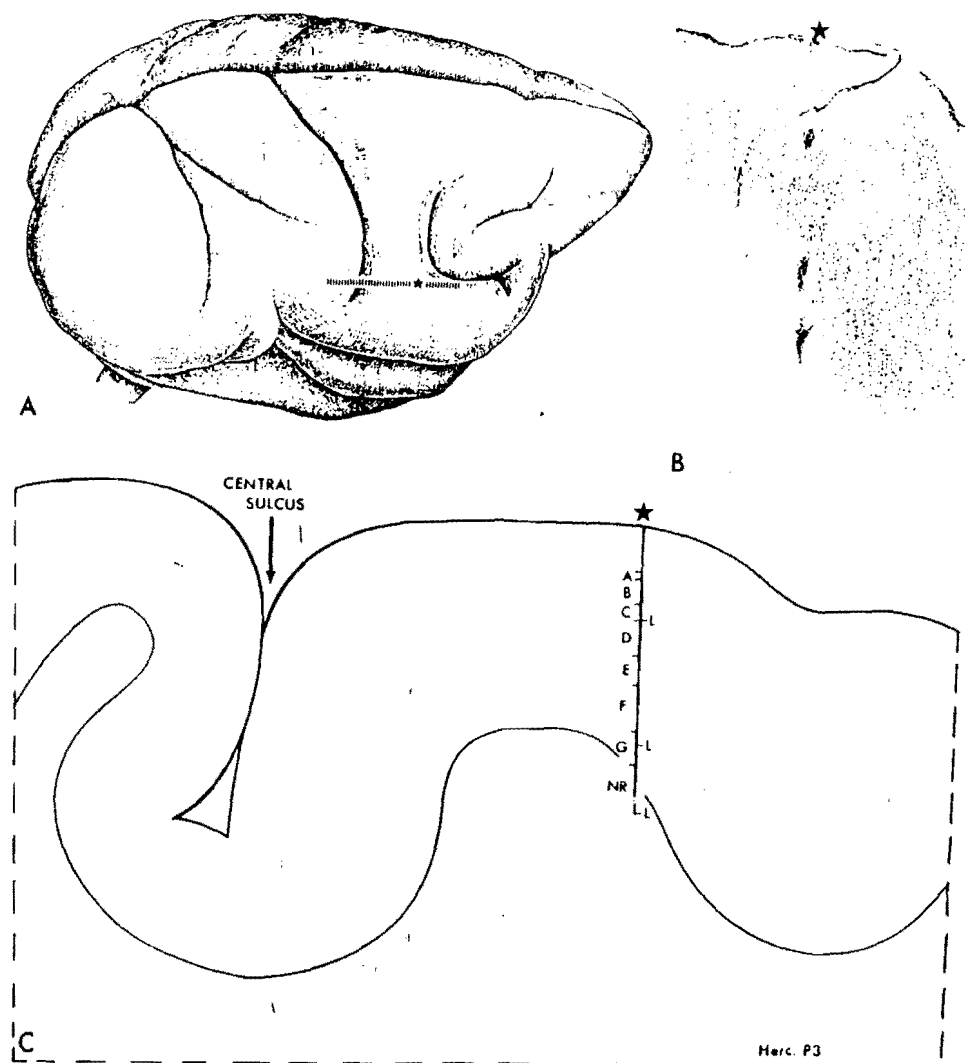


Fig. 4. The histological representation of an arcuate sulcus penetration from Herc. The line across precentral motor cortex shows the location from which the section was taken; the star indicates the site of the electrode penetration. Letters on the left of the penetration in the line drawing of a brain section correspond to responses shown in Figure 5. The L's on the right indicate the locations of lesions which can also be seen in the photomicrograph of the same section in the upper right hand corner.

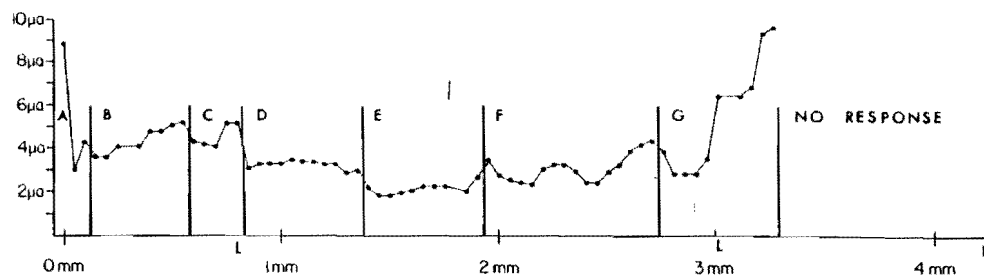


Fig. 5. A response-by-depth curve for the penetration shown in Figure 4. Each filled circle indicates a responsive site. The abscissa is current threshold in microamperes. The lettered responses drawn on the face correspond to the letters above the line in the graph. Response (i not illustrated) was on the tip of the tongue. Hatched lines were used to indicate the point at which the response changed.



