FUNCTIONS OF FRONTAL ASSOCIATION AREA IN PRIMATES

C. F. JACOBSEN, PH.D.
NEW HAVEN, CONN.

Each frontal lobe, which consists of the tissue in the cerebral hemisphere lying anterior to the fissure of Rolando, may be divided into three major fields: the motor and the premotor area, already discussed by Bucy [1] and by Fulton and Viets [2] and the association area. The present communication concerns itself with the function of the association area; the terms "frontal association area," "frontal area" and "prefrontal area" are used interchangeably to designate that portion of the frontal lobe which lies anterior to the motor and the premotor area.

It is nearly one hundred years since misfortune befell Phineas Gage and gave to neurologic literature the famous "American crowbar case." The functions of the frontal area and the disturbances of behavior ensuing from lesions of this so-called "silent" area, have continued to interest both the clinical neurologist and the student of cerebral physiology. The Italian neurologist, Bianchi,[3] has summarized the defect following injury to the frontal area as a reduction in the capacity for "synthesizing" and for "serializing" groups of impressions without an obvious impairment of the capacity for receiving individual sensory impressions. The advances in modern surgical treatment of the brain have yielded clinical material of even greater value than have the earlier pathologic studies, since the longer survival of the patient makes possible the postoperative analysis of transient and residual deficits. The

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Dr. J. F. Fulton and Dr. Margaret Kennard cooperated in the surgical work of the investigation, which has been a joint undertaking of the Laboratories of Physiology and of Comparative Psychobiology. A detailed report of the experiments on monkeys will be made in another journal; the results obtained in the experiments on chimpanzees will be reported by Jacobsen, Fulton and Wolfe.

1. Bucy, P. C.: Frontal Lobes of Primates; Relation of Cytoarchitecture to Functional Activity, Arch. Neurol. & Psychiat., this issue, p. 546.

2. Fulton, J. F., and Viets, H.: Upper Motor Neuron Lesions, Analysis of Syndromes of Motor and Premotor Areas, J. A. M. A. **104**:357 (Feb. 2) 1935.

3. Bianchi, L.: The Mechanism of the Brain and the Functions of the Frontal Lobes, translated by J. H. MacDonald, New York, William Wood & Company, 1922.

studies of Brickner,[4] Penfield and Evans,[5] German, Fox and their associates [6] and Spurling [7] paralleled in many essential details the experiments on monkeys and on chimpanzees.

Brickner,[4] in harmony with Bianchi's formulation, interpreted the fundamental disturbance of behavior associated with injury to the prefrontal area as a defect in synthesis; he indicated that although relatively simple material may be adequately synthesized, there exists a discernible, although not objectively defined, limit to the organization of behavior in a person whose prefrontal areas have been removed. It is my hope that the experimental analysis of the functions of the frontal lobe in the lower primates may throw further light on the nature of the disturbances of behavior and may indicate in more objective terms the conditions under which synthesis breaks down.

METHODS

Except for a characteristic restlessness, the behavior in the cage of a monkey that has undergone bilateral extirpation of the prefrontal area can scarcely be distinguished from that of an intact animal. Hence, in studying the more complex responses of animals it is necessary to supplement the usual observational technics with procedures for objective training. Since the tests have been described in detail elsewhere,[8] only the essential features will be indicated here.

Visual Discrimination.—In these tests, the animals learned to discriminate between: (*a*) a white and a black square; (*b*) two squares of different sizes, independently of the absolute size, and (*c*) various patterns, such as a square and a circle, a diamond and a triangle and a cross and a crescent.

Problem Boxes.—In order to obtain the food which had been concealed inside the problem box, the monkeys learned the manipulation of various locks, such as turning a crank, pulling ropes and levers, raising a handle and unfastening a hook.

Delayed Response.—In this test the animal observed the hiding of food under one of two identical cups; after a delay of a few seconds or of a few minutes it was allowed to choose one of the two test objects; if the selection was correct

4. Brickner, R. M.: An Interpretation of Frontal Lobe Function Based Upon the Study of a Case of Partial Bilateral Frontal Lobectomy, A. Research Nerv. & Ment. Dis., Proc. **13**:259, 1932.

