SOMATIC MOTOR AND SENSORY REPRESENTATION IN THE CEREBRAL CORTEX OF MAN AS STUDIED BY ELECTRICAL STIMULATION.[1]

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(1) INTRODUCTION.

RECENT experimental work on the localization of motor function in the cerebral cortex has spurred us to make a complete analysis of the records of our patients (163 in all) upon each of whom we have carried out electrical exploration of the cortex under local anæsthesia.

[1] From the Montreal Neurological Institute and the Department of Neurology and Neurosurgery of McGill University, Montreal. Read before the American Neurological Association, Atlantic City, June 4, 1937.

This has led us to conclusions which differ somewhat from those published by other observers in regard to the localization both of sensory and motor function. *Often we have found it impossible to confine* functional representation within strict cytoarchitectural boundaries. The human cortex shows definite differences from that of other mammals and human pathological processes introduce important new elements.

(2) Historical Note.

Flourens (1842) carried out experimental removals of areas of brain and concluded that up to a point any part of the cerebral hemispheres could quite adequately exercise the function of the whole. This attitude, which bears some resemblance to that recently adopted by Lashley (1929) was considered to deny the possibility of circumscribed localization of function in the brain.

Broca (1861) gave the most effective impetus to the search for localization of function when he described an area of the left hemisphere of man as a specialized speech centre. Hughlings Jackson (1864) noted an association between speech defect and right sided chorea, saying that he saw "no more difficulty in supposing that there are certain convolutions superintending those delicate movements of the hands which are under the immediate control of the mind, than that there is one, as Broca suggests, for movements of the tongue in purely mental operations."

To Fritsch and Hitzig (1870) must be given credit for the first successful, controlled direct electrical stimulation of the mammalian cerebral cortex. By applying galvanic current through bipolar electrodes to the anterior half of the dog's hemisphere they obtained movements of muscle groups in the opposite half of the body. From the posterior part of the brain they secured no motor movements. Their map contains five motor points. Jackson was jubilant at this verification of his hypotheses and said (1873) the work of these experimenters demonstrated "that discharge of convolutions develops movements, notwithstanding that destruction of limited parts of the brain produces no obvious loss of movements."

Ferrier quickly took up the work in England and in 1876 published the results of repeated cortical stimulation in several species. Using a faradic current he obtained movement from points behind the Sylvian fissure, results which were roundly criticized by Hitzig. Nothnagel (1873), Hitzig (1874), Schiff (1875) and Hermann (1875) thought that the cortical centres were really sensory centres for "muscle sense," to use the words of the first two.

Dupuy (1873), Sanderson (1874) and Carville and Duret (1875) agreed that spread of current, principally to subcortical centres, accounted for the movements recorded. With this Ferrier (1876) could not agree, but he did admit that motor response might be an expression of sensation and that the character of the sensation might determine the nature of the movement. Although their work dealt chiefly with cortical removals, Luciani and Tamburini (1879) and Munk (1890) added confirmatory evidence to the sensorimotor conception of the Rolandic area.

In 1888 Dana reported 142 cases of sensory disturbance in man associated with cortical paresis. He observed that all cases of cortical anæsthesia were associated with some amount of paralysis.

Horsley and his collaborators conducted a minute examination of the motor area in apes. Beevor and Horsley's map of the cortex (1890) showed that there were motor points anterior and posterior to the Rolandic fissure, and overlapping of cortical areas. Bilateral innervation, they found, was confined to mouth and throat movements. In the higher apes they found inexcitable spaces among the normal areas of the pre-Rolandic cortex.

In 1894 Mott summarized the attitude of the three camps with divergent views on Rolandic cortex function. Ferrier, Schafer and Horsley believed the area to be purely motor. Schiff was certain it was purely sensory. Hitzig, Bastian, Bell, Wundt, Hughlings Jackson, Munk, Tripier, Luciani and Mott would call it sensorimotor. Sensory information in animals, of course, could be obtained only by extirpation experiments. Although it was not then clearly established, the idea of a sensorimotor cortex was generally held.

It was the work of Grünbaum and Sherrington (1901, 1903) which, according to Dusser de Barenne (1935), caused the change of opinion from the idea of sensorimotor cortex to the conception of a pre-Rolandic motor cortex separate from the sensory region. They worked with a unipolar electrode using weak currents to avoid seizures. The animals, however, were under general anæsthesia. In anthropoids, under those conditions, they found the excitable cortex to be limited to the precentral gyrus (fig. 1). This gyrus in anthropoids contains Areas 4 and 6.

In no case did they find primary motor response postcentral to the fissure of Rolando. They obtained discrete movements of ear, nostril, palate, lips, jaws, vocal cords, chest and abdominal wall, pelvic floor, anal and vaginal orifice as well as of the extremities. They found the insula to be inexcitable even with strong currents and were unable to obtain vocalization. Conjugate movements of the eyes to the opposite side were obtained by stimulation in the frontal lobe and the occipital pole in regions (fig. 1) which must have corresponded roughly to Area 8 and Area 17 of Brodmann. Grünbaum and Sherrington found that postcentral removal produced no paresis and precentral extirpation caused a severe, but rapidly diminishing paralysis of the movements which electrical stimulation of that area had previously produced. They

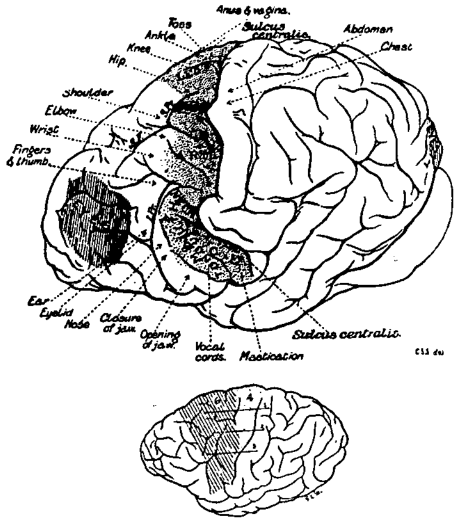


FIG. 1.—Results of cortical stimulation in the chimpanzee above (from Grünbaum and Sherrington, 1901). Cytoarchitectural localization of Areas 4 and 6 in the chimpanzee below (from Bucy, 1934). Comparison of the figures indicates that the isolated movements found by Grünbaum and Sherrington were not confined to Area 4 in the arm and face areas. Eye movements only were found from the detached frontal lobe centre. The same was true of the occipital centre for eye movement. Movement points end abruptly at the central fissure.

observed that the response from a cortical point might be "influenced by the particular forms of movement excited from neighbouring points just antecedently." They pointed out that a cortical point was, therefore, to some extent unstable and that by preliminary precentral stimulation a response from the post-central gyrus could be elicited. This process they called "facilitation." Graham Brown alone and with Sherrington followed up this problem at a later date (Brown, 1915, 1916), and showed that a spot stimulated might be sensitized by facilitation and that an echo response of secondary facilitation might be produced in a neighbouring point in the postcentral gyrus (activation). Furthermore, Graham Brown and Sherrington showed that a response might be qualitatively changed, i.e. from flexion to extension. This they called " reversal."

O. and C. Vogt combined careful cytoarchitectural studies with animal stimulation and produced for the monkey a map which resembles those of Grünbaum and Sherrington. By means of their cytoarchitectural studies of the human cortex they prepared a map of the human cortex and transferred functional localization points to it (1926). This map (fig. 2) corresponded to an extraordinary extent with that which

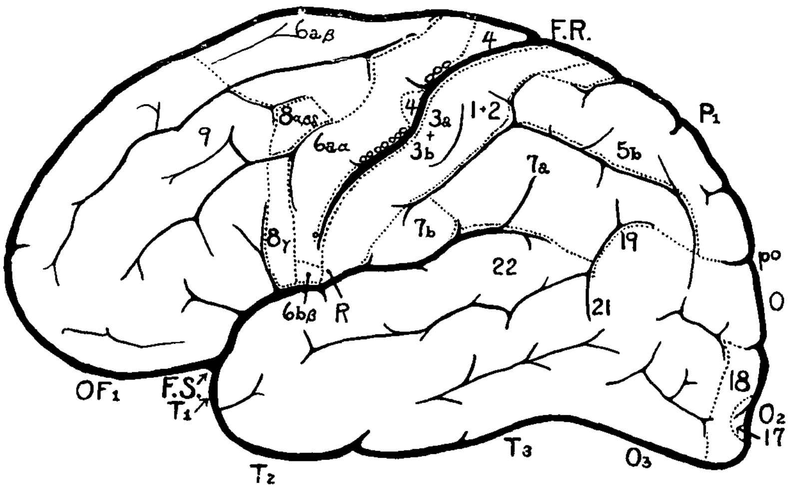


FIG. 2.—Cytoarchitectural fields of human cortex after Vogt and Vogt (1926). The functional interpretation is deduced by them from the homologous fields in monkey. F.R. = fissure of Rolando. F.S. = fissure of Sylvius. p.o. = parieto-occipital fissure. R. = respiration. 4 = true pyramidal cortex or "primary field for tonic specialized movement." 6*a alpha* = "secondary field for tonic specialized movements" which acts upon the primary field by conduction along the outermost layers of the cortex ; 6*a beta* = tertiary field where stimulation most easily causes turning of eyes, head, ears and body to opposite side (adversive movements); stronger stimulation gives movements of both upper and lower extremities ; 8 *alpha, beta, delta* = field from which adversive eye movements were most easily produced ; field 3*a*, 3*b*, 1 and 2 = postcentral convolution producing movement by action upon field 4. 5*b*, 7*a* and 7*b*, all produce adversive movements with strong stimulation ; 19 (also 17 and 18) = adversive eye movements : 22 = ear and eye adversive movements ; 6*b* = mastication.

Foerster prepared for man as the result of stimulation of patients, as indicated in the Vogts' publication just cited.

Recently Fulton (1936) and his associates, working upon monkeys and anthropoids, and using the fields of Brodmann and Vogt (fig. 2), have urged that the motor representation in the cerebral cortex is made up of: (*a*) motor area or Area 4 of Brodmann which gives origin to the pyramidal tract ; and (*b*) a "premotor" area made up of (i) Brodmann's Area 6*a alpha*, which together with Area 4, composes the precentral gyrus in man; and (ii) Brodmann's Area *6a beta* which in man lies anterior to the upper end of the precentral gyrus. Fulton used the term "extrapyramidal" motor cortex to indicate all of the cortex which might be motor in addition to Area 4.

The evidence from the study of human cases may be summarized as follows:—

Roberts Bartholow, an American surgeon of Cincinnati, is credited by Beevor and Horsley (1890B) with being the first to stimulate the human brain directly. It is true that Hitzig (1870A) had preceded his animal experimentation by indirect galvanic stimulation of the occipital region of a man, thus producing eye movements. The account of Bartholow (1874) is interesting to say the least and may be cited.

His patient was a 30-year old-domestic. As an infant this unfortunate had chanced to fall into the fire, burning her scalp so badly that "hair was never reproduced." A piece of whale bone in the wig she was forced to wear irritated the scarred scalp and, by her statement, three months before she was admitted, an ulcer appeared. When she presented herself for relief, this had eroded the skull over a space 2 in. in diameter "where the pulsations of the brain are plainly seen."

Although "rather feeble-minded" Bartholow observed that Mary returned replies to all questions and no sensory or motor loss could be made out in spite of the fact that brain substance apparently had been injured in the process of evacuation of pus from the infected area. The doctor believed, therefore, that fine insulated needles could be introduced without further damage.

First he observed that no pain was experienced from the brain substance proper and that mechanical irritation yielded nothing. Faradization of the dura "with the least possible current" produced muscular contractions of the opposite arm and leg, and head turning to the opposite side.

One of the needles was then passed into "the left posterior lobe so that the non-insulated portion rested entirely in the substance of the brain," the other needle resting on the dura. There was produced a muscular contraction of the right upper and lower extremities with "faint contraction of the orbicularis palpebrarum and dilatation of the pupils." She also complained of a "strong and unpleasant tingling in both opposite extremities, especially the arm, which she seized with the opposite (left) hand and rubbed vigorously." A similar manœuvre on the right side produced similar results.

While the electrodes were in the right side Bartholow decided to try the effect of more current. "Her countenance exhibited great distress and she began to cry. Very soon the left hand was extended as if in the act of taking hold of some object in front of her; the arm presently was agitated with clonic spasms; her eyes became fixed with pupils widely dilated; the lips were blue and she frothed at the mouth; her breathing became stertorous, she lost consciousness and was violently convulsed on the left side. This convulsion lasted for five minutes and was succeeded by coma. She returned to consciousness in twenty minutes from the beginning of the attack and complained of some weakness and vertigo." Three days after this stimulation, following a series of right-sided seizures, the patient died.

Sciamanna's results in 1882 were similar (see Beevor and Horsley, 1890B). Horsley (1887), Keen (1888), Nancrede (1888), Lloyd and Deaver (1888), Parker and Gotch (1893) and Bidwell and Sherrington (1893) corroborated in the human the motor responses previously obtained from the motor cortex of animals. In 1892 Ransom stimulated the cortex of a conscious patient and produced both sensation and movement.

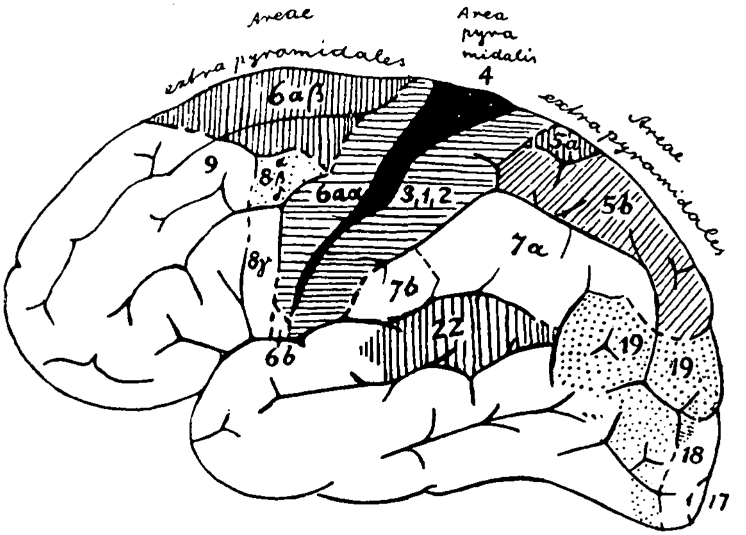


FIG. 3.—Extent of motor cortex in the human brain, after Foerster (1936). The cortical areas for motor response to electrical stimulation are outlined. The numbers refer to the cytoarchitectural fields of the Vogts described in fig. 2. Mass movements and adversive movements are reported from the extrapyramidal areas including 6*a beta*, 5 and 22. Movements from the pyramidal area are distinctly isolated in character. The extrapyramidal system produces mass movements of the opposite side, according to this author.

Cushing (1909) was the first to produce sensation without movement in man. He stimulated the postcentral gyrus of two conscious patients each of whom reported sensations in parts corresponding with areas where movement could be produced from analogous precentral regions. Van Valkenburg (1914) corroborated these findings.

Foerster (1936A and B), as the result of stimulating the human cerebral cortex, chiefly under local anæsthesia in cases of focal epilepsy, widely extended the motor cortex (fig. 3). He pointed out that the "precentral areas are chiefly motor and the postcentral convolution is chiefly sensory," but he included the postcentral convolution as motor in a sort of secondary category.

In general agreement with Fulton, Foerster added a frontal extra-pyramidal motor area ("6*a beta*"), a parietal extra-pyramidal area ("5") and a temporal extrapyramidal area ("22"). He stated that even in the absence of the pyramidal zone 4 these areas (as well as Area 6) were capable of producing a mass movement of the opposite side of the body when stimulated strongly by a faradic current. In the intact brain the post-central gyrus was able to produce isolated movements with a higher threshold than the precentral, but when Area 4 was absent this response ceased and only the mass movement described above was produced.

(3) CLINICAL MATERIAL.

The observations reported here were made during operations carried out since 1928 by one of us (W.P.).[1] Of the 163 operations in which cortical stimulation was carried out, 126 proved to have records suitable for the present analysis.