Fig. 6. Photomicrograph of a penetration in the center of the precentral gyrus of F-4, parallel to the radial fibers. L's are located next to the lesions in the penetration for which responses are shown in Figure 7. The star indicating the point at which the electrode entered the brain corresponds to the star on the brain drawing in Figure 7.

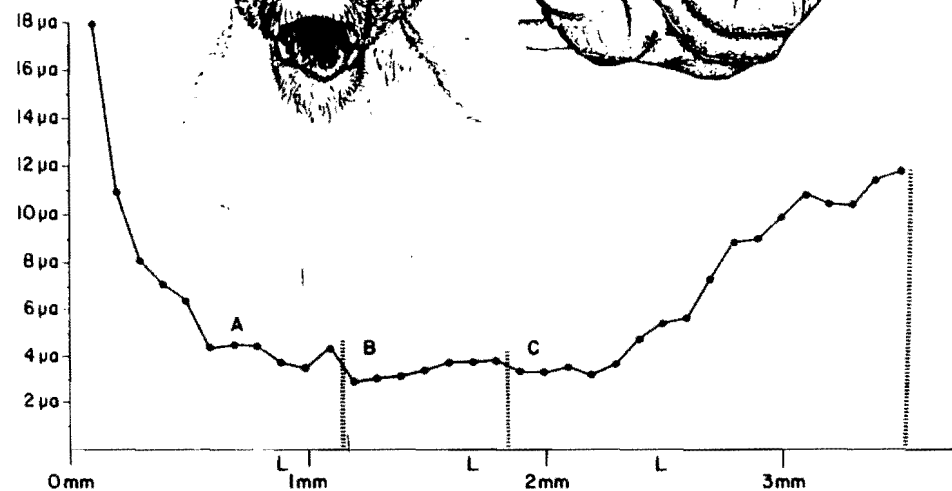
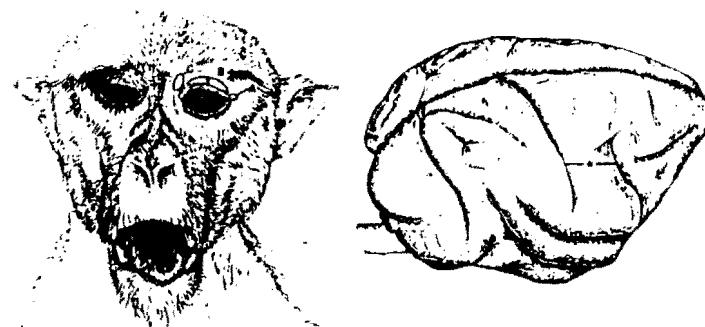


Fig. 7. A response-by-depth curve for the penetration shown in Figure 6. Each filled circle indicates a responsive site. The abscissa is current threshold in microamperes. The lettered responses drawn on the face correspond to the letters above the line in the graph. Hatched lines were used to indicate the point at which the response changed. The star on the brain drawing to the right indicates the point at which the electrode entered the brain. The hatched line on the brain drawing indicates the location from which the brain section shown in Figure 6 was taken.