5. Penfield, W., and Evans, J.: Functional Defects Produced by Cerebral Lobectomies, A. Research Nerv. & Ment. Dis., Proc. **13**:352, 1932.

6. German, W. G., and Fox, J. C.: Observations Following Unilateral Lobectomies, A. Research Nerv. & Ment. Dis., Proc. **13**:378, 1932.

7. Spurling, R. G.: Notes on the Functional Activity of the Prefrontal Lobes, South. M. J. **27**:4 (Jan.) 1934.

8. Jacobsen, C. F.: (*a*) A Study of Cerebral Function in Learning: The Frontal Lobes, J. Comp. Neurol. **52**:271 (April) 1931; (*b*) Influence of Motor and Premotor Area Lesions Upon the Retention of Skilled Movements in Monkeys and Chimpanzees, A. Research Nerv. & Ment. Dis., Proc. **13**:225, 1932. (*c*) Fulton, J. F.; Jacobsen, C. F., and Kennard, Margaret A.: A Note Concerning the Relation of the Frontal Lobes to Posture and Forced Grasping in Monkeys, Brain **55**:524, 1932.

it obtained the morsel of food, but if wrong, it was returned to the cage to wait the next trial.

For the purpose of later discussion it is desirable to emphasize certain characteristics of the tests. In the tests for visual discrimination and in the tests with the problem box, the essential cues which determine the animal's response are available in the subject's immediate environment at the time of the response; for example, the monkey can and does compare the two squares in the selection of the larger. But in the test of delayed response, immediate memory plays an important rôle, and it is necessary for the subject to recall the recent experience of seeing the food placed under one of the cups. Thus, while the sight of the cups may serve as a stimulus to recall the recent experience, it is not in itself adequate to give the differential cue necessary for a correct response.

EXPERIMENTAL RESULTS

Unilateral Lesions of the Prefrontal Area.—Unilateral lesions of the prefrontal cortex resulted in no impairment of the memory for the various tests which had been learned or of the ability to learn new problems. There was no evidence that either the right or the left frontal area was dominant over the other.

Bilateral Lesions of the Prefrontal Area.—Following bilateral lesions of the prefrontal area, either partial or complete, the results obtained differed in the two types of tests. After a complete bilateral extirpation the memory for the simple formed habits in the test with the problem box was unimpaired, and the ability to learn new habits of a similar nature was normal. Likewise, the adjustments to the tests for visual discrimination, whether they required discrimination on the basis of size, of form or of brightness, were not affected, and the animals lacking the prefrontal areas exhibited a normal ability to learn new visual discriminations.[8a] The tests of delayed response, however, revealed a profound deficit in what may be termed the recent or "immediate memory" (chart 1). Before operation the animal (frontal series, no. 5) scored a high percentage of correct responses after delays of fifteen, thirty and forty-five seconds. As the delays increased beyond one minute, however, the accuracy of performance decreased rapidly until after delays of one hundred and twenty seconds, the percentage of correct choices had no greater than a chance value. An inspection of chart 1 reveals that the complete removal of the frontal area on the left side did not impair the ability to execute the test of delayed response. However, the extirpation as well of the frontal association area of the opposite side permanently abolished the capacity for immediate memory, as measured by the test of delayed response. When placed in the testing cage, the animal observed with eagerness the loading of the food under one of the cups, and if it was permitted to seek the cup immediately, it made a correct choice in more than 90

per cent of the instances. However, if a delay as short as two seconds was interposed between the loading of the cups and the choice between them, the rate of accuracy of the response dropped to a value that might be obtained by chance. In a similar manner, when the animal responded to the loading of the cups without the introduction of delay, the momentary distraction of attention by incidental noises reduced the score to a mere chance value. It is significant that during the same periods in which the animal failed so completely in the test of delayed response, it skilfully manipulated the problem boxes and reacted with an accuracy of over 85 per cent to the tests for visual discrimination. Thus, the defect in the mechanism for delayed reaction cannot be regarded as a generalized deterioration of intelligence; it appears rather