In general, stimulation was only carried out in any operation when there was therapeutic justification for it. In some instances it was used to define the motor area of the hemisphere so that an infiltrating tumour could be removed as widely as possible without producing paralysis. More frequently stimulation was made use of as a preliminary to radical extirpation of an epileptogenic focus and as an aid in searching for that focus. The actual therapeutic results of such operations are completely summarized elsewhere (Penfield, 1936).

However, in the therapeutic approach, it should be pointed out that only very rarely has the Rolandic area been included in any excision and never has this region of the brain been touched unless a lesion was present that could be demonstrated grossly by operative inspection. This digression is made in the hope of discouraging surgical removal of normal brain from the Rolandic area, or elsewhere, whatever may have been the pattern of epileptic seizure.

The operations have been carried out as follows :—

Sterilization of scalp: local injection of nupercaine in solutions of 1 : 1,500 and 1 : 4,000 to which adrenalin is added. The sterile towels are then arranged perpendicularly so that the patient is cool, can see and move freely, and can be observed constantly. The rôle of anæsthetist is most important even though

[1] Thirteen of the reported operations were carried out by our associate Dr. William Cone and are included here by his kind permission.

a general anæsthetic is rarely given, and in all of the records found in this communication we are indebted to our anæsthetist, Miss Mary Roach, who constantly followed the behaviour and movements of the patients as well as their blood-pressure, pulse and general condition through the long and sometimes trying ordeal of electrical exploration of the cerebral cortex.

Osteoplastic craniotomy is used to expose large areas of the hemisphere, and the bone is replaced at the close of operation. The exposed brain is kept warm by the heat of lights focussed upon it, and moistened with Ringer's solution applied with an atomizer.

Stimulation is carried out by either unipolar or bipolar platinum electrodes which emerge from a glass handle and are attached to insulated wires, all of which may be autoclaved. Formerly we used a galvanic current for localizing purposes and a faradic coil to induce seizures. In recent years we have found a thyratron stimulator, similar to that described by Schmitt and Schmitt (1932), much more satisfactory and have usually employed a wave frequency of from 55 to 65 per second. This instrument is to be found now in use in physiological laboratories. It produces a current which resembles the faradic current of an induction coil, but here the thyratron tube filled with mercury vapour acts as the interrupter. The current is thus constant and may be altered accurately in rate and intensity.

It is essential that the patient should be in sympathy with operator and anæsthetist, and it is an interesting comment on the bravery and fortitude of mankind that almost without exception these subjects have gone through the ordeal of operation patiently and intelligently, even when young children. But however great may be their power of introspection, we make it a rule to restimulate all doubtful points without warning. Responses which cannot be reproduced, especially unusual ones, are eliminated.

Beginning with a subliminal stimulus, the strength is increased until a positive response is obtained. The threshold of the postcentral convolution is usually below[1] that of the precentral, although they are often the same. It is usually best to outline the Rolandic fissure thus before exploring further. Each time a positive response is obtained a small square of paper bearing a number is placed upon the brain at that point. These numbers or letters, beginning at 1 or A, indicate the order in which positive responses were obtained.

After outlining the fissure of Rolando the intensity of current is then increased and exploration carried further afield over the cortex. No record of the position of negative stimulations is made.

Details of the electrical exploration are recorded by a running dictated description from the surgeon to a stenographer who is present at this stage of the operation. She records the number of the stimulation, description of the response and the time of each. Photographs are taken in a camera outside the operating theatre through a mirror placed above the operating table (described

[1] Foerster has found the reverse to be the case.

by Hayden, 1936). The surgeon, with sterile paper and pencil, also makes a sketch at the close of stimulation, placing the numbers where he thinks they should fall upon a uniform life-size brain diagram like that employed for the charts in this communication. On this sketch he measures the distance from central fissure and from the fissure of Sylvius for each number.

(4) Method of Analysis.

Auditory, visual and olfactory responses have been eliminated from this report. Analysis of the drawings, photographs and operative notes has been made by one of us (E.B.) as follows:—

A separate summarizing chart was made for each individual movement or sensation produced by stimulation. For example, all movements of the thumb obtained by stimulation in the right hemisphere were placed on one chart with the reference number of each case. Movements of the thumb from the other hemisphere were first charted separately in like manner, and the index finger and other members similarly. When found to be alike the results from the two hemispheres were then combined for each member. Unilateral and bilateral responses were separately recorded.

Each operation in the series was given a number, and as the results were transferred from the operation records to the summarizing charts the operation number was placed beside each of its points, thus making it possible to refer back from the common movement or sensation chart to the operation report if desired. No movement or sensation which was part of a definite epileptiform seizure has been included here as a sensory or motor phenomenon.

In transferring the stimulation points they have been placed on the common chart by reference to photograph and sketch according to their distance from the Rolandic fissure. From above down the points were placed in proper orientation according to the distance from the Sylvian and the median longitudinal fissures. These are the only landmarks on the brain surface which can be recognized with any degree of accuracy. Indeed, the Rolandic fissure can hardly be recognized until after stimulation has identified it. Estimation of position was necessary in a few of the earlier drawings. In the large majority of instances, however, direct measurements and photographs have made the exact topographical localization of the points as accurate as is possible.

In this way 170 summarizing charts were made which have been condensed into the sixteen illustrative charts reproduced here. All results have been transferred to the right hemisphere for the sake of uniformity and brevity.

(5) Illustrative Case.

One operation record may be described here in detail as an example:—

Case 110.—M. G., a girl aged 21, suffering from Jacksonian seizures beginning with a sensation in the left hand. Right osteoplastic craniotomy; nupercaine analgesia, June 9, 1936. An area of abnormal brain was excised, the area being quite small and limited almost altogether to the postcentral gyrus. The procedure has not, alas, resulted in cessation of attacks. The report follows.

"*Objective Findings.*—The dura was under slightly increased pressure and the bone was unusually indurated. There was a scalp scar in the posterior parietal region and a great deal of thickened tissue underneath the scalp, showing that there had been a considerable subaponeurotic hæmorrhage at some time or other. The brain seemed to be normal excepting that the gyri in general were a little small. It was noted that one gyrus was slightly yellow and somewhat flattened and that just below this yellow area the gyrus was extremely narrow; this proved, on stimulation, to be the postcentral gyrus and the actual focus from which the attacks were coming. The extreme narrowing seemed to be slightly below the focus from which the attack could be produced and the narrow area corresponded with the letter "K" which produced sensation in the thumb and running over toward the index finger. This was the most satisfactory response as far as postcentral gyrus was concerned."

"I think that even a greater subdivision of responses could have been obtained if time had been available. The same weak strength of stimulation, namely 24, was used all along the motor gyrus without producing any tendency toward an attack. The three attacks were all produced within a short radius in the abnormal convolution."

"*Procedure.* — A moderate sized osteoplastic flap was turned down posteriorly, the dura was opened and after the electrical exploration an oval incision was made in the brain about the epileptogenic focus. Cutting with thread, the incision was carried down to a depth of about $1\frac{1}{2}$ cm. It was noted that after the threads were tied, outlining the block to be excised everywhere except at the bottom, there was no reduction in the strength of her grip; this in spite of the fact that the area must have been cut round quite well. After removal of the block of tissue, however, she lost almost complete use of her hand." (See dictated note below.)

"The removal was practically all postcentral but it must be noted that there was some injury to the precentral gyrus but not to a depth of greater than 2 to 3 mm. and over an area not greater than 1 cm. in length. All devitalized tissue was removed. The dura was closed excepting under the temporal muscle where a small decompression was left. The bone flap was fastened with steel wire at two points mesially and left free below. The aponeurosis and skin were sutured by Dr. Walker."

Dictated Record of Stimulation.

(Stimulating thyratron intensity 30, raised to 24 from B on; frequency about 65, bipolar electrode; letters and numbers laid on brain as shown in fig. 4. The following record is given as dictated but quotation marks are used only to signify the patient's own words.)

Four negative stimulations.

A. Pain in right side of face; unable to secure this from dura adjacent.

Repeated twice—failed twice, should be ignored.
Two negative stimulations.

B. Arm and hand "feels as though it was going to sleep."
Repeated once without warning.

C. Numbness left side above umbilicus. This location seems to be epigastric.

D. Sensation in right arm and hand; when repeated, said to be more in arm.

E. Sensation in hand and fingers; when asked what the sensation was like she replied: "like going to sleep." When asked if it was numbness or tingling, she replied "Both."

F. Sensation in ring and little finger.

G. Sensation in same fingers.

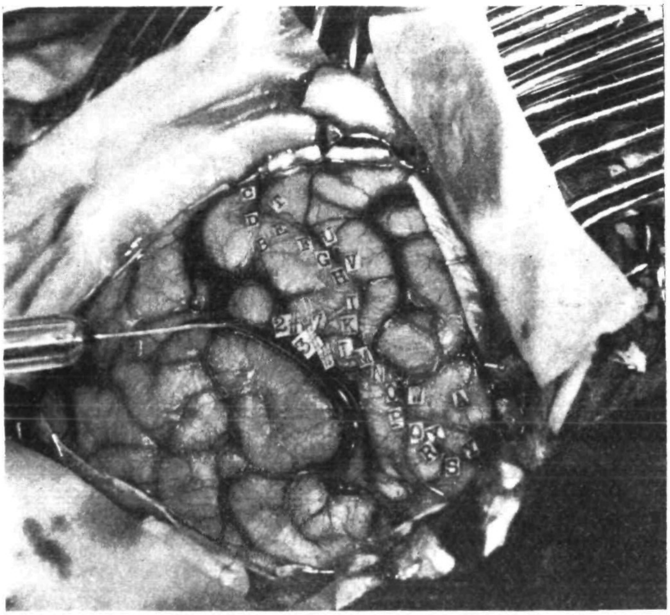


FIG. 4.—Cerebral cortex in Case 110 photographed during operation. The tickets of reference indicate responses which are described in text. *See* fig. 24 for diagram of same case.

Changed from Bipolar to Unipolar Electrode.

11 a.m. Left leg "going to sleep"—no stimulation.

H. Same feeling in index and large fingers.

I. Sensation in index finger—same feeling.

K. Sensation in thumb.

L. Sensation in thumb and toward index finger, but not in that finger.

M. Sensation left side of face—numbness.

N. Patient laughed a little; sensation in lower left lip.

O. Lower lip, left side.

P. Upper and lower teeth and gums.

Q. Left side of tongue and tip.
R. Tip of tongue, left side.
S. Back of left side of tongue.

Three negative stimulations.

T. Marked flexion of forearm on arm.
Repeated—no sensation. Same just above "T."
U. Inward rotation of hand and arm and slight flexion of fingers.
Indefinite sensation of numbness in hand and fingers.

One negative stimulation.

V. Slight flexion of hand and fingers; no sensation.

Two negative stimulations.

W. Mouth drawn to left and downward; no sensation.
X. Tongue drawn downward and to left; no sensation.
Y. Tongue drawn to left; movement of neck to left.
No response between "V" and "W."

Two negative stimulations.

11.10 *a.m.* *Attack following stimulation at* ♯.—Patient said she had sensation in the left thumb; next that it was going to the hand: next up the arm. Then convulsion characterized by slight convulsive movement of left hand and arm. Her first observation at the end was "Did he see it? I have had an attack." Pulse at wrist present throughout attack. Slight confusion at close and restlessness. No clonic movements elsewhere. Duration from sensation in fingers to her question after the attack was 1 min. 54 secs. In the brain it was observed that the hemisphere as a whole was pulsating during the attack. At least one artery was observed not to be pulsating during the attack. This artery showed visible pulsation at the close. An artery further posterior was also seen to begin to pulsate at the close of the attack.

11.17 *a.m.* *Attack* 2.—Patient was silent. Change in circulation of brain was noticed and spoken of before we realized an attack was starting. I do not know how to describe the alteration. A few seconds later Miss Roach stated that an attack was beginning. Brain then bulged and for a few seconds there was no pulsation in the cerebral arteries. Pulsation in the arteries began before the end of the attack and the brain began to recede. Pulse was present in wrist all the time.

Patient was not conscious that she had had an attack but she remembered that she had had sensation in thumb and then that it was going to her fingers. Stimulation producing each of the attacks was no longer than one second. Three negative stimulations.

Z. Sensation in thumb.

Experimental activation (*or secondary facilitation*).—Stimulation on the anterior margin of the precentral gyrus at level of T in figure 4 gave no response. Stimulation at T gave marked flexion of elbow as previously. This stimulation was then followed at one second intervals by a succession of stimuli which advanced anteriorly across the convolution to the anterior margin of the gyrus. Each stimulation was followed by elbow flexion of about the same intensity. This movement was thus produced from an area which had previously refused to give movement. The same thing was repeated in the postcentral gyrus. Thus a sensation in the arm was produced at D and reproduced by each successive stimulus back to the posterior margin of the gyrus, although there had been no sensation when the posterior margin had been previously stimulated.

Attack 3.—Same as time before. Did not know she had one. Followed by slight emotional change and flushing of face. There seemed to be a variation in pulsation of the arteries. Pulse felt in wrist continuously. Duration of third attack thirty seconds.

Examination following excision.—Immediately after all the cutting sutures were tied the patient was able to squeeze the dynamometer up to 13 with her left hand, while she could do it up to 15 with her right hand. After the extirpation, however, she could not squeeze the dynamometer at all although she was able to extend her wrist, just causing the hand to close a little. On leaving the operating room I found that pricking with a needle of any one of her fingers or thumb gave her pain and she was able to localize it to the proper digit. However, if any of the digits were pinched, moved or touched she had no intimation of it. She did not seem to know where her hand or arm was. On showing her teeth there was possibly a very slight weakness of the left side but nothing more than that.

(6) Topographical Analysis.

The responses for each subdivision of the body are analysed separately below and summarized in accompanying charts. Points which are widely displaced from their natural groupings can usually be explained by "epileptic spread" which will be discussed under a subsequent heading, or by the gross cerebral deformation due to a pre-existing lesion.

(7) Movements of the Tongue (fig. 5).

There are sixteen accepted points producing tongue movement in this series. Thirteen of these are precentral and three are postcentral. Ten points, including all of the postcentral ones, are from the left hemisphere. Because of the tongue's objective inaccessibility its movements can be discovered only through voluntary information from the patient, so that some movements may have been missed. For the same reason it was impossible in most instances to record the exact type of movement whether contralateral, ipsilateral, or bilateral.

Only point 44 is very far removed from the fissure of Rolando. This was the case of an epileptic who had a bilateral cerebral lesion. Point 18 from the same patient was found on the opposite hemisphere. On neither side did the point seem to be displaced by an "epileptic habit." Point 40 may perhaps have been displaced by the patient's lesion, an infiltrating glioma.

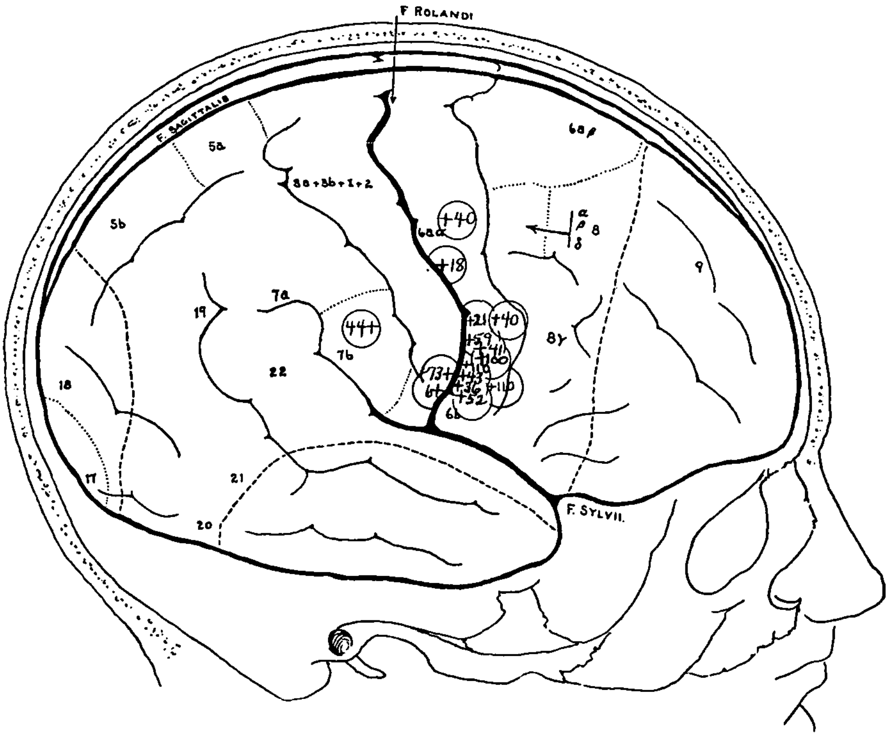


FIG. 5.—Movements of the tongue.