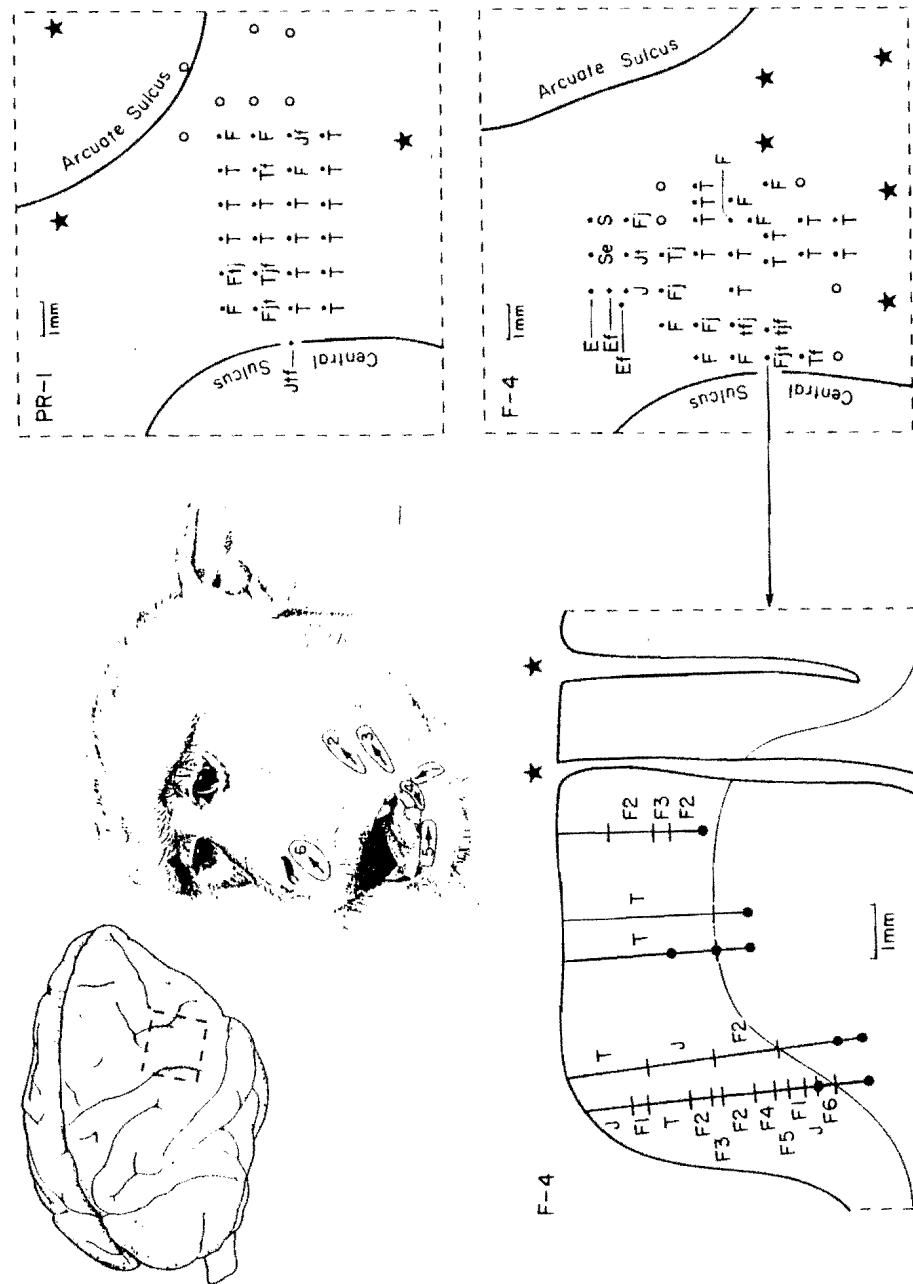


Fig. 8. Penetrations from the two monkeys for which we have the most complete maps are plotted on the surface of brain photographs. The outlined shaded region on the drawing of a complete brain shows the location from which the enlarged insets were taken. On the brain maps F indicates responses were mimetic muscles in the lower face; E, eyelid; T, tongue; J, jaw; and S, shoulder. Multiple letters are used when more than one type of response was seen in a single penetration. In these cases a capital letter indicates a response elicited from more than half of the stimulation sites in the penetration, and lower case letters are used for response types elicited from less than half of the sites. Stars indicate marker electrode penetrations and open circles indicate no response penetrations. The brain section on the left shows a row of responses from monkeys F-4 in greater detail. The mimetic muscle responses are designated F-1, F-2, etc.

penetrations is illustrated in Figures 2 and 3. Cytoarchitecturally the motor-somatosensory boundary is difficult to define exactly (Jones et al., '78). In other animals the motor-somatosensory boundary appears to be somewhat lower on the sulcal wall, presumably in the region of the fundus of the central sulcus. In penetrations in these animals we encountered the white matter before running out of motor cortex. The anterior boundary was more difficult to define. We have fewer penetrations anterior, and since area 6 is also readily excitable (Woolsey et al., '50; Kwan et al., '78), we could not confirm the border physiologically.