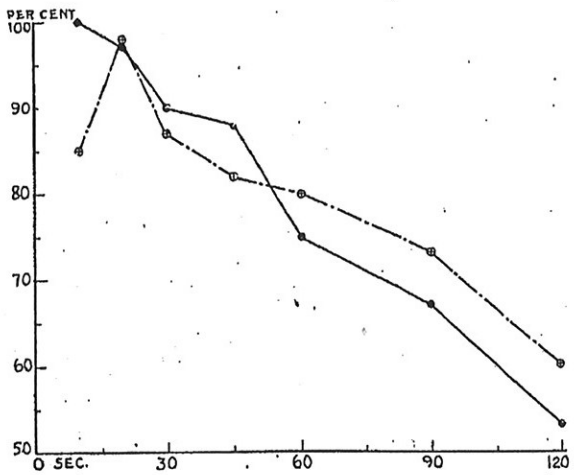

Chart 1.—Training record in tests of delayed response in a mangabey monkey, Cercocebus torquatus lunulatus (frontal series, no. 5), which underwent complete bilateral extirpation of the prefrontal area in two stages. In this chart and in the accompanying charts, the ordinates represent the percentage of correct choices; the abscissas, the length of the delay expressed in seconds. Likewise, the normal reactions of the preoperative period are indicated by a solid line with solid circles, and those following unilateral extirpation, by a broken line with circles and crosses. Complete failure to respond to the tests followed the bilateral extirpation.

to be a specific impairment of recent memory existing in the face of the normal adjustments made to other situations.

Partial Lesions of the Prefrontal Area.—The character of the deficit in memory is brought out more clearly by cases of incomplete lesions of the prefrontal area. In the preoperative tests (chart 2) the subject responded with a high degree of accuracy after delays of ninety seconds or less. As in the case of animal 5 of the frontal series, the extirpation

of one frontal lobe did not materially influence the performance; if anything, the monkey profited slightly from the additional training. The anterior portion of the remaining frontal association area was then excised, leaving intact a band of cortical tissue several millimeters in width lying anterior to the premotor area. In this instance the animal responded with a score of over 80 per cent after delays of from five to ten seconds, but it failed when the delays exceeded ten or fifteen seconds. There can be no question of the animal's ability to attend to the loading of the cups and to remember this experience for a short time. The retention of habits previously acquired with the problem box tests and the mastery of new tasks of a similar nature were not impaired by the lesion. During the eight months of postoperative

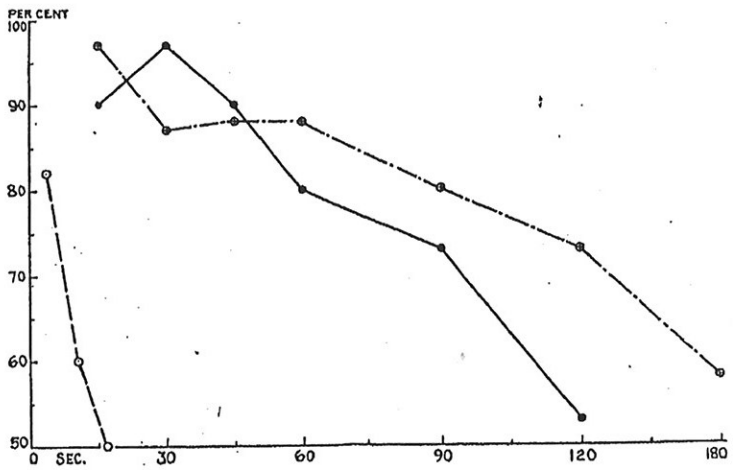

Chart 2.—Training record in tests of delayed response for a baboon, Papio papio (frontal series, no. 9), which underwent complete extirpation of the left prefrontal area and ablation of the anterior portion of the right prefrontal area. The broken line with hollow circles indicates the results obtained in the tests after the incomplete bilateral extirpation.

reeducation, more than forty times the number of trials which had been required to learn the problem in the preoperative training were given, but there was no significant improvement over the level of performance as it was measured one month after operation.