(8) SENSATION IN THE TONGUE (fig. 6).

Patients show great capacity for exact localization on the tongue. The information received has resolved itself into six groups listed as contralateral side, tip, middle, base, place not stated and taste. There is a total of 99 postcentral, 24 precentral, and 2 superior temporal points.

The sensation was recorded as contralateral side 48 times, of which 39 are postcentral, 8 are precentral and 1 is temporal. Twenty-three postcentral, 3 precentral and 1 temporal point gave sensation at the tip. There was feeling in the middle of the tongue during 8 postcentral and

4 precentral stimulations. Two postcentral and 2 precentral points gave a sensation at the base.

The exact point on the tongue was not stated in 33 instances, 26 postcentral and 7 precentral. In one instance only (postcentral) the sensation was on the ipsilateral side. Twice the sensation was that of movement. One precentral point gave a feeling of "inability to control my tongue."

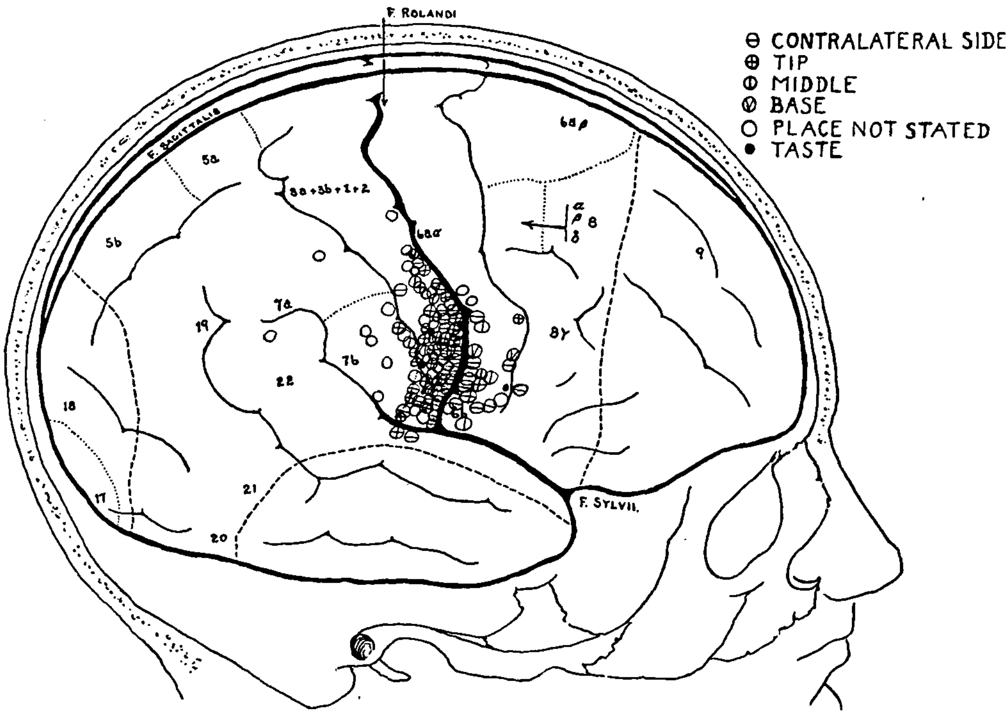


FIG. 6.—Sensation in the tongue.

In five cases the patient described the sensation as being one of taste. Four of these points were postcentral and one precentral. The particular kind of taste was not described. The two points beneath the Sylvian fissure were checked without warning with the same result.

The fact that points on the chart take up space gives the impression that the cortical points extend farther from the Rolandic fissure than is often the case. Usually the responsive areas were very near the anterior lip of the postcentral gyrus. It is obvious, however, that the region may extend one and one half centimetres behind the central sulcus and the same distance in front of it.

Bilateral and ipsilateral sensations are more frequently encountered in the tongue than in any other part of the body. In those cases, seven in all, where sufficient detail was available, it was found that the tip of the tongue had a position on the cortex above the side and base in five instances, and below the side and base in two instances.

(9) MOVEMENT AND SENSATION IN THE MOUTH (fig. 7).

For the mouth and lips there are 3 postcentral and 18 precentral motor points to be compared with 21 precentral and 53 postcentral points for sensation. The sensations reported were described much as

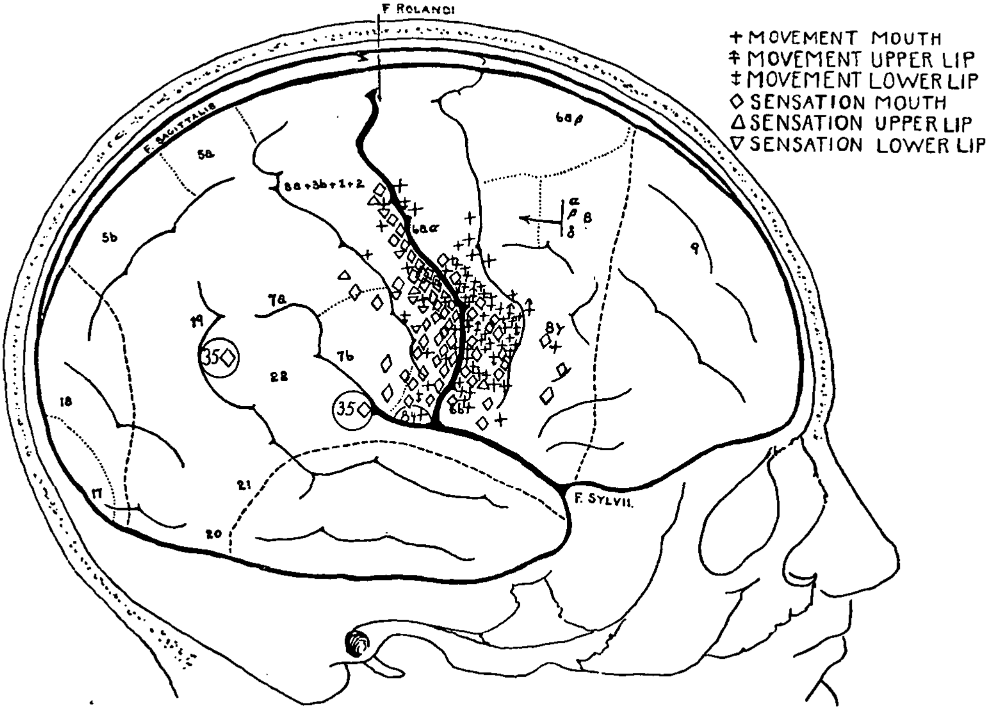


FIG. 7.—Movement and sensation of the mouth.

elsewhere, usually as tingling or numbness. Movements have been most often twitching in character, but also opening and closing, smacking, sucking and trembling of the mouth. Ipsilateral lip movement occurred eight times.

Special attention should be called to the comparatively large number of precentral sensory and postcentral motor points in this group. It is also of interest that the sensory localization extends farther, both anterior and posterior to the fissure of Rolando. Motor point 84 (near the inferior end of the postcentral gyrus) was the sole motor response from this patient. Shortly before operation she had developed a hemiplegia following status epilepticus.

(10) Jaw Movement and Sensation within the Mouth (fig. 8).

For the purposes of this chart "in the mouth" means in the teeth, palate and jaws. There are 40 postcentral points and 16 precentral points which have produced such sensation. Ipsilateral feeling has been moderately frequent. One point gave a sensation of cold. None of these patients experienced pain in jaws or teeth, but usually numbness.

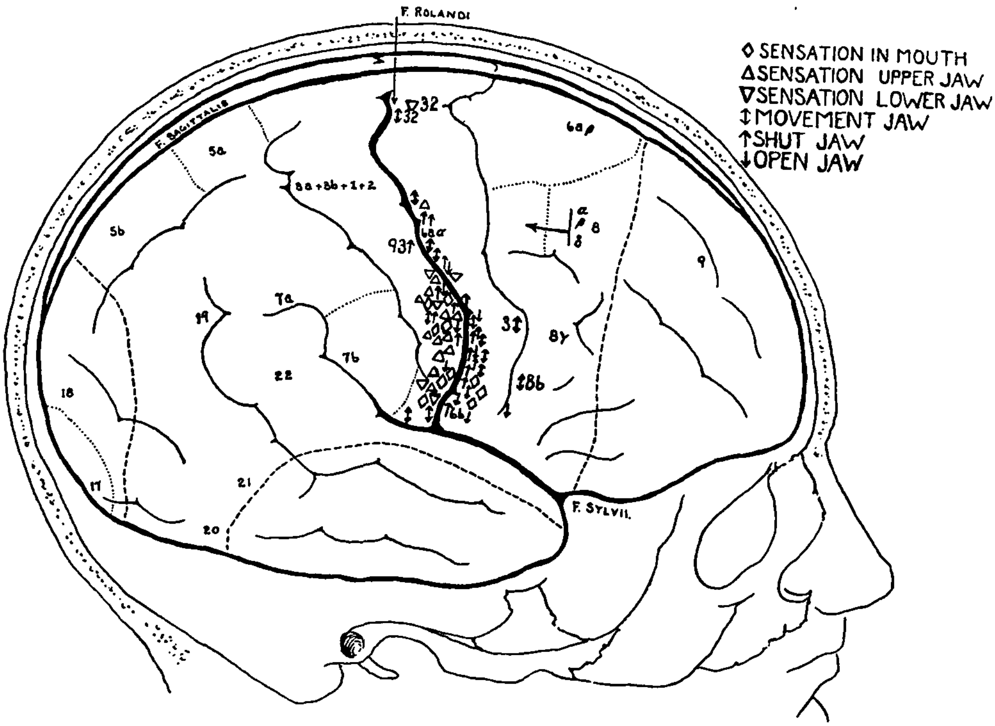


Fig. 8.—Jaw movement and sensation within the mouth.

Forty-one points produced jaw movement. Twenty-nine of these were precentral and the remainder were postcentral. Simple "jaw movement," which usually means opening and closing, occurred 25 times, 19 of which followed precentral stimulation. Six precentral and 4 postcentral points produced jaw closing; 4 precentral and 2 postcentral points produced opening of the jaws. With two exceptions all of these points are within a centimetre of the Rolandic sulcus.

The points 32 are obviously well away from the general centre.

The scar in this epileptic subject was over 4 cm. below and in front of these points. It is doubtless an example of displacement of response due to habitual epileptic discharge, a subject to be discussed presently.

(11) Movement and Sensation of Face (fig. 9).

The striking thing about this chart is the relative rarity of motor response from the postcentral gyrus as compared with other areas of the body. Thirty precentral and one postcentral points produced eyelid movement; of these, eyelid closing was the most frequent

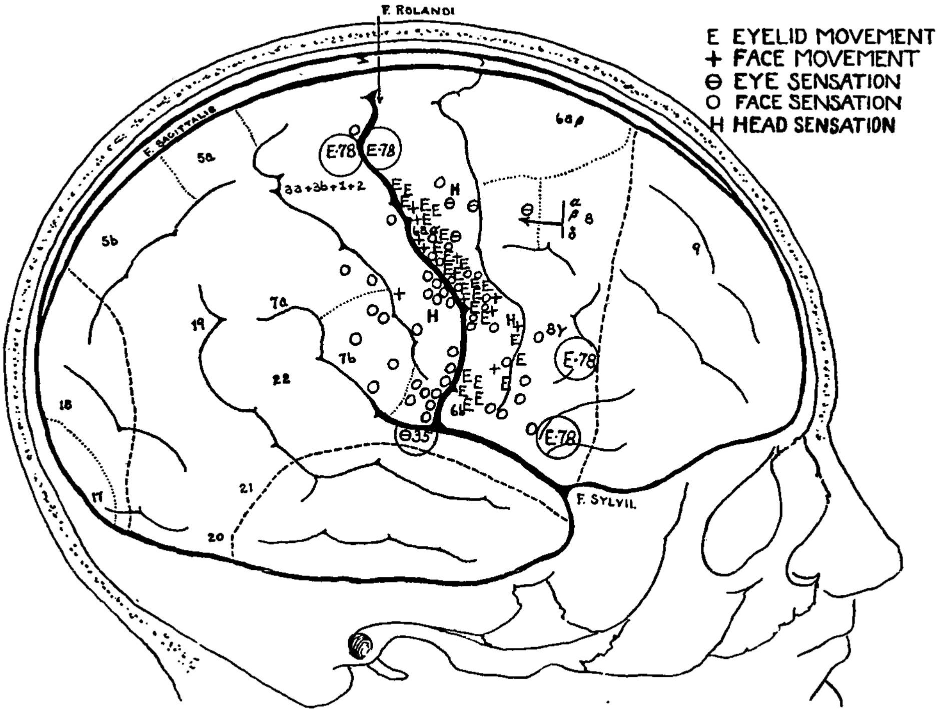


Fig. 9.—Movement and sensation of the face.

response. Other common movements were twitching and opening of the lids. Twelve other motor responses were simple "face" movements, usually twitches and including nose and brow. The four atypical points of case 78 were thoroughly re-checked. There were no other points in the vicinity which could give this response.

Somatic sensation in the eye occurred after four precentral and one temporal stimulation. Sensation in the remainder of the face was quite common. There are 20 precentral and 24 postcentral points on the chart. There is a suggestion of a grouping of these face sensations at the inferior end of the postcentral gyrus.

One motor point in Case 118 produced elevation of the opposite brow, opening of the opposite eyelid and turning down of the corners of the mouth. This was not part of an habitual epileptic pattern. It seems to have been a grimace activated from a single motor point.

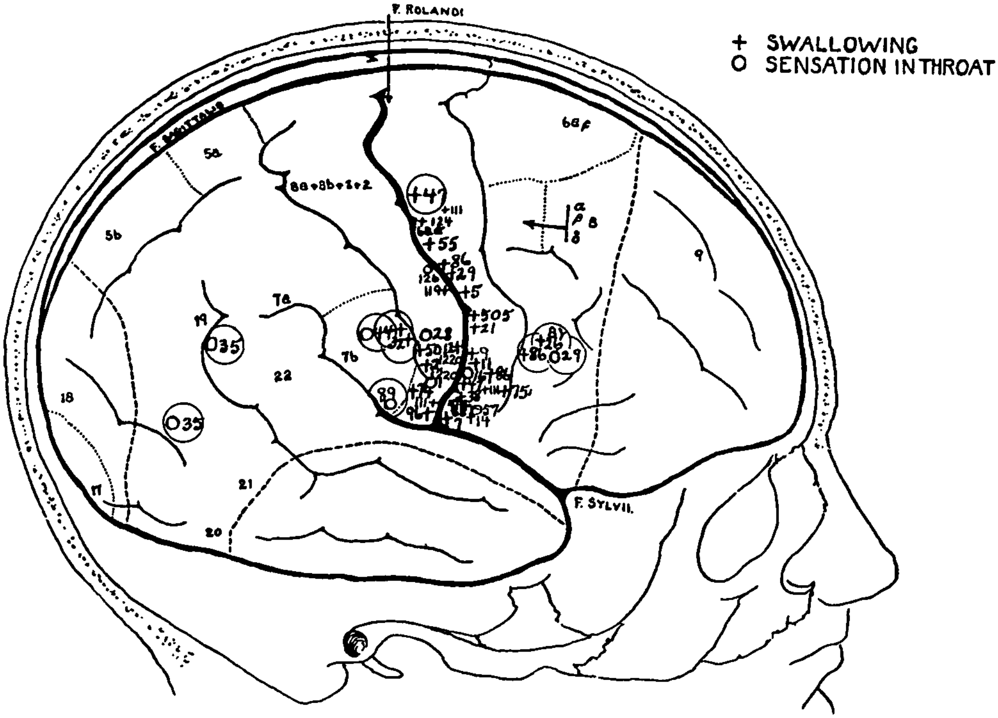


FIG. 10.—Swallowing and throat sensation.