DISCUSSION

Our major finding is the additional evidence for efferent zones less than 1 mm across in motor cortex. By moving the electrode in steps of 50 or 100 μ m in sulcal penetrations we were able to plot threshold by depth curves across the cortical zone devoted to a given muscle response. In such cases near the center of a zone where thresholds were lowest one was presumably exciting the maximal number of neurons projecting to a motor neuron pool in the facial nucleus activating that muscle. As the electrode approaches the edge of a zone one is able to activate a smaller proportion of the neurons projecting to a given pool of motor neurons and threshold increases.

The region from which one activates equal numbers of neurons projecting to two different motor neuron pools is presumably quite small since we were seldom able to activate two responses with threshold current levels, even moving in 50 μ m steps. We were unable to test for inhibitory effects with the preparation we used.

The discreteness of responses and the lack of overlap supports the view that current spread from microstimulation is quite limited. Certainly at current levels under 5 μ A we are confident that we were exciting a very limited region of cortex. Particularly at the low currents, thresholds were quite sharply defined. Often an increase in current of 0.1 μ A was sufficient to

change from a state in which there was no observable response to a state in which there was a response elicited by each stimulus train. Responses were so sharply defined that we would have had considerable difficulty finding a point at which a response occurred 50% of the time had we attempted to use that definition of threshold. Low threshold responses appeared to be all-or-nothing events.

Our data suggest the basic organization of motor cortex to be narrow efferent zones devoted to individual muscles which are grouped together, possibly within larger movement patterns. We do not think such movement patterns could represent complete facial expressions. The data are compatible with the idea that small groups of muscles which act together to form one component of such patterned movements are represented together in cortex. There are two possible arrangements of efferent zones. They could be either more or less cylindrical, or narrow mediolaterally oriented bands that the electrode intersected at different points in cortex. Such bands could also be multiply represented in cortex and could be of varying lengths. At this point the data are compatible with either hypothesis and we cannot reject either on the basis of microstimulation data.

We consider the predominant organization of motor cortex to be columnar, but we do not mean to imply that all efferent neurons in a given zone of cortex project only to neurons in the facial nucleus activating the muscle which moves when the zone is stimulated. The question of columns is not easily answered by microstimulation alone. Our data strongly suggest a mosaic of discrete efferent zones. The vertical component of cortical organization is less clear since our electrodes never traversed cortex exactly parallel with the radial fibers. It is a fundamental limitation of the technique that when stimulating at threshold currents one observes only the dominant effect. It has been suggested that by stimulating at higher currents one could obtain a clearer picture by also activating minority populations of neurons (Andersen et al., '75). Stimulating with such