Lesions of Other Cortical Areas.—It is pertinent to inquire whether the defect in immediate memory is peculiar to lesions of the frontal association areas or whether it may also be found after injuries to other areas of the cortex. On this point the data are not as complete at the present time as might be desired, but it is significant that there have been no indications that lesions in other areas of the cortex abolish the

ability to perform the tests of delayed response. The areas which have been thus far investigated include the parietal association area, the premotor area and the temporal lobe. The results obtained from bilateral extirpation of the parietal association area are presented in chart 3 (frontal series, no. 8). If any difference is ascribed to the curves, one is forced to conclude that the performance improved after bilateral extirpation of the parietal association area. This animal was subjected to further experimentation, and the frontal association area of the left side was subsequently removed. Although the test has not been completed, no impairment of the subject's ability to respond after delays of at least forty-five seconds is indicated. The interpretation that the disturbance of recent memory is peculiarly dependent on lesions of the frontal lobes

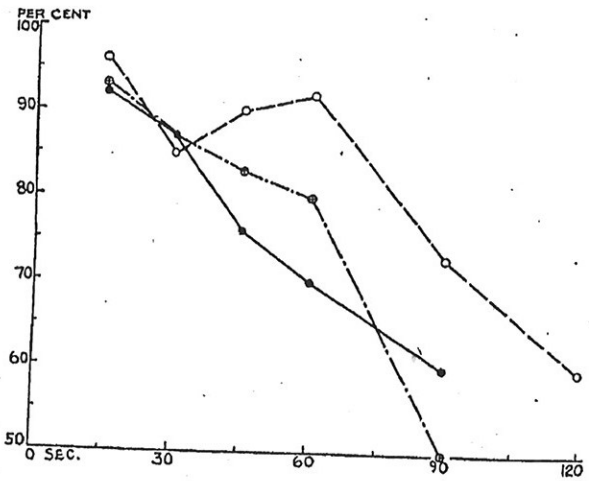

Chart 3.—Training record in the tests of delayed response for a mangabey monkey, Cercocebus torquatus lunulatus (frontal series, no. 8), which underwent bilateral extirpation of the parietal association area in two stages. The broken line with hollow circles represents the results of the test following the second operation.

is further supported by Breslau's [9] experiment on the postcentral gyrus which he removed bilaterally without the impairment of ability. The mass of cortical tissue involved in the animal (frontal series, no. 8) with extirpation of both parietal association areas and of one frontal area exceeded that in the animal with bilateral extirpation of the frontal lobe (frontal series, no. 5). Hence, the defect in behavior cannot be attributed merely to the extensive injury of the cortex. On the other

9. Breslau, B.; Barrera, S. E., and Warden, C. J.: The Effect of Removal of the Postcentral Convolution of the Macacus Rhesus Monkey upon Delayed Response, J. Comp. Psychol. **18**:207 (Oct.) 1934.

hand, the specificity of the frontal area is indicated in the mediation of the function which is measured by the test of delayed response.

COMMENT

It is evident from the foregoing material that bilateral lesions of the frontal association area modify certain aspects of the animal's behavior, while leaving intact the neural mechanisms requisite to its adjustment to other situations. The basic change associated with lesions of the prefrontal area is the loss of capacity for immediate or for recent memory. Hence it becomes pertinent to inquire whether a monkey without the prefrontal areas is capable of learning problems which, while not measuring immediate memory in the simple situation of the delayed response, depend on a capacity for immediate memory for their solution.

Jacobsen and Nissen [10] taught monkeys to open alternately a pair of doors in the training cage. Since the doors in themselves gave no differential cues on successive trials, it was necessary for the animal to remember which of the doors had been selected in the preceding trial. Bilateral extirpation of the frontal association area resulted in complete loss of this habit, and it is of even greater interest that in more than a thousand trials during postoperative training the problem was not relearned. This test illustrates another interesting aspect of the behavior of animals which have undergone the operation. The normal monkey in learning to respond to this situation readily became discouraged if it chanced to make as many as five or six successive errors, and even under the best of conditions it rarely made more than twenty or twenty-five trials per day. On the other hand, the animal which had been operated on performed as many as one hundred and fifty trials in a single period, in spite of the fact that it made frequent mistakes and that fifteen or twenty trials might be performed without a correct reaction. It seemed that the animal which had been operated on had little realization of the failures which before operation had disrupted the procedure of training.