(12) SWALLOWING AND THROAT SENSATION (fig. 10).

It has been necessary to exercise great care in the distinction of spontaneous swallowing from swallowing as a response to cortical stimulation. There were 32 examples of definite swallowing secondary to stimulation. Of these 23 were from precentral points. This means proportionally a much greater number of postcentral motor points than for face.

Throat sensation resulted from nine postcentral and four precentral points. Even when the grossly atypical location of the stimulation point of Case 35 is ruled out, these sensory points are spread over a much wider territory than are motor.

In Case 35 the response is doubtless displaced by a very large cyst posterior to these points from the margin of which epileptogenic discharge evidently took place. The patient described the sensation produced as " a feeling of filling up in the throat."

(13) VOCALIZATION (fig. 11).

Six examples of vocalization included in this series were published by Penfield (1937) as the first example of such a response to stimulation

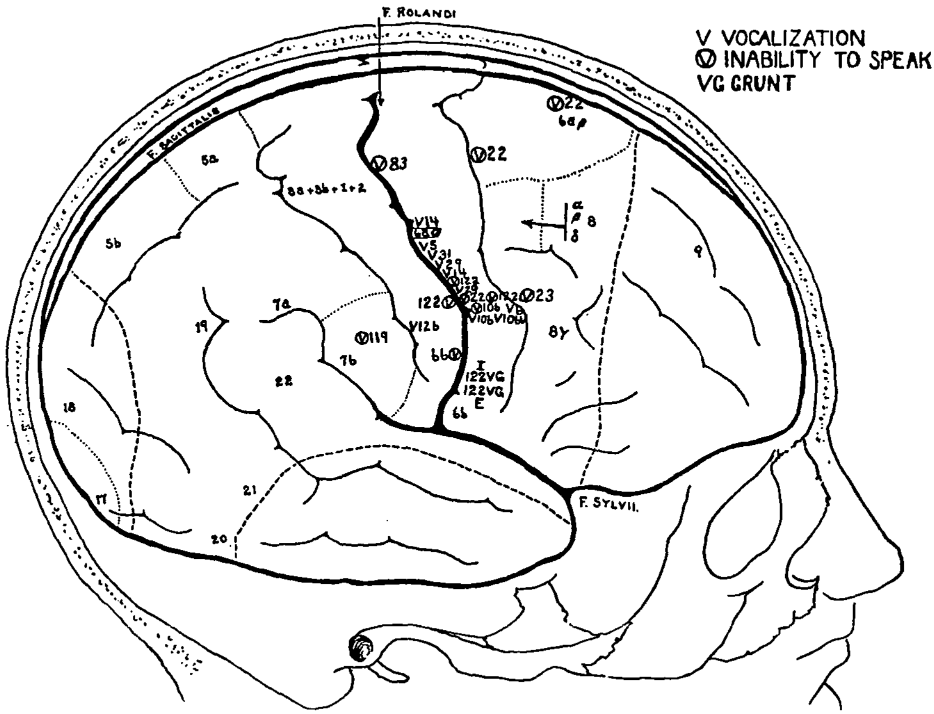


FIG. 11.—Vocalization.

of the cerebral cortex. We have been most interested in the rather sharply localized area for vocalization which is shown in this chart. In most cases, the response is obtained from a small area of a few millimetres in diameter. Once the area extended in a narrow band across the precentral convolution.

Vocalization may be produced by cortical stimulation in the precentral gyrus on either hemisphere. It was produced four times from the dominant and four times from the non-dominant hemisphere. It occurs without any associated motor phenomena. Its localization is between the area for eyelid movements above and mouth below.

The response may be illustrated by some of the findings in Case 14. This was the first example of vocalization encountered, and surprised the surgeon quite as much as the subject. Two discrete points were found near each other in this patient. The upper point in this patient was stimulated thirty-one times in succession and vocalization was the response each time. There was nothing to suggest the formation of words. The patient was unable to stop the cry or to influence it in any way, even when urged to do so. Stimulation at points a few millimetres distant gave no response. The second point lower down on the gyrus (V-14, fig. 11) gave vocalization, but at a definitely lower pitch. At the intensity used no movements could be elicited anywhere over the cortex. That is, the stimulation threshold was lower for vocalization than for anything else in this case.

In Case 122 it will be observed that inspiratory and expiratory sounds (122 VG, fig. 11) were produced from adjacent points. Both of these sounds, however, were grunts of short duration and were associated with sensation in the mouth. The expiratory grunt was repeated. These are not examples of true vocalization as found in the other cases. They resemble rather the grunt which has been reported by Foerster and others previously, but not the loud continuing cry of true vocalization.

In vocalization the sound continues if the stimulation continues until the patient's breath expires, when he may take a breath and cry again. Usually the vocalization is an expiratory vowel sound. The three points for 106 which are distributed across the precentral gyrus were adjacent to another point from which the sense of inability to speak was obtained. Only one vocalization point has been found on the postcentral gyrus.

The patient's subjective feeling of inability to speak, indicated by the letter "V" in a circle in fig. 11, has been elicited from a scattering of points which became more numerous near the vocalization region. These evidences of inhibition are not associated with convulsive discharge. Inability to speak was subjective as a rule. Patient 22, however, was told to count aloud and, while doing so, appropriate stimulation caused a definite hesitation, though it did not completely stop her. Afterwards she volunteered that it had been difficult to speak when she had been about half way through. Others have stopped counting, or have volunteered that they could not speak.

(14) Head Sensation.

No chart is made for this group. Out of the 11 responses called head sensation 6 were characterized as painful. Of these 6 responses, 3 were ipsilateral, 2 frontal and 1 not stated. It seems apparent, therefore, that all of these painful sensations are to be looked upon as evidences of referred pain from stimulation of the brain as an organ. This would seem to be contradictory to the statement made elsewhere by one of us (Penfield, 1934), that the brain is insensitive and pain within the skull is produced only by stimulation of dural sinuses, large dural arteries and deep in the fissure of Sylvius where the middle cerebral artery enters it.

In a case where stimulation of the hemisphere does produce pain or headache, the pain or headache comes from numerous points, showing that it is not a matter of cortical activation. Such pain is very rare, but it does exist. There were two other ipsilateral sensations in the general group which may also be considered as referred sensation.

This leaves only three contralateral head sensations which seem to be evidences of sensory head representation. To these may be added two contralateral neck sensations. All five of these points fall roughly into the general vicinity of the face area and are recorded in fig. 9 as H.

Head aura occurred eleven times. That is to say a head sensation was produced which was characteristic of the patient's habitual epileptic aura. This aura seemed to have no localized representation, but occurred from points spread widely over the hemisphere.

(15) Movement of Fingers (fig. 12).

Finger movements are among the best localized of the responses found in this study. Although the responsive points extend $5\frac{1}{2}$ cm. along the length of the fissure of Rolando, very few are found more than 1 cm. distant from it.

Of the 102 recorded points, 77 are precentral and 25 are postcentral. The most common response was movement of all the fingers together. It seems likely that this may be looked upon as an individual movement, not a combination of separate movements with individual representation. This occurred from 45 precentral and 12 postcentral points. Flexion of the individual fingers followed 23 precentral and 4 postcentral stimulations. Extension was the response from 16 precentral and 4 postcentral. The other movements were twitches or were not described in detail. The thumb was next in frequency of response with 15 precentral points and 6 postcentral. The order of frequency of individual fingers or combinations of fingers in this series is as follows: Index, 4 precentral and 1 postcentral; little, 4 precentral and 1 postcentral; ring and little, 2 precentral and 2 postcentral; index and middle, 2 precentral and 1 postcentral; middle, ring and little, 3 precentral; thumb and index finger and ring finger, 1 each precentral and postcentral.

It was interesting to note that the only grouped finger movements were of the thumb and index, the index and middle fingers, the ring

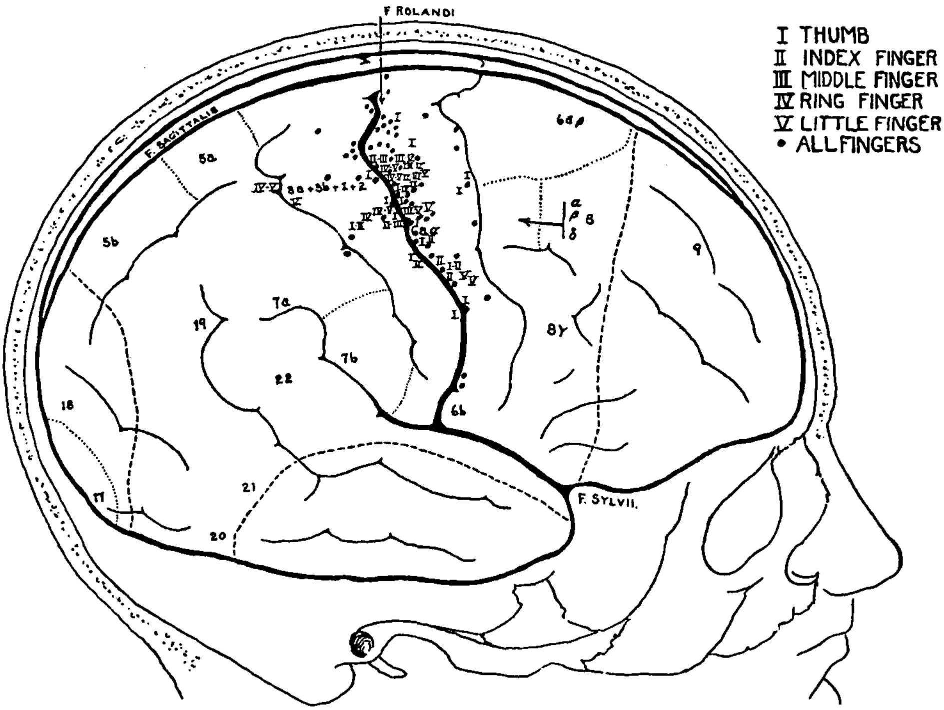


FIG. 12.—Movement of digits.

and little fingers, and the middle, ring and little fingers. We were surprised that the point for so useful and used a digit as the index finger was not encountered more frequently. It responded no more frequently than the little finger.

Flexion and extension responses were often separable in an individual case, and points for one digit were sometimes found separated rather widely as though these members had a comparatively large amount of cortex devoted to them. Patient 118 had some interesting finger responses. One point produced extension of the index finger together with flexion of the thumb on the palm. Three other points responded with extension of all of the fingers and flexion of the thumb on the palm. But in this case an epileptogenic focal lesion lay near the finger area sensitizing it.

(16) Sensation in Fingers (fig. 13).

At first glance the striking feature on this chart is the comparatively small number of precentral points. Even so, they constitute over one-sixth of the total, for of the 158 points 130 lie behind the Rolandic

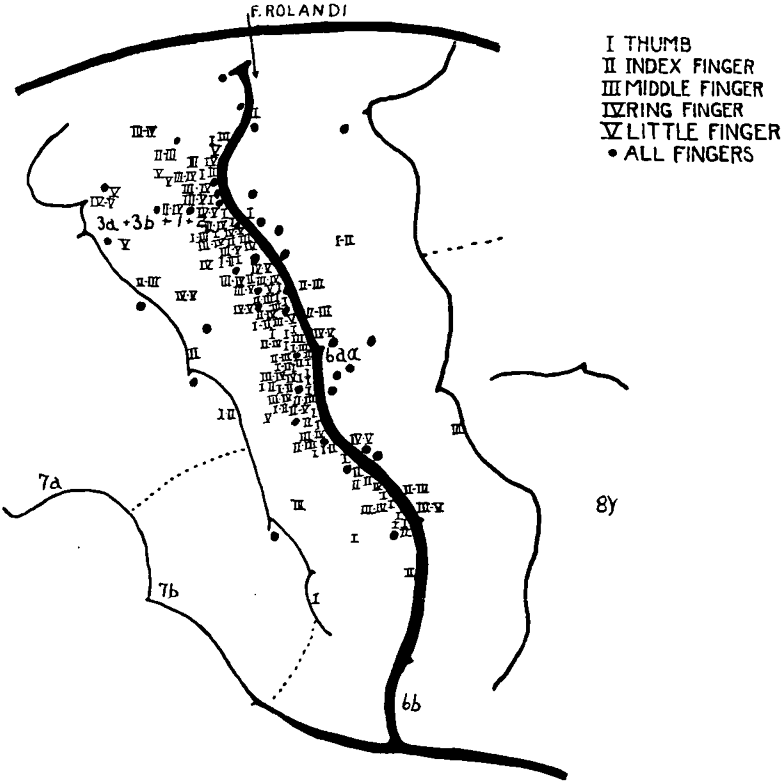


Fig. 13.—Sensation in digits.

fissure and 28 in front of it. They extend along the edge of that sulcus for about the same distance as the motor points, and are limited to a strip of surface cortex unusually narrow for sensory points when compared with the extensive spread already seen in previous sensory charts.

On forty occasions the patient felt sensation in all of the fingers. Twenty-seven of these points are postcentral and 13 precentral. In forty instances there was thumb sensation, 34 from postcentral and 6 from precentral points. The remaining points are distributed as follows: index finger 13, index and thumb 10, index and middle 9, ring and little 9, middle and ring 12, little finger 7 and middle finger 5, ring finger 3, middle, ring and little finger 5, index, middle and ring finger 3, and thumb, index and middle finger 2.

We also have remarked that here, as well as in finger movement, multiple finger response has been seen only in consecutive digits. Painful sensation accompanied two of these stimulations, both points being postcentral. Sense of movement was present with 4 postcentral and 1 precentral stimulations.

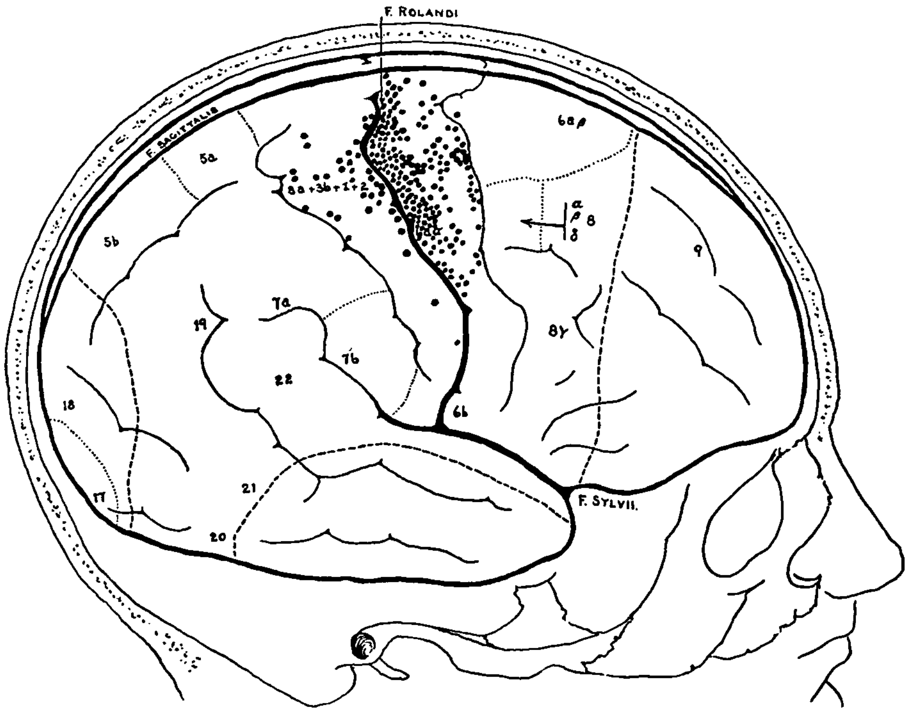


FIG. 14.—Movement of hand, arm and shoulder.

(17) MOVEMENT OF HAND, ARM AND SHOULDER (fig. 14).