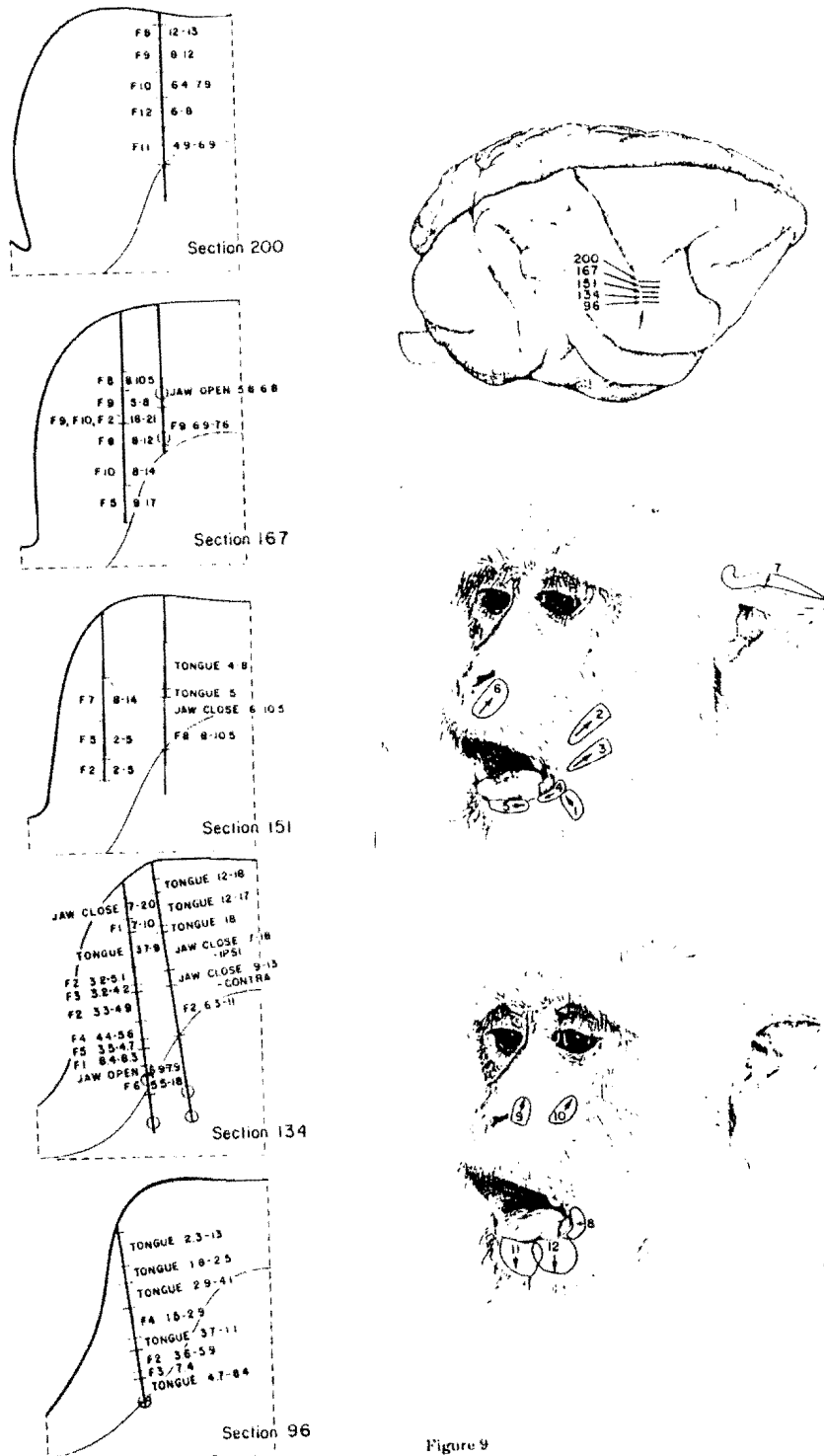


Figure 9

currents as low threshold points tends eventually to activate adjacent muscles if one uses a high enough current. Since adjacent muscles on the face tend to be represented in adjacent regions of motor cortex it is difficult to ascertain whether additional movements are being elicited by activation of a minority population of neurons in the same zone which activates the initial muscle movement or whether recruitment of a second muscle is due to current spread to adjacent regions of cortex. Given that the zones we have found stimulating with threshold currents are extremely narrow (usually much less than a millimeter), it is difficult to see how one could stimulate with higher currents without activating adjacent zones. In addition one has the problem that excessively high currents (over $40 \mu A$) cause damage in motor cortex (Asanuma and Arnold, '75). It may be possible using other techniques to give a more complete picture of which muscles are related to neurons in a given region of cortex. Results from microstimulation cannot exclude the possibility that there are neurons related to muscles other than the observed response intermingled within an efferent zone.

The fine organization of the narrow efferent zones is embedded in a larger macro-organization. In the face region the mimetic muscles fall into an anterior and a posterior cluster separated mainly by the tongue. The mimetic muscles may be continuous at the medial extent of the region. There is a suggestion of a narrow strip of continuous mimetic muscles across the medial edge of the face region where the eyelid movements are represented. Our results might best be characterized as two representations of the facial muscles which are roughly mirror symmetrical around the tongue and possibly the eyelid. Given the narrowness of efferent zones devoted to any given muscle, sampling problems make it difficult to be certain of the precise progression with penetrations 1 mm apart.

Several recent studies on the forelimb representation in macaque and squirrel monkey have some bearing on the issue of multiple representation of muscles. Kwan et al. ('78) have found in macaques multiple representation of individual muscles in the forelimb region. They describe the macro-organization to be one of nesting around joints with digit within wrist within shoulder. This clearly cannot be true of the face, where there is only one joint, and mus-

cles, other than those of mastication, act principally against each other and to move skin. One does not see a single map of either the face or forelimb, but rather clusterings of adjacent muscles. In the face region we find the mimetic muscles separated into two clusters by tongue, whereas Kwan et al. report the joints form loosely concentric rings in the forelimb region.