Relation of Experimental and Clinical Studies.—The case of bilateral frontal lobectomy studied by Brickner [4] and his associates is particularly interesting because of the sharply marked surgical limitation of the lesion and because of the probable absence of complicating factors which usually mark the further growth of a neoplasm. Lack of restraint, as seen in the hostility of the patient toward his family and his friends, boastfulness, self-aggrandizement and distractibility characterized the patient during the postoperative period. The remote memory was less

10. Jacobsen, C. F., and Nissen, H. W.: The Influence of Frontal Lobe Lesions on the Delayed Alternation Habit, to be published.

impaired than was the memory for recent events, which was variable and faulty. There were indications that, although the learning of simple facts could be accomplished, the mastery of complex problems was difficult if not impossible. It was in the realm of the complex activities which are included under the terms reasoning, logical thinking and solving of problems that the intellectual defect showed itself most clearly. Spatial orientation was good, but orientation in time was faulty. Thus, the patient was disoriented as to the day of the week or of the month, and he had difficulty in remembering whether a given event had occurred a few days or several months previously, although the event itself could be recalled.

The fundamental deficiency in this case and in other cases of prefrontal lesions in man has been interpreted as a failure in synthesis, especially in synthesis of a more complex nature. But my associates and I in the experiments with the lower primates have shown that for such tasks as visual discrimination and the manipulation of the problem box both the memory and the ability to learn were normal. Hence it does not suffice to characterize the defect simply as a diminution of the capacity to learn or to synthesize, or to say that simple problems can be learned but that complex acts cannot be mastered, since in fact the impaired habits required less training than the responses which were retained. In the light of the results obtained from the experiments in delayed response, the description may be carried one step further. After an injury to the prefrontal areas those activities of the organism which in their very nature demand integration over a period of time cannot be carried out effectively. Temporal patterning fails because the subject can no longer remember a single experience for even a few seconds in the face of new incoming sensory data. The loss is not unlike that described by Bouman and Grünbaum [11] in their discussion of organic dementia—an inability to keep in mind a number of separate elements and at the same time to manipulate them in thought.

If allowance is made for the richer and more diversified nature of human behavior and primary consideration given to the functional equivalents in the adjustment to environment, the similarity between the deficiencies in behavior in man and those in the lower primates after prefrontal injury is indeed striking. To identify the processes of human thinking with those of delayed response in the monkey leaves one open to criticism; nevertheless it is pointed out that with the destruction of the frontal association areas a mechanism has been removed that is essential to the more complex forms of behavior, which are termed

11. Bouman, L., and Grünbaum, A. A.: Experimentell-psychologische Untersuchungen zur Aphasie und Paraphasie, Ztschr. f. d. ges. Neurol. u. Psychiat. 96:481, 1925; cited by Lashley and Wiley.[12c]

logical thinking, judgment, and so on—that is, the capacity to organize the activity of the moment in terms of the immediate past experience. This ability seems to be peculiarly dependent on the intactness of the frontal areas.

Restitution of Function After Cortical Lesions.—The problem of the restitution of function after cortical lesions of greater or less severity is one of importance to the clinical neurologist as well as to the student of cerebral physiology. It has been recognized that after many cortical injuries a degree of functional recovery is possible, although, as Lashley [12] has pointed out, the mechanism of such a restitution is by no means clear. In the present experiment many times the amount of training required for preoperative learning was given the animals which had suffered complete bilateral lesion of the frontal association area, but there was no indication that they profited from the training. Harlow [13] studied the effects of the extension of the bilateral prefrontal lesions, produced by the periodic insertion of capsules of radon into the brain. The successively poorer performance in the tests of delayed reaction was correlated with the increasing size of the prefrontal lesion. In the cases in which the spread of the lesion was arrested before the complete abolition of function, more than a thousand trials for reeducation were given to the animal, but without significant improvement. Thus it seems likely that the extent of the lesion set a definite limit to the level of performance which was not altered by long and exhaustive training in the particular task. The course of recovery as noted in Brickner's patient is essentially in harmony with the results that we have obtained from extensive lesions in the monkey and the chimpanzee. With respect to the basic defects of behavior, Brickner's patient showed little improvement in the three or four years of postoperative life. He learned to make certain superficial adjustments to his social environment, but the basic defects, especially in the intellectual sphere, remained relatively unaltered.