From practically the same general cortical area as that from which we have already reported finger movements there appear those of hand, arm and shoulder. Two hundred and twenty-two of these responses appear and but thirty-six of them are postcentral. There is a curious subgrouping of responses between 1 and 2 cm. in front of the central fissure.

The joints represented in this chart are metacarpophalangeal, wrist, elbow and shoulder. Metacarpophalangeal joint movement has been described regularly as "movement of the hand" by persons reporting the objective responses at operation, and has been transferred to the charts as such. There are 71 precentral and 22 postcentral cortical motor points for hand movement. Forty stimulations produced flexion and 11 extension. The remaining movements were not further described.

In the arm proper 39 stimulations produced wrist movement, 67 gave movement of the elbow and 23 resulted in shoulder movement. Ulnar deviation of the wrist occurred once. Flexion was four times as frequent as was extension.

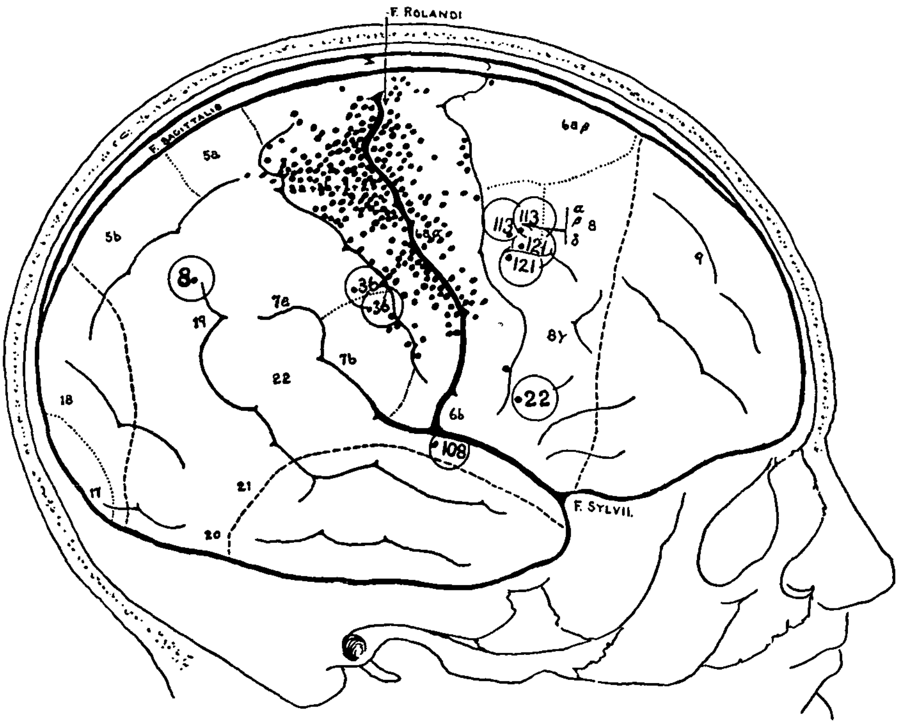


FIG. 15.—Sensation of hand, arm and shoulder.

It will be noted that the antero-posterior extent of motor response is not as great as that of sensation, recorded in the following paragraphs. The most distant motor points are 1½ and 2 cm. respectively from the Rolandic sulcus. The vertical distribution of points is for 5½ cm. along the central fissure.

(18) Sensation of Hand, Arm and Shoulder (fig. 15).

There are 279 points on this chart, 91 of these (32 per cent.) lie in front of the fissure of Rolando. Sensation in the hand was present during 36 precentral and 73 postcentral stimulations. No attempt has been made to differentiate between the back and the palm of the hand.

There are 170 points, stimulation of which has resulted in arm sensation. Fifty-five of these points lie in front of the central fissure. The response was localized in the wrist 5 times, in the forearm 20 times, in the elbow 4 times, in the shoulder 15 times. The remaining 126 points were called "arm" sensation. This term has not been exclusively confined to the region between elbow and shoulder.

Most of the sensations have been numbness or tingling. Pain has occurred twice. Sense of movement and desire to move were frequently located in this member. The sensations as such will be discussed later.

Of the atypical points on the chart point 108 on the temporal lobe was checked three times. The operative note made at the time states that it is "unexplained but must be accepted." Point 8 was not repeated but was quite definite. The patient had a tumour of the temporal lobe which may have displaced the cerebral tissue somewhat. In Case 36 an epileptogenic meningo-cerebral cicatrix lay just behind the sensory points indicated. Case 22 was that of a patient whose focus was near the midline in Area *6a beta*. Points 113 and 121 are unusual only in their grouping together at a fairly distant point.

Attention is again called to the remarkable spread of sensory points anterior to and behind the central fissure.

(19) Movement of Trunk and Legs (fig. 16).

The voluntary muscles of the trunk and lower extremity respond only rarely. Doubtless more responses would have been obtained had it been feasible to stimulate the edge of the hemisphere and the mesial surface in the median longitudinal fissure more frequently. The danger of bleeding from sinus and tributary veins makes it unwise to stimulate here unless it is clearly necessary.

Twenty-six precentral points, two of which are on the mesial surface, produced these movements. Twenty-three of the points are for the lower extremity alone. The movements are quite equally divided among the different joints with the exception of the back, for which but one point was found. No motor points for individual toes were found.

In addition there are eight postcentral motor points. Neck movements, but not head turning, are included in this chart, because the neck might be considered "trunk" from a functional standpoint. It is interesting, however, to note that neck movements (5 cases) are found in the vicinity of face movements at the lower end of the Rolandic cortex. This is the same area where certain rare trunk sensations grouped themselves in fig. 17.

The widely displaced points in Cases 62 and 111 are well removed from the epileptic focus of each which seemed to be high up in the

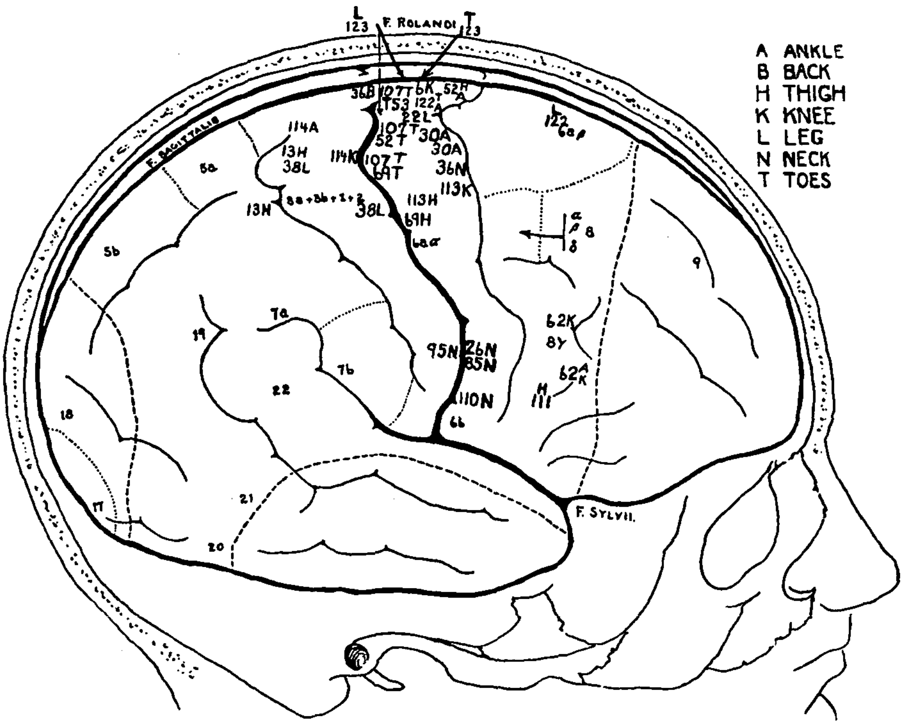


FIG. 16.—Movement of trunk and legs.

precentral region. Similarly in Cases 13 and 38 the patients were epileptics. In the first instance the focus was located at the very uppermost end of the central fissure. The lower end of the fissure was the firing point for the other.

(20) SENSATION IN THE TRUNK (fig. 17).

In the main group of response points there are eighteen postcentral and four precentral points. None were reported during stimulation within the longitudinal fissure. The response was often referred accurately to a portion of the trunk which might extend from the opposite axilla to hip. In topographical sequence upon the cerebral cortex the trunk lies below thigh and hip and above shoulder. Epigastric auras in epilepsy will be discussed below but are not included here.

Curiously enough sensation was very rare in the lower sacral and genital regions. This fact may have resulted from the comparatively small number of stimulations within the central fissure, or possibly to a

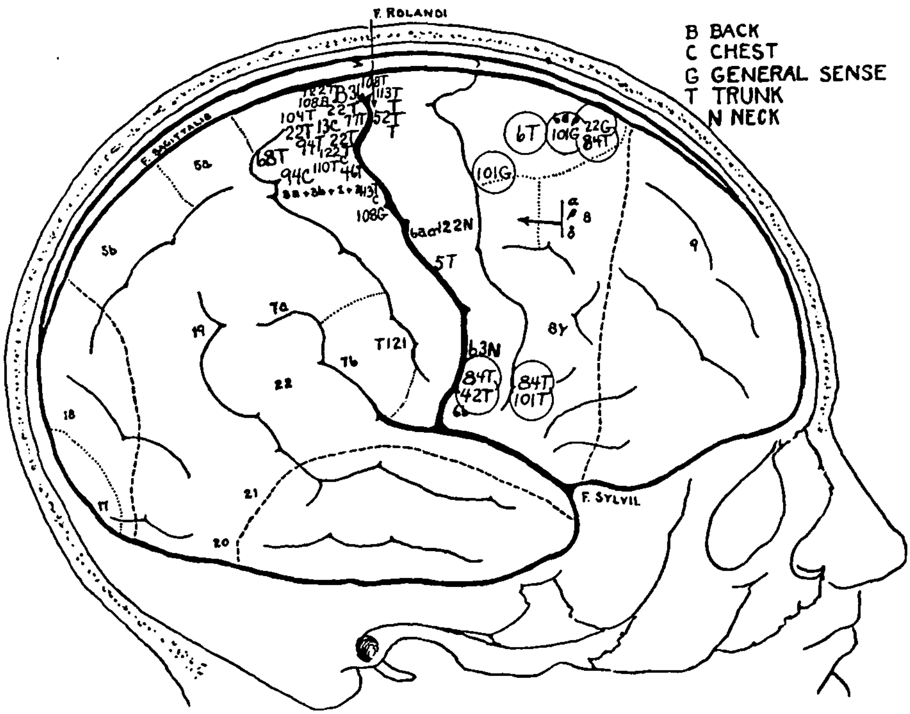


FIG. 17.—Sensation in trunk.

false sense of modesty. Sensation has been produced, however, in the contralateral side of the penis but no motor response. A second group of trunk sensation responses is to be found at the lower end of the fissure of Rolando. This recalls the fact that the neck and throat too are represented in this lower area where they lie adjacent to the face, and not above which would adjoin the principal trunk area.

Of this lower group Case 84 was that of a continuing post-epileptic hemiplegia in which sensory responses were present and more or less normally placed, but motor responses were lacking except mouth movements. In none of these four cases was any trunk sensation elicitable in the principal trunk centre.

The responses from the lower centre were described as "pins and needles" in the contralateral side of the body, except for patient 84 who reported a sudden sense of being "paralysed in the right side." The sensation evidently spread through limbs as well as trunk.

A third group of responses were found to lie anteriorly in Field 6*a beta*. Response 6 produced a feeling of "flush" down the contralateral side of the body. This was repeated with the same result

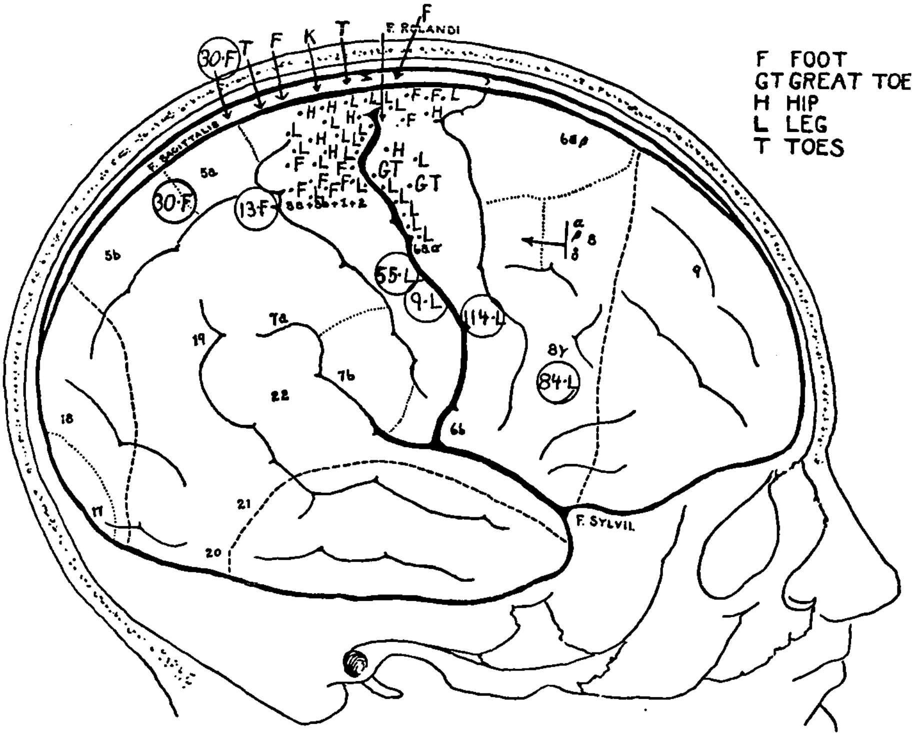


FIG. 18.—Sensation in leg and foot.

and there was no objective evidence of change of colour in the skin. The patient remarked after the second stimulation: "Sometimes I have that feeling before an attack." The responses 101 G were described as a feeling in the nerves all over and the epileptogenic focus seemed to be here. The sensation in that case was reproduced several times without warning.

The term "general sense" has been used in the chart (fig. 17) when the patient has been aware of some change in his body aside from an epigastric aura but has been unable to localize it exactly. Thus one patient reported a feeling "as if something were moving inside." Three points in Area 6*a beta* and one point in the postcentral convolution elicited this response.

As far as our evidence from stimulation goes this Field 6*a beta* has more to do with bodily sensation than it has with the adversive movements which are discussed below.

(21) Sensation in the Leg and Foot (fig. 18).

Sensation is a more frequent response to stimulation than is movement in the lower extremities. There were 16 precentral and 33 postcentral sensory points, 1 precentral and 5 postcentral of which were on the mesial surface in the longitudinal fissure. In addition to tingling and numbness, sense of movement was reported once, desire to move once (114 H), and once a painful sensation. Sensation in the great toe alone accompanied two precentral stimulations. No ipsilateral sensation was described.

One point in Case 30 is seemingly far displaced but the responses were checked carefully. The other points separated from the main group are doubtless examples of epileptic effect, and Case 84 is that of the patient who was operated upon during post-epileptic hemiplegia.

(22) Adversive Turning of Head and Eyes (fig. 19).

By adversive movements is meant conjugate deviation of the eyes to the contralateral side and turning of the head to that side. Adversive movements of the eyes alone occurred as a large group of responses in an area which centres roughly in Areas 8 (*alpha, beta, delta*), but it extends back on to the precentral gyrus. It is remarkable that in spite of frequent stimulation the Area 6*a beta* above has not, in our experience, produced adversive movements of head and eyes as recently suggested.

Adversive movements of the head and eyes together occurred only in a few instances. These responses group themselves in the general area of face representation, as though head turning to the opposite side was allied to mouth pulling to that side. During operation the patient's head lies upon a soft ring and it is prevented from very much turning by the towels, but any attempt at turning is evident both to anæsthetist and surgeon. The more likely explanation of the difference between our results and those of Foerster is that we have probably used less intensity of current and that we have eliminated from this study all true epileptic responses.