Strick and Preston ('78) have found a slightly different form of multiple representation in the squirrel monkey motor cortex. They see a progression from wrist to digit, back to wrist, and again to digit, when moving across cortex in posterior to anterior rows. This is somewhat different from macaque, where the individual muscles are represented at a number of points in motor cortex in a more scattered fashion. The basic principle is similar to our clusters, although the dual representation in the squirrel monkey hand and wrist region alternates, whereas in the macaque face region the representations appear to reverse at the midline.

It is difficult to accept that the basic pattern of organization in macaque motor cortex would differ radically for the forelimb and the face. It is quite possible that there is a dual cluster pattern in the forelimb region which is somewhat masked by the nesting reported by Kwan et al. The nested organization they describe could easily occur within two clusters. The actual data shown by Kwan are not incompatible with this. Zant and Strick ('78) have presented anatomical evidence for macaque showing that the digits at least are found in two separate loci. Should this be confirmed physiologically it would bring the macaque forelimb into accord with both macaque face and squirrel monkey hand.

Somatosensory—Motor comparisons

Somatosensory cortex has been shown to contain a number of complete somatotopic representations in a number of species of primates (Paul et al., '72; Merzenich et al., '78; Kaas et al., '79). The region spanning cytoarchitectural areas 3a, 3b, 2, and 1 traditionally called S1 contains at least three complete representations and possibly a fourth, although the organization of 3a is still somewhat ambiguous (Kaas et al., '79). Each complete map of the body corresponds to one cytoarchitectural area. Although there are discontinuities, the organization within each area is basically topographical. For macaque there is some discrepancy as

Fig. 9. A series of sections in medio-lateral sequence showing penetrations down the anterior wall of the central sulcus in monkey F-4. Numbers on the brain correspond to section numbers and indicate the locations from which sections were taken. F indicates a mimetic response, and the number following it corresponds to the response shown on the drawing of the monkey's face. The number after each response indicates the ranges of thresholds found for that response in microamperes.

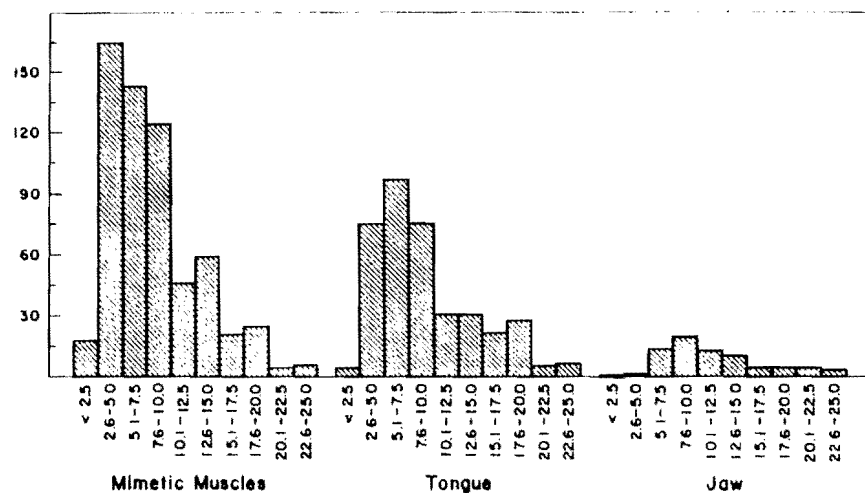


Fig. 10. Bar graphs showing the number of responses by threshold currents in microamperes for categories of muscle responses.

to the precise organization. Paul et al. ('72) found an alternating pattern in 3b and 1 with the distal hand in area 1 adjoining the proximal hand in 3b, while a more recent study (Kaas et al., '79) found a mirror reversal at the 3b-1 border. In owl monkey Merzenich et al. ('78) report a mirror image representation with a reversal at the 3b-1 border; part of the face representation was explored and a reversal is reported at the midline of the upper lip. The overall progression we see in the face region of motor cortex, going from mimetic muscles to tongue back to mimetic muscles, appears to be somewhat similar.

Some caution must be used in comparing motor cortex to somatosensory cortex. In the motor system the muscles themselves are discontinuous; thus topographical order in motor cortex must be affected by the necessity of representing discontinuous and in the face region extensively overlapping muscles on a basically two-dimensional surface. This difficulty also occurs in area 3a of somatosensory cortex where the afferents from the muscles are represented (Kaas et al., '79).