The gradual but excellent recovery reported by Spurling [7] following unilateral lobectomy and the severe compression of the opposite prefrontal area stands in sharp contrast to that of the poorly oriented patient described by Brickner after a destructive bilateral lesion of the prefrontal area. It at once becomes apparent, both from the clinical and from the experimental data, that a degree of function is possible provided a cer-

12. Lashley, K. S.: (*a*) Integrative Functions of the Cerebral Cortex, Physiol. Rev. **13**:1 (Jan.) 1933; (*b*) Brain Mechanisms and Intelligence, Chicago, University of Chicago Press, 1929. (*c*) Lashley, K. S., and Wiley, L. E.: Studies of Cerebral Function in Learning: IX. Mass Action in Relation to Number of Elements in Problem to be Learned, J. Comp. Neurol. **57**:3 (Feb.) 1933.

13. Harlow, H. F.: Personal communication.

tain minimum of tissue of the frontal area remains intact but that a definite limit to the degree of function remains in spite of extensive reeducation after operation.

Equipotentiality of Cortical Areas.—A problem closely associated with the restitution of function and the limitation of recovery is the functional equipotentiality of different cortical areas. Lashley's [12] observations on the cortex of the rat clearly indicated that for certain problems a high degree of functional equivalence exists between the various cortical areas and that the extent of recovery bears a definite relation to the mass of intact cortical tissue, regardless of the locus of that tissue. It is apparent both from the experimental data obtained by my associates and me and from clinical observations that the widespread equipotentiality which Lashley found to operate in the rat does not exist in the brain of the primate. Thus, the delayed response could not be reacquired by animals after bilateral lesions of the frontal lobe, and in the case of partial lesions the degree of function could not be materially improved. This impairment, however, cannot be attributed to the mere destruction of cortical tissue, since even larger lesions of other parts of the cortex were made without the disturbance of the functions which are disrupted by lesions of the frontal area. It seems probable that between the functional activity of the brain of the rodent and that of the primate a further specialization has taken place, not only in the sensory and motor fields, as has been recognized, but in the associative functions of the organism. It would be erroneous, however, to leave the impression that the principle of mass action does not apply to the brain of the primate. No indication has been noted that a particular region of the frontal association area is necessary to the execution of these functions, and the available evidence suggests that the degree of the deficit is related to the amount of intact tissue of the frontal lobes. It is possible to harmonize the two divergent views, that of specificity on the one hand and of equipotentiality on the other, by the recognition of the principle, advanced by Poljak [14] and by Lashley,[12b] of areal equipotentiality.

SUMMARY AND CONCLUSIONS

The rôle of the frontal association areas in the mediation of complex behavior has been studied in the lower primates. Monkeys and chimpanzees were trained by several types of behavior tests: First, situations in which the essential cues were available in the subject's environment at the time of response, and second, situations in which

14. Poljak, S.: The Main Afferent Fiber Systems of the Cerebral Cortex in Primates, Univ. Calif. Publ. Anat., vol. 2, Berkeley, Calif., University of California Press, 1932.

the essential cues had to be recalled from recent experience. Experimental lesions were then made in various areas of the cerebral cortex, and the ensuing disturbances of behavior were analyzed.

The following conclusions are drawn from the study:

1. Unilateral lesions of the frontal association area (prefrontal area) resulted in no impairment of performance in any of the tests. There was no evidence of hemispherial dominance.

2. Bilateral prefrontal lesions, either partial or complete, produced different results with the two types of tests. Memory for the habits acquired with the problem box and for the visual discriminations based on size, form or brightness was not impaired, nor was there reduction of the ability to learn new tasks of a similar nature (tests of type 1).