It is of interest that no downward deviation of the eyes was observed. This may, in part, be due to the fact that the patient's position under the tent makes it likely he would deviate his eyes down to see the observer spontaneously so that no change might be noted.

The deviation of the eyes to the opposite side from the lower point of Case 28 (fig. 19) was reported by the patient to be "towards a light"

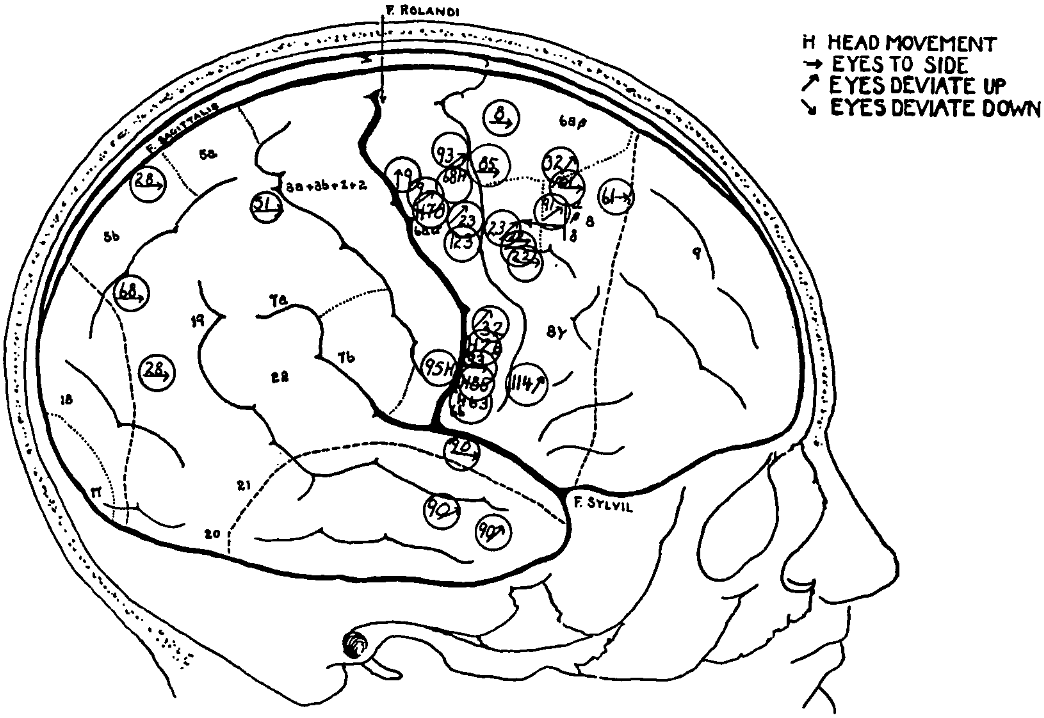


FIG. 19.—Adversive movements of head and eyes.

which he saw as a result of the stimulation. This is of interest in view of the ideas of some of the early investigators on adversive eye movements in animals. However, none other of the patients made a similar observation.

In Case 90 the unusual location of points for eye-turning led the surgeon to re-examine the responses with no warning before his stimulation, but the response was invariable. In two of the frontal responses the movement was towards the *ipsilateral side* instead of contralateral as in all the others. This might serve to explain turning to the side of the lesion in focal epileptic fits which occurs as a rare exception to the almost universal turning of the head and eyes away from the discharging lesion. The frequency of head and eye-turning in such fits might lead one to expect it to appear more frequently than it has as a result of cortical stimulation.

The frequency of upward deviation of the eyes in epileptic seizures may perhaps be related to the frequency of upward deviation produced by frontal stimulation.

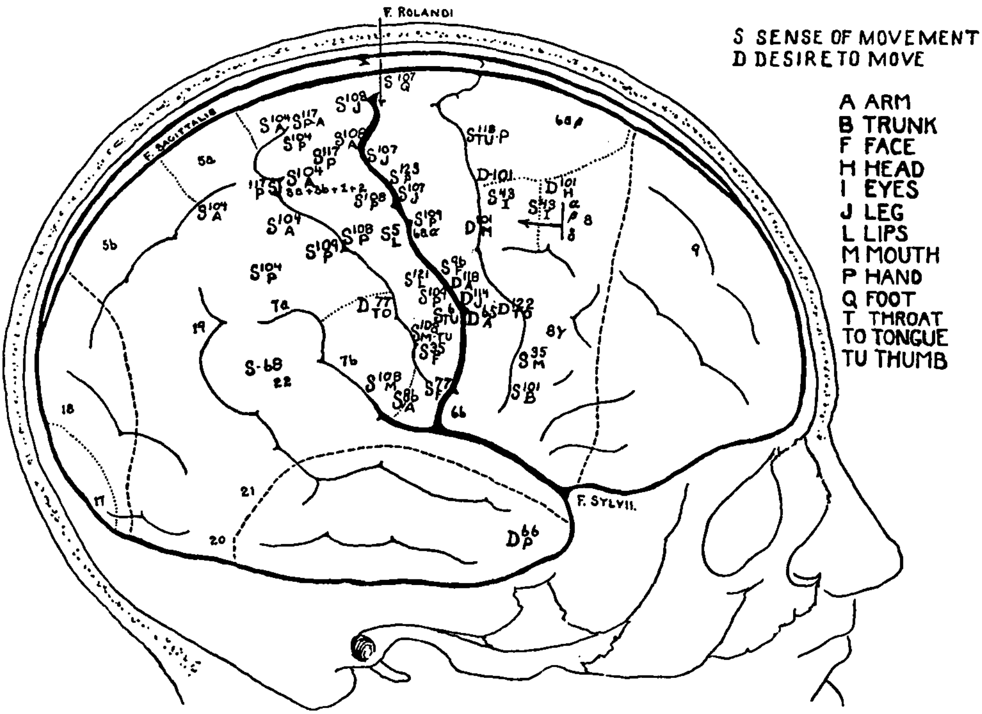


FIG. 20.—Sense of movement and desire to move.

In summary, therefore, there is evidence in this analysis only of a grouping of adversive head-turning responses in the lower Rolandic cortex and there is a larger grouping of conjugate eye deviation responses in the general location of the cytoarchitectural field 8 *alpha, beta, delta* called by the Vogts (1926) the most easily stimulable area for eye movements as the result of their work upon the ringtailed monkey (Meerkatze).

(23) SENSE OF MOVEMENT AND DESIRE TO MOVE (fig. 20).

The sensation of movement in a part was reported by Cushing. We have been somewhat surprised at the frequency of this sensation as it has proved to be the third most frequent description, coming thus after numbness and tingling. The patient realized he had not moved but observed that it felt as though his finger, arm, foot, &c., had moved. When the point (S118 TU P, fig. 20) was stimulated the patient said, "Look at my thumb; it feels as though it were twitching. That's the warning I get." He referred to his habitual aura. There was no observable movement of the thumb.

This response has occurred fifteen times anterior to the fissure of Rolando and twenty-seven times posterior to it. In general the points fall within the same zones as other forms of sensation (*see* S, in fig. 20), the face lying below and upper and lower extremities above.

The response of desire-to-move is also a definite experience to the patient and, like all other unexpected responses, was usually verified by re-stimulation without warning to the patient. These responses were all in front of the central sulcus except D77, which was a desire to move the tongue. The patient said the tongue did not actually move, but as the mouth was closed this could not be verified objectively. D66 lay upon the temporal lobe in the case of an intelligent young woman who observed that she wanted to move her opposite hand up and down. It was associated with a slight sensation in the abdomen. This abdominal sensation was similar to her habitual epileptic aura and a typical attack was produced by stronger temporal lobe stimulation later on. Nevertheless, as the desire to move the hand was again produced at an adjacent point and could not be produced from stimulation elsewhere, it is included here.

The tendency to localization of the desire-to-move anterior to the precentral gyrus is interesting, as it seems to relate this desire for movement to motor rather than to sensory function.

(24) Ipsilateral and Bilateral Responses.

There were no examples of verified isolated ipsilateral sensation. This is true even for face and tongue.

There were no motor responses of the ipsilateral extremities and none of the face, except where the movement was part of a bilateral grimace. There was one exception to this last statement, and that was in the case of a little girl who had a focal traumatic lesion just anterior to the Rolandic face area. This produced marked epileptic spread of response and an ipsilateral face movement that was verified repeatedly.

Bilateral motor responses in the extremities are also completely lacking. Bilateral sensation has occurred only rarely, as mentioned above, when a sudden generalized feeling throughout the whole body was produced from Area 6*a beta* (101, fig. 17). Bilateral sensations do occur in the face and in the tongue and bilateral movement in the face, tongue and jaw. Three times patients have reported sensation in both eyes. Once the description was "both eyes like paralysed." The other two had a sensation of lifting the eyes when the eyes did not actually move.

(25) AUTONOMIC RESPONSES.

Pupillary change could not always be watched for. In one case both contraction and dilatation of the pupil was produced at different points by frontal lobe stimulation. Alteration in pulse was observed only once when stimulation of the right frontal pole caused the pulse-rate to double. Repetition of this stimulation, however, caused only a quickening for a few beats.

We have found no valid evidence of a vasomotor centre on the convexity of the cerebral cortex. Once the face flushed as the result of stimulating in the postcentral face area, but it may have been a manifestation of an epileptiform discharge. Perspiration seems to have occurred once as a result of low precentral stimulation.

Salivation occurred in two instances, both from the lower postcentral region, and it accompanied tingling in the tongue once and swallowing the other time.

There is no evidence of gastro-intestinal response to stimulation of the cortex. But in four patients a sensation of nausea was produced. Patient 29 felt nauseated while precentral stimulation was causing vocalization. The other three all had nausea produced by stimulation of the parietal lobe. In each instance it was a familiar aura of an attack. In Case 15 stimulation at two points along the margin of a parietal lobe cyst produced nausea and a little later, when the patient wakened from a natural sleep, he was found to have had a bowel movement. Little importance should be attached to this, however. Vomiting has occurred in one case and was probably incidental.

Epigastric aura.—Sensation in the epigastrium is so frequently an epileptic aura that it was searched for carefully, but was elicited only three times as an aura. In all three cases the localization was in the posterior-superior parietal lobe just behind the postcentral convolution. One patient (Case 24) called it a feeling in the chest, one (Case 94) a rising feeling in the chest and one (Case 20) a weakness in the abdomen. So far as this meagre evidence goes, therefore, the epigastric aura has a localization in the superior parietal lobe posterior to the Rolandic area.

Emotional disturbance.—Weeping has occurred suddenly in two cases only and in both instances the stimulation was high precentral. Laughing occurred only once (Case 110—*see* report above) and then resulted from postcentral stimulation which gave sensation in the lower lip and it was not repeated. It may be said that stimulation of the cortex gives rise to an emotional sensation only very rarely. In fact, there was only one repeated and verified response and in this case weeping was habitual at the onset of a convulsive seizure.

(26) DISCUSSION OF ILLUSTRATIVE CASES.

A number of factors must be considered before these results are compared with data from animal experimentation and anatomical charts. It must be remembered that although we have transferred our results to a standard human chart on which are marked cytoarchitectural fields we do not know what the architectural pattern is in any particular case and how much these boundaries may vary from individual to individual. We have only measured roughly from the central fissure and from the fissure of Sylvius and the sagittal fissure. No greater accuracy can be achieved in any stimulation study.

It has been our routine procedure to begin with the lowest effective stimulation strength and to work up gradually. The central fissure is always outlined by stimulating up and down both sides but sometimes sufficient time was not available for complete mapping. Sometimes the Rolandic cortex proved to be refractory to stimulation except at a few points. The reader may get a truer perception of the meaning of our figures by reviewing the following electrical explorations.

Case 6.—F. W., a boy, intelligent and co-operative, suffering from focal epileptic seizures characterized by a sudden feeling in the right side of body and movements of right hand. Left osteoplastic craniotomy was carried out and excision of a small area of abnormal indurated cortex anterior to precentral gyrus.

Referring to figs. 21 and 22 the results from above down on the post-central gyrus were:—

14. Tingling from the knee down to the right foot, no numbness.
13. Numbness all down the right leg, did not include the foot.
12. Numbness over the wrist, lower border, right side.
11. Numbness in the right shoulder.

3. Numb feeling in hand and forearm up to just above the forearm.
10. Tingling feeling in the fifth or little finger.
9. Tingling in first three fingers.
4. Felt like a shock and numbness in all four fingers but not in the thumb.
8. Felt sensation of movement in the thumb; no evidence of movement could be seen.
7. Same as 8.
5. Numbness in the right side of the tongue.

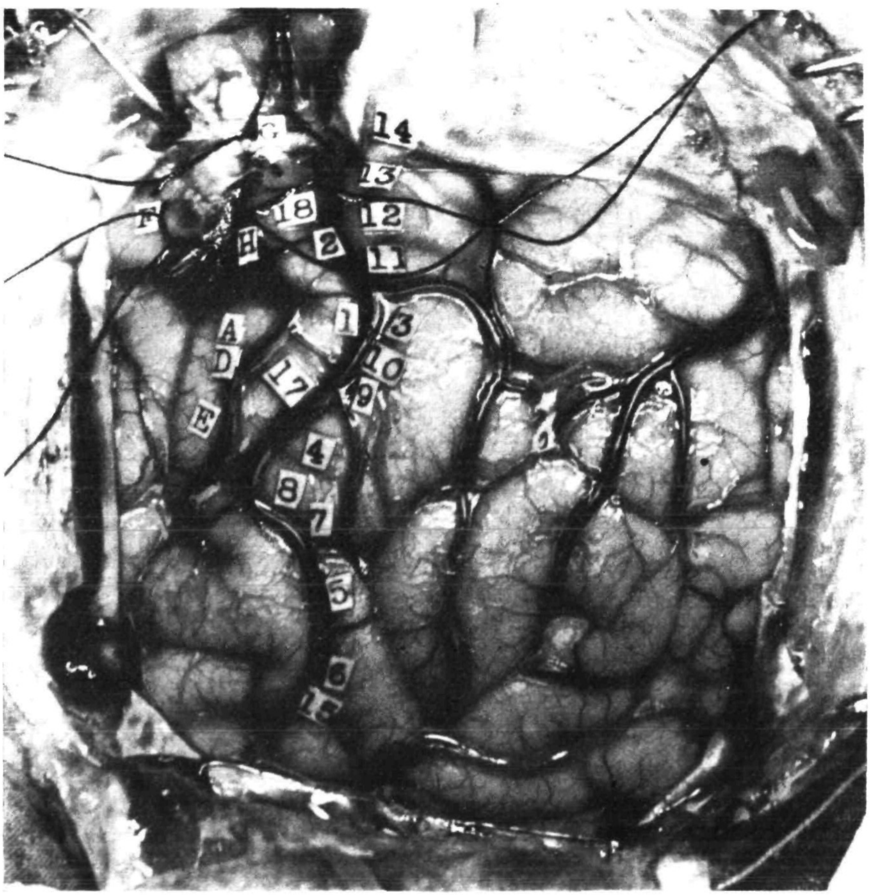


FIG. 21.—Cerebral cortex of Case 6, as photographed at operation. The tickets of reference indicate responses which are described in the text. *See also* fig. 22.

6. Tingling feeling in the right side of the tongue, more at the tip.
15. Tingling in the tongue, associated with up and down vibratory movements.
16. Numbness, back of tongue, mid-line.

Precentral gyrus from above down:—

(G) Flexion of knee.
18. Slight twitching of arm and hand like a shock, and felt as if he wanted to move them.
2. Shrugged shoulders upwards; did not feel like an attack.
(H) Clonic movement of right arm, shoulders, forearm, no movement in trunk.
(A) Extreme flexion of wrist, elbow and hand.
(D) Closure of hand and flexion of his wrist, like an attack.
17. Felt as if he were going to have an attack, flexion of arms and forearms, extension of wrist.
(E) Slight closure of hand; stimulation followed by local flushing of brain; this was repeated with the strength at 24. Flushing was followed by pallor for a few seconds.
(B) Patient states that he could not help closing his right eye but he actually closed both (fig. 22).
(C) Made a little noise; vocalization. This was repeated twice. Patient says he could not help it. It was associated with movement of the upper and lower lips, equal on the two sides (fig. 22).