Facial muscles

Examination of the patterns of innervation illustrated in Huber ('33) suggests that when a single muscle is innervated at several points the cortex treats each branch as a discrete unit.

It may be appropriate to consider cortical representation of the face as organized by groups of neurons projecting to a facial nucleus motor neuron pool innervating a specific branch of the facial nerve rather than a specific muscle. Orbicularis oris, zygomaticus, and orbicularis oculi are all instances of morphologic muscles that act as several muscles both in terms of innervation patterns and discrete responses.

We think that the amount of cortex devoted to a given muscle may reflect frequency and intensity of the use of a muscle in normal behavior. The large representation of zygomaticus is particularly impressive since it is a purely mimetic muscle, unlike orbicularis oris and the jaw muscles, which are used in eating and drinking as well as emotion. The major function of zygomaticus is retraction of the corners of the mouth and side of face. This is a striking feature in both fear and anger expressions with intensity of the muscle contraction related to the intensity of the emotion.

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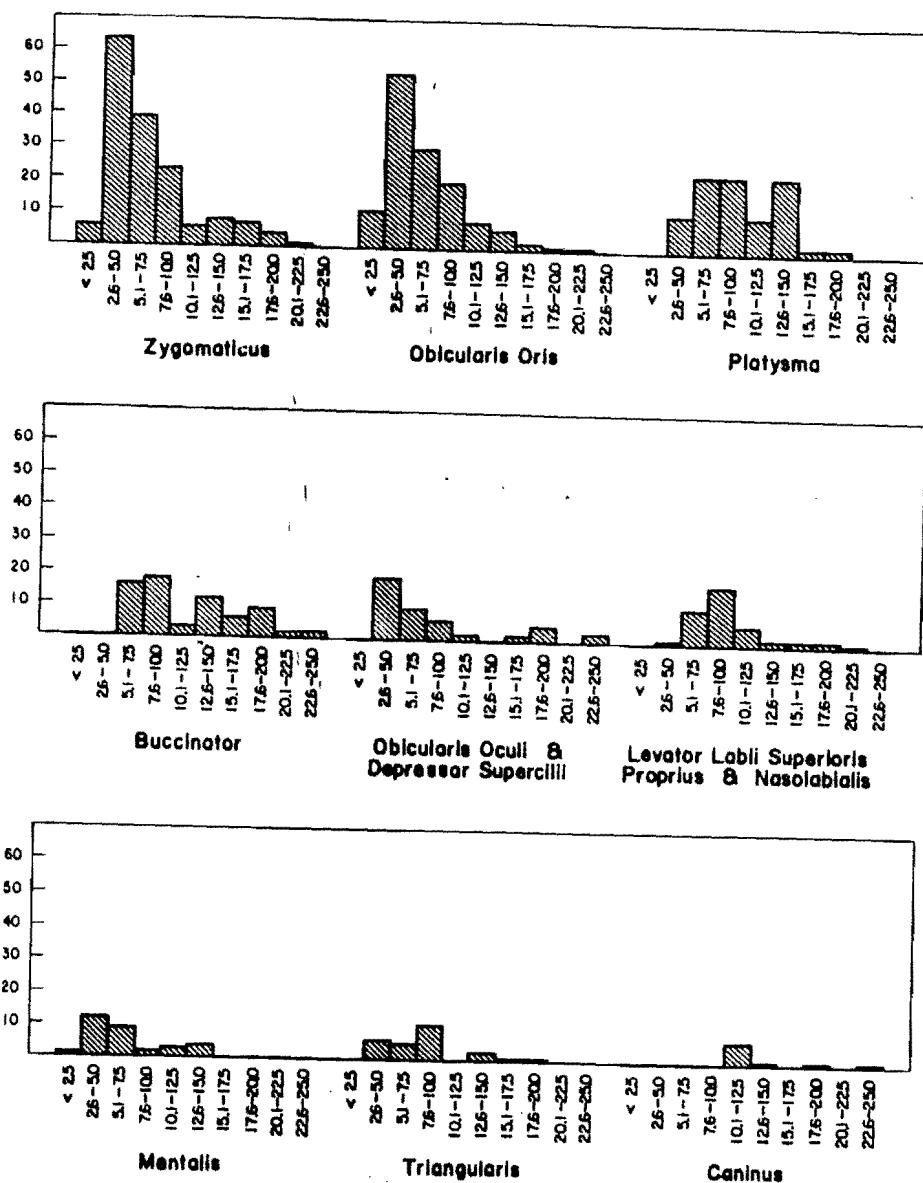


