# A Further Experimental Analysis of the Behavioral Deficit That Follows Injury to the Primate Frontal Cortex

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The results of seven experiments that use monkeys are reported. Behavior is examined in modifications of the Yerkes or Wisconsin General Testing Apparatus and in operant conditioning situations. The focus of the studies is the effect on behavior of removal of the frontal eugranular isocortex; unoperated controls and controls with the inferotemporal cortex removed serve as background to the studies. The first two experiments test whether the effects of frontal lesions are restricted to the visual or the somatic sensory mode. The results show that they are not. The next two experiments test whether the effects of the lesion are similar to changes in behavior produced by starvation. Again the results show that there is no similarity. However, the experiment that follows reveals an interesting finding: Monkeys with frontal lesions do not react as do the controls when the test apparatus runs out (deliberately) of rewards. The final pair of experiments explore further the conditions over which this altered behavior can be demonstrated. The results of these experiments show that when the situation is made ambiguous in one manner—i.e., by increasing the number of alternatives of choice—the frontal injury has no effect. On the other hand, the lesions do modify behavior when the ambiguity of the situation is increased by making the relationships between stimuli (cueing or reinforcing) and response variable, i.e., unreliable.

## Introduction

In the neurological clinic injury to the "association areas" is often accompanied by agnosias and apraxias that are secondarily related to one

or another of the sense modalities. Experiments with monkeys have shown that removals of the more posteriorly located of these areas, i.e., those covering the parietal, temporal, and preoccipital convexity of the hemisphere, result in specific defects in capacities to perform complex tasks and that the locus of removal is correlated with the sensory mode to which the impairment is restricted (23). But, with few exceptions (2), the effects of frontal injury have not as yet been rigorously examined with the question of modality-specificity in view. Anatomical, electrophysiological, and psychological considerations suggest that an experimental program initiated by this issue would prove interesting.

Among the exciting discoveries of the past few years have been those which describe a series of nonmodality specific systems within the internal core of the cephalic portion of the neuraxis. These systems share the characteristic that neural activity arising in a variety of receptors converges on units within these systems (17).

The thalamic portions of these systems include the central, mid-line, and intralaminar nuclear complex and the anterior thalamic group. Starzl and Whitlock (36) systematically plotted the cortical sites where "following" or "recruiting" of the electrical response occurs when the thalamus is stimulated by repetitive (6 per second) electrical excitation. They found that the association areas and the areas on the medial and basal surfaces of the hemisphere were especially responsive. However, the effects on the posterior "association" cortex are limited in distribution to a very small portion of this cortex—that which is the projection of the nucleus lateralis posterior of the thalamus (8). The characteristics of the response in this posterior cortex were "feeble," smaller, and often imperfectly following the stimulus. On the other hand, the effect obtained in the frontal area (projection of n. medialis dorsalis) was clear-cut. This finding poses the question as to whether the frontal cortex has some special affinities to the nonspecific systems.

Comparative anatomical studies of the dorsal thalamus throw some light on the problem (25). The nucleus medialis dorsalis which projects to the frontal "association" cortex is cradled within the "nonspecific" central, mid-line, and intralaminar nuclear groups and its boundaries are in many species indistinguishable (31). These data plus the fact that this nucleus shares with the "nonspecific" nuclei, electrophysiological characteristics from which strong cortical recruiting can be obtained gives substance to the question: Are the effects on behavior of frontal injury modality-specific, or are they not?

The tasks which monkeys with frontal lesions can no longer perform have been detailed a decade or so ago (12). Many are somewhat similar to the ordinary "shell game"—the delayed reaction and alternation. These tasks were originally devised to demonstrate that animals could have rudimentary "ideas"—ideas which help solve problems when the clues to the solution of these problems are given only prior to and not at the time of opportunity for solution (15). The question has been raised, though never satisfactorily answered, whether the performance of these tasks depends on some proprioceptive or kinesthetically maintained memory trace. The decrement in performance in delayed reaction or alternation tasks that follows frontal injury could therefore be related to a single mode.

An important alternative to the "kinesthetic" hypothesis has been suggested—that the visual mode is especially involved in the deficit that follows frontal injury. This suggestion derives in part from the fact that vision is necessary for the performance of most tasks used in animal behavior experiments. In addition, the cortical area implicated in delayed reaction and alternation and in the clinical neurological "frontal" syndrome is adjacent to and overlaps the "frontal eye fields" (24, 30).

Denny-Brown (9) ably summarized this view as follows: "The types of visual response which are served by the frontal lobe proper can be narrowed down by exclusion, but are difficult to define. They are not optical fixation or visual attention, though the mechanism for these is certainly inefficient for a brief time after frontal excision. There may be a difficulty in transferring fixation from one object to another, but this appears to result from an overaction of the occipital fixation system. It is certainly not visual recognition of objects, though this also suffers in the first impact of ablation. It is a defect in behavior in response to visual events projected in time. Such a defect in behavior includes not only the motor response but also the affective reaction that accompanies any projected behavior, including the appropriate fear, excitement, or rage. Indeed, in our view, interest, and hence sustained attention and initiative, are also such emotional appendages, attached to the sensorimotor process, in the same manner as consciousness, in the sense propounded by Hughlings Jackson (1931). A most illuminating remark in this connection was made by a patient of Freeman and Watts (1942) after leucotomy: 'Now that I have done it, I can see that it was not the thing to do, but beforehand I couldn't say whether or not it would be right.' He could under-

stand the consequences of an act when they were explained to him, that is, presented through other senses, or directly visualized, but did not behave appropriately, or 'visualize the consequences' to the actual situation. Such patients can visualize objects or scenes. The difficulty is abstract, projected in time and space, and directly concerned with visualizing motor and affective resultants. It is more dynamic than 'imagination.' It is this inability to visualize consequences which is the unique effect of leucotomy".