On the other hand, tests which depended on recent memory (tests of type 2) revealed profound deficits. Thus, after complete bilateral lesions, there was severe impairment of recent or of immediate memory after delays as short as two seconds. Incomplete bilateral lesions resulted in shortening of the length of time through which recent memory was effective, but they did not entirely abolish this capacity. The defect in memory cannot be regarded as a generalized deterioration of intelligence but appears to be a specific impairment of recent memory existing in face of the normal adjustments made to other situations.

3. The defect of recent memory cannot be attributed merely to an extensive injury to the cortex, since lesions to other areas produced minimal, if any, changes; on the other hand, the specificity of the frontal area in the mediation of this function is indicated.

4. The fundamental deficiency in cases of bilateral prefrontal injury in man has been interpreted as one of failure in synthesis. Observations on the lower primates suggest that this failure in synthesis and in temporal patterning of behavior is due to a defect of immediate memory.

5. Extensive reeducation after operation failed to reestablish the capacity for immediate memory in animals with complete lesions, and it did not materially improve the performance after partial lesions.

6. The experiments indicate a high degree of specialization in the associative functions of the cortex in primates in contrast to the widespread equipotentiality which has been shown to operate in the cortex of the lower animals.

333 Cedar Street.

ABSTRACT OF DISCUSSION

On Papers of Drs. Bucy and Jacobsen

Dr. T. Diller, Pittsburgh: Reference has been made in this symposium to the famous crowbar case, which occurred one hundred years ago. It was a remarkable case. Ever since that time students have wondered about the frontal lobes. It is said that there are no silent areas in the frontal lobes, with which I agree.

I see considerable clinical difficulty which must be faced by these investigators. In cases of organic lesions in various parts of the brain other than the frontal lobes, mental symptoms may arise. With all of the light that is shed today on the function of the frontal lobes, clarity is still lacking. The confusion which may arise from mental symptoms due to disturbances in other parts of the brain must be borne in mind. Although the material that has been presented here is commendable, it should not be thought that much is known of the frontal lobes.

Dr. A. L. Skoog, Kansas City, Mo.: I should like to ask Dr. Bucy one question. He presented a slide on the screen showing the brain of the monkey and of man in which the frontal and prefrontal areas were blocked out in a large number of small areas, numbered specifically. He gave physiologic data relative to some of these areas, but none on many of the others. The question arises whether the areas really represent cleancut physiologic territories as Dr. Bucy suggested. I question whether they can be too closely implied in clinical psychiatric practice.

Dr. Henry R. Viets, Boston: Dr. Bucy's note regarding the localizing value of forced grasping is, of course, of great importance to clinical neurologists. I think the point should be made that unilateral forced grasping has marked localizing significance, whereas bilateral forced grasping has much less. As Dr. Bucy has pointed out, general intracranial pressure may give rise to bilateral forced grasping and may not indicate a primary lesion of the premotor area.

Dr. Walker Freeman, Washington, D. C.: I hope that Dr. Bucy's previous work on forced grasping resulting from lesions in other locations in the brain will not come back to plague him. It is my opinion that in cases of many acute lesions of the brain this phenomenon can be elicited but that in the chronic preparations forced grasping is characteristic of lesions in the premotor area or in its underlying tissues.

Dr. C. F. Jacobson, New Haven, Conn.: In reply to Dr. Diller's question I wish to say that I agree with him that mental disturbances may result from lesions of other portions of the cortex.

The point in which I was particularly interested was the patterning of the defects which are associated particularly with the frontal area. It is also possible that mental disturbances may be found in cases of lesions in other portions of the cortex and may be due to secondary factors, such as increased pressure.

Dr. Paul C. Bucy, Chicago: Dr. Freeman spoke of the two cases of forced grasping associated with lesions outside of the frontal lobes which I reported a few years ago. Both of the cases were of tumors, and in both bilateral forced grasping was manifested. These cases are not arguments against the origin of forced grasping from lesions of area 6; they merely point out that in cases of increased intracranial pressure forced grasping, especially when bilateral, is of little localizing significance.

Dr. Skoog asked concerning the physiologic significance of the numerous cytoarchitectonic fields of the human frontal lobe. These fields are purely anatomic and are localized by means of microscopic examination. The physiologic significance of most of them is as yet unknown.