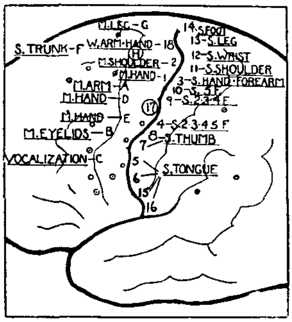


FIG. 22.

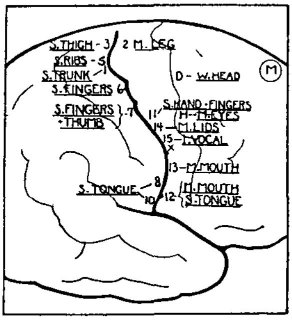


FIG. 23.

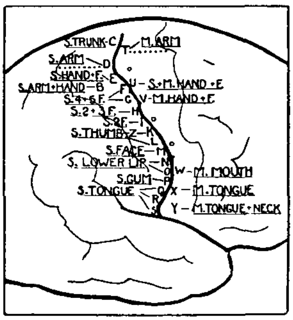


FIG. 24.

FIG. 22.—Chart of cortical stimulation of Case 6, as prepared at the time of operation. The points are the same as in fig. 21.

FIG. 23.—Chart of cortical stimulation of Case 22, as prepared at operation. The figures and letters indicate localization of points referred to in the text.

FIG. 24.—Chart of cortical stimulation of Case 110, as prepared at operation. The points correspond to those in fig. 4 and the responses are described in the text.

Below C and 17 on the precentral gyrus no responses were obtained even with a strong stimulation, although small attacks had been produced at 17 with a weak stimulus and at H with a stronger one. This refractory condition may be transient but is often encountered at various areas in these cases.

This case illustrated several peculiarities mentioned above, i.e. the desire to move the arm and hand at 18 whereas all other sensory responses were postcentral. The curious sensation as of flushing in the opposite side of the trunk was an aura of his attack and yet sometimes similar sensation has been secured from this area in other cases.

Case 22.—H. T., a woman aged 20, suffering from focal epilepsy originating apparently in the right frontal lobe near 6*a beta*, characterized by: an aura in which "the surroundings seem a little queer" and her thoughts turn to past events. This is followed by loss of consciousness, tonic rotation of eyes and head to the left, twitching of the left face, clonic convulsive movement of left arm and leg, tongue biting and incontinence, in the order given.

Stimulation from above down on the postcentral gyrus with thyratron (bipolar) at 26 gave (fig. 23):—

3. Feeling in leg, "numb," hip to knee left side.
5. Prickly feeling left side of trunk at lower margin of ribs.
1. Numbness left side of body from axilla to crest of hip.
6. Tingling all fingers except thumb.
7. Feeling in all fingers including thumb (no movement).
8. Numb feeling left side of tongue near tip.
10. Same as 8.

On the precentral gyrus:—

2. Tonic movement, left leg, no sensation, "leg moved itself."
11. Tingling left hand and fingers, no movement.
14. Marked closure of both eyes; deviation of left eye to side of stimulation. Other eye not seen.
15. Patient said she was unable to speak and unable to open eyes. No movement.

(X) Convulsive attack not like her habitual ones. It was characterized by clonic movements of mouth, left eye and left face with vocalization.

13. Mouth drawn markedly to left, no feeling in tongue near tip.
12. Mouth drawn to left and feeling left side of tongue near tip.

(D) Peculiar feeling in head; unable to talk for several seconds. Felt as though she wanted to turn her head to the left. No eye movements.

(H) and (G) Eyes deviated markedly upward and to left.

(M) Several small attacks produced from this point and its vicinity during one of which eyes went to left and downward. Once head went to left and once, after stimulation at depth of 2 cm. in brain, the eyes went sharply to left and upwards followed by sharp turning of head to left. Once stimulation near M caused her to say, "felt very peculiar, everything far away, a little bit like before the attacks occur." Sensation in face and lip was elicited but the markers were washed away.

This case illustrates certain points of interest. Sensation in hands and fingers was elicited from the anterior lip of the fissure of Sylvius at 11. At 15 there was inability both to speak and to open eyes. At

D she did not use the word "speak," but said she could not talk. At 12 the same stimulation produced movement of mouth and sensation in the tongue, which means that that point will appear twice on our summary charts, once for each response.

Adversive movements of the eyes were obtained easily at H and G, but no head-turning was obtained until small epileptic seizures were produced. The desire to turn the head was obtained at D and with it a sensation in the head and inability to talk. She used the word "speak" for 15 as mentioned above.

If figs. 22 and 23 are compared the sequence is seen to be the same, but some responses that might be expected are absent in each. No sensory response referred to the trunk was obtained in one, none to the leg in the other, to the face in one or to the throat in either. As is often the case less detail is elicitable from the precentral gyrus. In fig. 22 vocalization is obtained but no response in the lower face or tongue. In fig. 23 vocalization is lacking but mouth and tongue are present.

This variability probably depends upon pre-existing conditions which are not always the same, for we have found, in those cases that were opened up a second time, that different responses were elicitable. The pattern of responses may depend also upon which spots are first stimulated on the day of operation. But the existence of grossly atypical and distant responses argues that in these cases there is a very important role played by abnormal lesions and particularly by the epileptic habit.

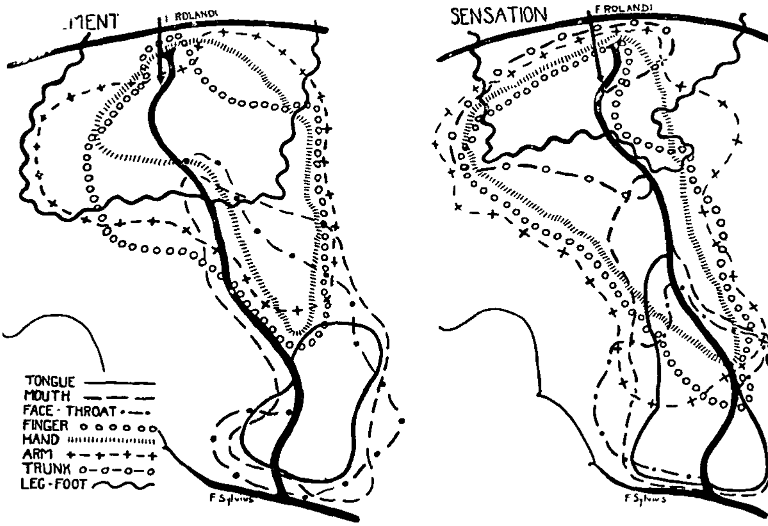
(27) Summary of Localization.

During any one exploration the responses of the sensorimotor cortex vary little, if at all. After stimulation has been carried up and down both sides of the fissure of Rolando and tickets placed upon each positive response, as in fig. 4, the whole process may be repeated with the same intensity of stimulation and the result will usually be identical. The same areas will give no response and the positive points will repeat themselves. But if the same hemisphere be explored at a later operation after a lapse of time, as we have done in five cases, the result may be quite different because areas quite active at the first operation may be mute at the second, and areas which gave no response may later be easily activated.

If a point on the precentral gyrus two-thirds of the distance from the longitudinal fissure to the fissure of Sylvius be stimulated in six different individuals the result will vary greatly so that any standardized chart which localizes the position of those points upon the cortex may be correct for one individual (e.g. figs. 22, 23 and 24) but not for all.

Superimposing all the points of individual cortical charts results in the diagram drawn up in fig. 25. The outlines of finger localization correspond to that of arm and yet in any individual chart (*cf.* figs. 22 and 23) arm will be found above fingers.

As may be seen by reference to this figure (fig. 25) movement has a proportionally larger representation anterior to the central fissure and sensation a larger representation posteriorly, and the two areas, motor and sensory, overlap each other consistently and correspond to each other horizontally.



A. B.

Fig. 25.—Summary of sensory and motor findings in figs. 5 to 20. The lines enclose the areas within which responses were obtained for each subdivision of the body. A. movement. B. sensation.

But in spite of this variability of geographical location illustrated in fig. 25, the sequence of motor and sensory representation from above down is almost invariable. We have expressed the motor sequence in summary form in fig. 26. The list from "toes" above down to "swallow" at the bottom indicates that our conclusions in regard to this sequence is that of the general consensus of opinion with a few additions. The horizontal bar opposite each name indicates proportionally by its length the total number of such responses obtained. The length of the bar to the right of the vertical line shows the number of precentral responses and the length to the left the number of postcentral responses. This illustrates that the hand has responded most frequently, lips next, followed by elbow, wrist, jaw, swallowing and thumb, etc.

Fig. 27 is made up in the same manner for sensory sequence, and here again the hand leads in total number of responses. Tongue now is second in numerical sequence with lips, arm, jaw, face, thumb, and leg following after. Hand and arm sensation have a comparatively large number of precentral responses as well as face and leg, whereas fingers and thumb have relatively few precentral responses.

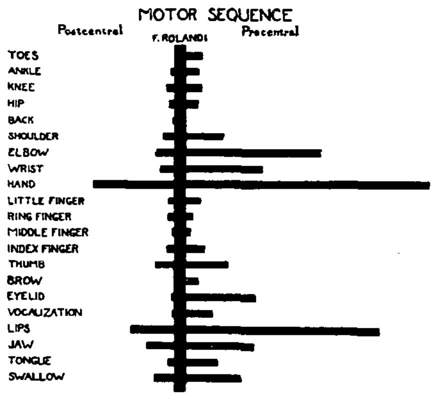


Fig. 26.

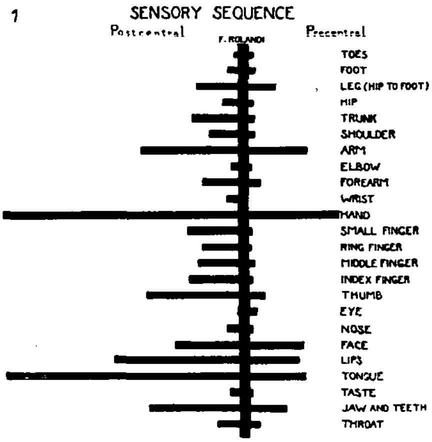


Fig. 27.

Fig. 26.—Motor sequence chart for right hemisphere. The list from "toes" to "swallow" indicates the sequence of motor responses in the Rolandic cortex from the median fissure above to the Sylvian fissure below. The broad vertical line represents the fissure of Rolando. The length of the individual horizontal lines to the right indicates the proportional number of points anterior to central fissure. Their length to the left indicates the number of points posterior to that fissure which gave responses in the part as shown by the names in the column to the left. All face movements are included under the heading of "lips" on this chart. Neck movements have been omitted because of the inconclusive localizing value of the small number of points found. Hand movements in this chart include movements of all of the fingers together.

Fig. 27.—Sensory sequence chart prepared as in fig. 26. Contrary to movement, face sensation is separated from lips. Head sensations have been too scattered to justify their inclusion, and neck sensation points are too few in number.

The sequence relationships may be considered from another point of view illustrated by the homunculus in fig. 28. In figs. 26 and 27 it is seen that toes begin at the top and the members follow in order as though representing a man hung upside down, but that thumb is followed by the head as though the head and neck were erect and not inverted. The larynx represents vocalization, and pharynx swallowing and throat sensation.

The homunculus gives a visual image of the size and sequence of cortical areas, for the size of the parts of this grotesque creature were determined not so much by the number of responses (as for figs. 26 and 27) but by the apparent perpendicular extent of representation of each part when these responses were multiple for the same part.

The large size of the thumb and lips indicates that the vertical extent of Rolandic cortex devoted to those parts in individual cases is very large. Thus the trunk is quite small and the legs and head

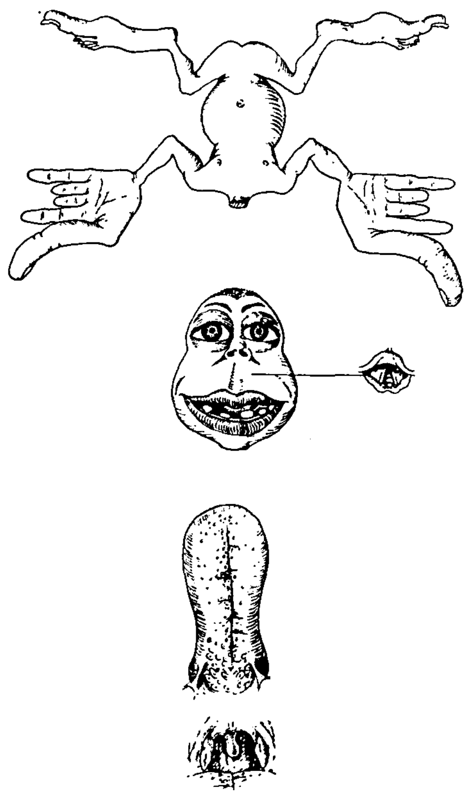


FIG. 28.—Sensory and motor homunculus. This was prepared as a visualization of the order and comparative size of the parts of the body as they appear from above down upon the Rolandic cortex. The larynx represents vocalisation, the pharynx swallowing. The comparatively large size of thumb, lips and tongue indicate that these members occupy comparatively long vertical segments of the Rolandic cortex as shown by measurements in individual cases. Sensation in genitalia and rectum lie above and posterior to the lower extremity but are not figured.

exceedingly small, while the tongue, which usually occupies a comparatively long strip of the Rolandic lip, is large. The homunculus may be said to be both motor and sensory as the sequence pattern is roughly the same, although there are differences. Comparison of figs.

26 and 27 shows that eyelids have a large motor representation. Sensation in the eyes is usually of movement. Eye-turning is not included in the chart. It will be noted, too, that neck is above lips in both sequence charts. The number of responses is as yet too small to be finally certain of the sequence position of neck, of taste and of nose. Foerster places neck between thumb and upper face for both sensation and movement. He likewise places jaw below tongue for both, whereas we would place sensation in teeth and gums below tongue but jaw movement above. Aside from these observations the homunculus represents true sequence. Presumably rectum and genitalia should be placed above feet, that is within the longitudinal fissure, but our evidence is not sufficient for conclusion and they seem to be somewhat posterior to feet.

(28) Quality of Cortical Sensation.

The quality of sensation resulting from cortical stimulation is of interest. In 369 responses the quality was not stated simply because it was the same as in the first or second stimulus which was recorded. In 204 responses it was called tingling or electricity, 131 times numbness, which at times was explained to mean numbness with tingling, at other times absence of all sensation. In 49 responses the patient had a sense of movement when no objective change of position occurred. This applied to a sense of movement of both eyes to sense of movement in one arm, one finger, &c.

There is no localization of quality of sensation, either pre- or postcentral. Eleven times the patient reported a sense of pain in one extremity or peripheral part; it was never severe. Thirteen times a feeling of cold was reported. This last sensation was most frequently applied to the face. As the sense of heat was only mentioned twice it seems possible that tingling was taken for a sense of coldness. A sense of blood rushing was felt ten times. Thickness was the description five times and each time applied to the tongue; swelling once and this also to the tongue.

Desire-to-move, as indicated in fig. 20, has been a definitely reported experience. It is not clear that this is a sensation, but as it was verified by repeated stimulation without resultant movement it becomes an interesting phenomenon, especially as it was anterior to the central fissure in all but one instance. This is to be contrasted with the sense of movement which is chiefly postcentral in location. A feeling of inability to carry out some movement has also been described as though the patient were made aware of stimulation of an inhibitory mechanism. This has most often been described as inability to speak.

(29) Cause of Atypical Responses.

Gross lesions of the brain which deform the hemisphere and displace or alter the Rolandic portion of the brain cause displacement or obliteration of representation. This may explain some of the unexpected results in this report. The lack of anæsthesia doubtless accounts for many differences between human and experimental results, as practically all experimental investigations have been carried out under light ether or barbiturate anæsthesia which gravely alters the reactive state of the cortex. Further, however, it may well be that the human cortex has normally wider associative connections more easily activated.