Fig. 11. Bar graphs showing the number of responses by threshold current levels in microamperes of individual mimetic muscles. In two cases muscles have been combined. Orbicularis oculi and depressor supercilii are shown together because the two muscle groups are closely related and work together functionally in moving the eyelid. Levator labii superioris proprius and nasolabialis were sometimes difficult to distinguish from one another; the majority of the points shown we considered to be levator; only six were definitely identified as nasolabialis. Although levator is the deeper muscle, thresholds for the unambiguous levator points were lower than the unambiguous nasolabialis points. In mode of action both tend to raise the muzzle region and side of the nose, nasolabialis extending across the bridge of the nose and levator attaching to the lower portion of the orbit at two loci. Since we had comparatively few points for either muscle, rather than discard the ambiguous responses we combined the two muscles.

grammable stepping motor microdrive. We also thank Leslie Wolcott, who drew the illustrations, and Betty Hanson, who typed the manuscript. The research was supported by a grant from the Pew Charitable Trusts and research funds from the California Institute of Technology. J.M.A. was supported by U.S.P.H.S. Career Development Award NS-00178.

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The Primate Cochlear Nuclei: Loss of Lamination as a Phylogenetic Process

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ABSTRACT In primates from prosimians to hominoids (lorisoid prosimians, marmoset and ceboid monkeys, cercopithecoide monkeys, and gibbon), there are differences in the location, depth, and extent of the granular layer of the cochlear nuclei. In the prosimians, the deep granular layer of the DCN is similar to that of other mammals, but there is, in addition, a superficial or subependymal layer of granule cells in the DCN. In ceboid and cercopithecoide monkeys, only a superficial or external granular layer is present in the DCN, and the granular layer over the VCN is much reduced. In the gibbon, there is no granular layer in either of the cochlear nuclei. In conjunction with the progressive reduction of the cochlear granular layer in primates, fusiform cells lose their position as a radially oriented peripheral cell layer in the DCN and become located in the central region of the nucleus. These changes in primates are interpreted as resulting from failure of inward migration and increasing cell death in the ontogeny of the cochlear external granular layer, with concomitant changes occurring in the position and orientation of their target neurons, the fusiform cells.

The structure of the outer portion of the cochlear nuclei in most mammals is that of a modified laminar cortex, most closely resembling that of the cerebellar cortex. The dorsal cochlear nucleus (DCN) is covered by a molecular layer, deep to which is a cellular layer of radially oriented fusiform neurons lying in a dense band of granule cells. The granular layer continues anteriorly to form a superficial granular layer over the ventral cochlear nucleus (VCN), though it lacks both a molecular layer and associated macroneurons in this nucleus (Webster et al., '68; Osen, '69; Brawer et al., '74). Granule cell axons from both the dorsal and ventral nuclei run as unmyelinated parallel fibers to contact the apical dendrites of fusiform cells within the molecular layer of the DCN (Lorente de No, '33; Mugnaini et al., '79a,b).

In the human cochlear nuclei, there is a complete and selective loss of these peripheral layers of the nuclei—that is, of the molecular and fusiform-granule cell layers of the DCN and of the granular layer of the VCN—while deeper parts of the nuclei remain comparable in their cytoarchitecture to the corresponding regions in other mammals (Dublin, '76; Moore and Osen, '79a,b). In the present study, ex-

amination of the brains of a number of adult primates reveals that there exist, in the various groups of primates, transitional stages between the full development of a cochlear granule cell system and a laminar cytoarchitecture, as is seen in nonprimate mammals, and the complete absence of this cell group and lamination, as is the case in man.

MATERIALS AND METHODS

The cytoarchitecture and myeloarchitecture of the cochlear nuclei was studied in normal brains of the primate species listed in Table 1. In each case, the animal was perfused transcardially with 0.9% saline, followed by 10% formalin solution. The brain was removed the following day and stored several days in fixative before dehydration and embedding in celloidin. Two adjacent series of 30 μ m sections, every third to tenth section depending on the size of the brain, were stained with cresyl violet and Woelcke's hematoxylin, re-

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