But what is the significance of a response to electrical stimulation of the cortex? When a motor response is thus produced it is evident that a chain of neurones is activated and an effective impulse passes out to the periphery. When cortical stimulation produces a sensation the mechanism is not at all obvious. It may be that a neurone chain has been activated. If so, whither is the impulse carried? It seems likely that normally the sensory circuit in question is activated by a peripheral stimulus, the resultant impulse of which rises in the central nervous system to a point as high as the postcentral convolution.

Does it stop there or is that point only a way-station on the road to a higher level? It is quite possible that sometimes the stimulation may affect the further course of that sensory pathway toward a higher physiological level. It is also possible and probable that for both motor and sensory responses distant stimulation may activate the primary motor and sensory areas through a connecting neurone chain. These connections are doubtlessly established by pre-existing and sometimes transient conditions.

Sherrington has pointed out the instability of a cortical point. In Case 110 (figs. 4 and 24) above we have shown that a motor response may be moved from the posterior lip of the precentral gyrus to the anterior lip and a sensory response from the anterior lip of the posterior gyrus across that gyrus to its posterior lip by the activating effect of rhythmic repeated advancing stimulation. We have made the same observation in several other cases.

But widespread displacement or extension of function from its usual localization is in these cases most often due to the local or diffuse effect of a lesion which is giving rise to epileptiform seizures, or to the fact that epileptic discharges habitually take place in the cortex even though no objective lesion can be found.

It seems evident that this process may: (*a*) Sensitize or activate areas of cortex; (*b*) may cause widespread displacement of response, and perhaps (*c*) under other circumstances, render normally excitable areas inexcitable to the electrode.

(*a*) *Epileptic activation.*—The epileptic process may sensitize a part of the cortex so that evidence of the nature of neural activity inherent in that part may become evident, although under normal conditions no response to stimulation would be expected.

This applies especially to the parietal and temporal lobes where visual phenomena and even memory processes may be elicited as reported by Penfield (1937). Under such circumstances the repeated epileptic discharge seems to have established a sort of conditioned reflex. A similar effect is seen upon the sensori-motor cortex about the Rolandic fissure in certain cases where an oft-repeated seizure has produced a Jacksonian march. As a result the parts of the Rolandic cortex involved in the habitual march may give a more detailed and finely divided response to electrical stimulation than usual. This we have called epileptic activation.

(*b*) *Spread.*—For example, if an epileptogenic focus be located at some distance from the Rolandic cortex at the level of the arm area stimulation of the arm area gives, as expected, a sudden feeling in the arm. But stimulation of the cortex about the focus and over the intervening cortex produces likewise the same identical sensation in the arm. It is apparent that the whole large area in question has developed the capacity of discharging selectively that one Rolandic response.

This is an evident spread of response due to the influence of an epileptic focus. In a so-called idiopathic case of epilepsy where no objective focus can be demonstrated the same spread may occur.

(*c*) *Inhibition* of response evidently obtains in the cerebral cortex of epileptic patients. It seems likely that in some cases this is due to post-convulsive vascular changes (Penfield, 1933). In others there may be a true post-seizure refractory stage.

(30) Discussion.

After the elimination of instances of widely displaced responses due to epileptic spread and to pathological distortion there remain the great majority of responses to be considered as evidence of localization of function. These are normal responses to be expected from the human cerebral cortex free from any anæsthetic effect.

We find no evidence in favour of the extension of the motor cortex to Areas 6*a* *beta*, 5 and 22 as described by Foerster (1936A) and illustrated in fig. 3. Somatic motor responses are obtained from the Rolandic cortex, i.e. pre- and postcentral gyrus, but not from other areas of cortex if subconvulsant stimulation be used. Even turning of the head and neck to the opposite side (adversive movement) is not obtained under normal conditions outside of the Rolandic cortex. From the animal experiments of the Vogts we had expected that in man stimulation of Area 6*a* *beta* would produce head aversion, but so far in our experience and with the technique which we have employed, Area 6*a* *beta* has not proved to be a "frontal adversive field."

The difference between our conclusions in this regard and those of Foerster may be only a difference of interpretation explained as follows: We have used a minimal intensity of stimulation in the Rolandic zone and have then increased it markedly and even altered its wave frequency to try to produce results in the more distant cortex. But we have not included epileptiform seizures among our responses. On the contrary we have eliminated all convulsive movements, whether tonic or clonic. The criterion of an epileptiform seizure is that the phenomena produced by stimulation continue and may advance after withdrawal of the electrode.

There is great similarity in the mass movements or turning movements which Foerster obtained from the different "extra pyramidal" cortical areas outside the Rolandic cortex, and it seems likely that use of strong faradic currents made it possible to obtain them and that they are in reality evidence of an epileptiform discharge. Adversive movements occur so frequently during such discharges, in various localities as soon as the discharge involves any considerable part of the hemisphere, that it seems probable the mechanism of its production is brought into play by the fit without its being a manifestation of localized cortical function.

As a simple motor response adversive head-turning is produced occasionally from the lower end of the precentral gyrus, while conjugate contralateral deviation of the eyes may be produced by stimulation in the vicinity of Area 8 *alpha*, *beta*, *delta* in and just anterior to the precentral gyrus.

Our results indicate that stimulation of the precentral gyrus in a zone next the central fissure most frequently gives rise to motor movements (fig. 29). But with no increase in stimulation strength there are in numerous cases responses from points anywhere over the precentral gyrus. From the postcentral gyrus also, but much less frequently, motor responses may be obtained, especially its anterior lip as shown in fig. 29.

Thus our results from stimulation resemble those of Grünbaum and Sherrington in the chimpanzee except that they got no responses from the postcentral gyrus (*cf.* figs. 1 and 29). This may be due to a

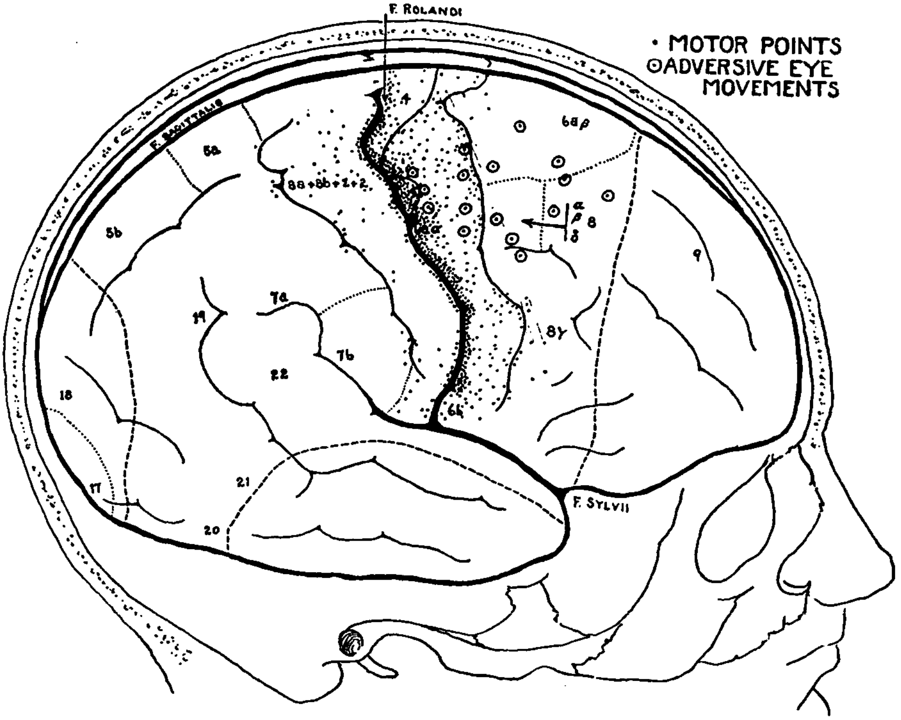


FIG. 29.—Motor cortex. Each black dot represents an actual motor response. The number 4 indicates where Area 4 extends from the anterior wall of the fissure on to the surface, according to Vogt. The remainder of the outer surface of the precentral gyrus is made up of Area 6*a alpha*. ⊙ = conjugate movements of eyes to the opposite side or upward.

difference in man and anthropoid, or more likely it is due to the light anæsthesia which it was necessary for them to use during the stimulation. If in fig. 1 the cytoarchitectural map of Bucy below be compared with the stimulation map of Grünbaum and Sherrington above it is evident that the motor responses occurred in both 4 and 6 with no particular tendency to follow the cytoarchitectural pattern, except to cover about the same extent anterior to the central fissure. In the same way in fig. 29, where every dot indicates a response, it is shown that close proximity to the fissure on the precentral gyrus renders response most likely without any particular change in those regions where Area 4 spreads out on the surface.

As Area 4 occupies the whole anterior wall of the central fissure this is no doubt the part activated, but Area 6*a alpha* on the precentral gyrus obviously contains neuronal connections with 4, which may often be activated by a minimal stimulus. Such secondary connections must

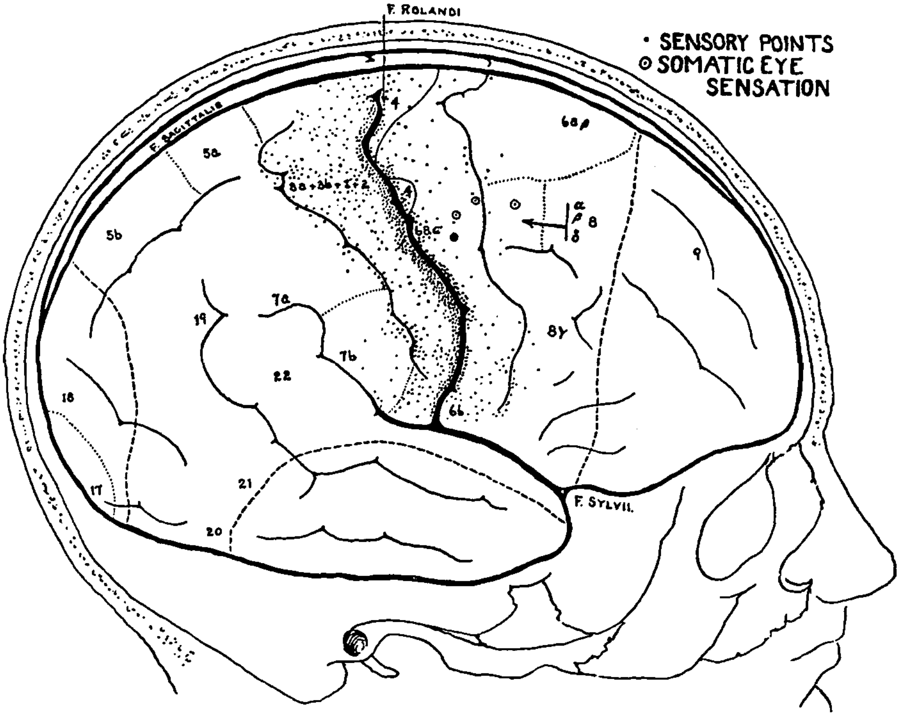


FIG. 30—Sensory cortex. Black dots represent actual sensory responses in some part of the body. ⊙ = sensation in the eyes.

also be possible from the postcentral convolution, especially for movements of hand, arm and shoulder (fig. 14), although these connections are less numerous or less stimulable.

Including these secondary areas the motor cortex, in the broadest sense, should be said to include precentral and postcentral convolutions; that is Areas 4, 6*a alpha*, 3, 1 and 2. But Area 8 *alpha beta delta* probably should be added, as conjugate deviation of the eyes seems to extend forward over this general region as shown by the dotted circles in fig. 29.

Similarly, cortical representation of somatic sensation is found in the postcentral convolution and most often in its anterior lip. But it is also found in Areas 4 and 6*a alpha* of the precentral gyrus (fig. 30). Here again it is impossible to tell from stimulation results whether the responses are obtained primarily at one point and secondarily at another. The fact is that the responses were obtained by the same strength of stimulus, usually minimal. The extension of sensation over the precentral gyrus is more frequent than of motor responses over the postcentral gyrus (*cf.* figs. 29 and 30).

These results are in perfect accord with the anatomical work of Poliak (1932) who predicted that sensory representation would prove to be both pre- and postcentral. It also conforms to the theories of Dusser de Barenne (1935, 1936) based upon strychninization of the cerebral cortex. His work suggests clearly that both pre- and postcentral gyri are normally involved in some way in the elaboration of cortical sensation.

It is not infrequent that stimulation produces sensation and movement both in the same part, but never sensation in one and movement in another. So far as our own results go, therefore, it seems appropriate to refer in a broad sense to sensori-motor Rolandic cortex. The invariable consistency of both motor and sensory sequence, however, indicates that within this general area there are two clearly separable anatomical patterns, one sensory and one motor, and that the sensory and motor elements for each part are closely related to each other.

Stimulation along a zone that crosses the precentral and postcentral convolutions roughly at right angles may activate one of the sensory elements as though circuits in both convolutions were normally involved in the registering of sensation. The same is true of the motor representation although it will be seen in figs. 25A and 29 that motor encroachment upon the postcentral gyrus is infrequent in the inferior half of this gyrus except for a small area adjacent to the fissure of Sylvius. The relative frequency of extension of motor and sensory responses across the central fissure for each region of the body may be seen in figs. 26 and 27. Both motor and sensory points seem to be constant for any one individual, but there is great variation in the topographical position of each point from patient to patient.

Ocular sensation, although rare, does exist. It is usually a sense of movement. This might be expected, a priori, when one considers the fact that there is only sense of pain and sense of position in the eye, and sense of pain has little if any representation in the cortex. These ocular sensation responses were few in number but were situated anterior to the central fissure as shown by the dotted circles in fig, 30, corresponding with the conjugate eye movements shown in fig. 29.

Ipsilateral response practically does not exist for motor movements. Only in one case out of 126 explorations did an isolated movement occur and that was of the ipsilateral side of the face. But this was produced from outside the Rolandic cortex and was due to the effect of an epileptogenic lesion. Foerster (1936B) also reported that he never obtained ipsilateral response but stated that Penfield had done so. This must have been a misunderstanding.[1] The same is true for sensation, which is always contralateral, not ipsilateral, even in the tongue and face.

Bilateral sensory responses, however, do occur as epigastic aura and head aura. Bilateral sensation occurs also in face, tongue and eyes. Bilateral movement likewise occurs only in eyes, face, tongue and jaw. This bilateral response is in such striking contrast to its complete absence in the extremities that it must indicate a small degree of true representation of bilateral function in each hemisphere.

Displacement of response by secondary facilitation, which has long been known to be possible for motor points in animals, is also possible for sensory points. Occasional great spread of responses over the cortex due to the influence of an epileptic process and the facilitation sometimes produced by that condition is discussed above but will be taken up at greater length in a subsequent publication.

Vocalization (fig. 11) is a phenomenon with well-circumscribed representation in each precentral gyrus. It is made up of a well-formed loud vowel sound which continues until the patient's breath is exhausted, and indeed he may actually begin again after drawing a breath if the stimulation is continued. It is quite distinct from the grunting which has been previously described and which seems to have its representation at a point lower in the Rolandic cortex and nearer the fissure of Sylvius.

Quality of cortical sensation seems to have no particular localization. Numbness and tingling were the descriptive terms most often used. The frequency (forty-nine responses) of sense-of-movement which was predominantly postcentral is of particular interest in view of the desire-to-move which was precentral in distribution (fig. 20). The fact that

[1] This misunderstanding may have resulted from informal conversations with my friend Professor Foerster. At all events I can now corroborate his finding in this regard completely.—W.P.

only eleven times out of well over 800 responses did the patient use the word pain to describe a cortical sensation, probably indicates that pain has little, if any, true cortical representation. The pain was never severe and never caused the patient to object. The diffuse bodily sensations occasionally produced by stimulation of Area 6*a beta* must await further verification from a larger number of cases. The same is true of epigastric aura which seemed to have a localization in the parietal lobe near the mid-line posterior to the postcentral gyrus.

The responses of the cerebral cortex to punctate stimulation are crude. The movements are never dexterous and the sensations are simple, like elements in a Jacksonian march. But however much these responses may caricature true physiological function they nevertheless give insight into the rôle which the sensori-motor cortex must play in the process of integration. And these human records have certain advantages over experimental evidence, for an animal cannot speak and must be anæsthetized, while a patient usually shows a keen, and often impersonal, interest in the activity of his own cerebral cortex.

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