Seven experiments employing monkeys (*Macaca mulatta*) are reported herewith. The first of these demonstrates what happens to monkeys' performance of an alternation task after frontal injury even though "place" or "position" are randomized. In this experiment proprioceptive or kinesthetic clues to the solution of the problem are excluded and performance depends essentially on stimulus changes within the visual mode. Then, the second experiment demonstrates what happens when the visual clues to the solution of the alternation problem are, in turn, excluded.

### Experiment I

*Procedure.* The subjects for Experiment I were twelve monkeys, four with bilateral anterior frontal resections, four with bilateral inferior temporal resections (control operation), and four unoperated controls. All animals had had comparable past experience in delayed reaction, alternation, and visual discrimination tasks presented in a Wisconsin General Testing Apparatus (13).[2]

[2] These experiments served in part as behaviorally determined controls for the efficacy of each of the lesions. Just prior to the experiment reported here, classical alternation and visual discrimination tasks were given to the subjects in a Wisconsin General Testing Apparatus. Each of the monkeys with frontal lesions performed at chance for 1,000 trials of alternation; the best score attained by a monkey with an inferior temporal resection was 76 per cent after 1,000 trials in a + vs. discrimination. Unoperated controls reached a 90 per cent criterion on both tasks within 500 trials. These results are in accord with the results obtained by the author and his collaborators in an extensive survey of the behavioral effects of making this type of lesion in monkeys (19, 20, 21, 23, 24, 25).

The rest of the experiments repeated the earlier ones already reported; however, naive subjects were used and somewhat better controls instituted. The results confirmed those of the earlier experiments. However, one additional finding was obtained: Naive monkeys with frontal lesions, although they perform well in the modification of the delayed reaction which uses only a single cup (go-no-go) and distinctive predelay cues, do so at the cost of a considerable number of "correction" errors, i.e., these animals will repeat an erroneous response more often than will controls.
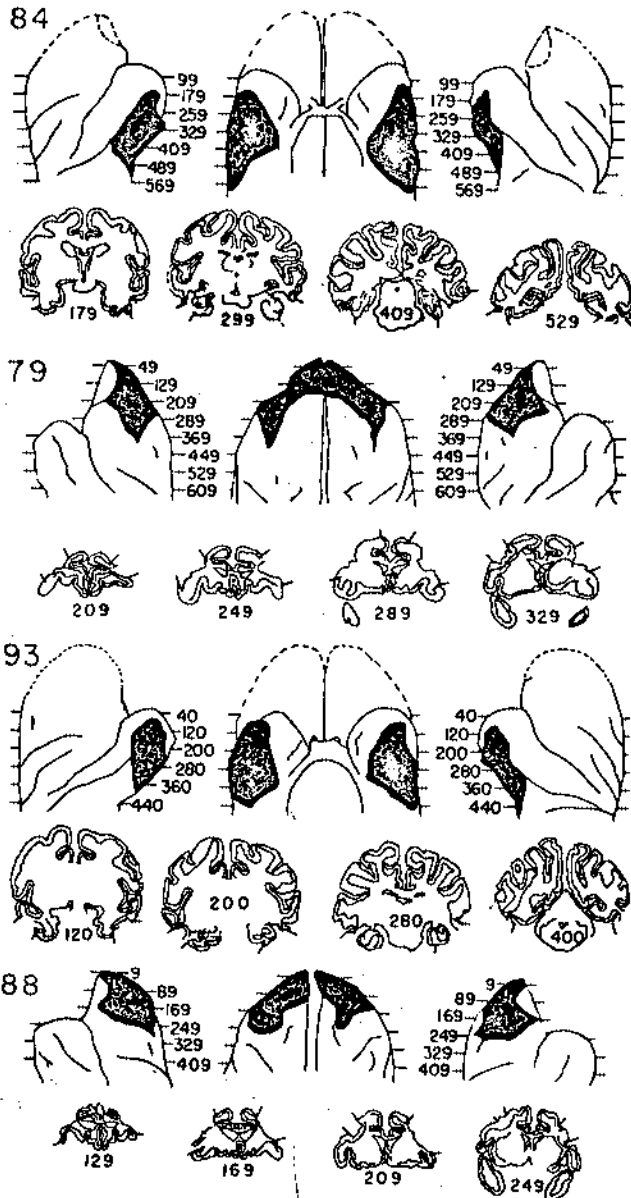
FIG. 1. Sample reconstructions of the extent and depth of lesions in the brains of monkeys used for Experiments I, VI, and VII.

The data for the present experiment were obtained in the period between 18 and 24 months after surgery. Anatomical controls of the site and extent of lesion are presented in Fig. 1. They were prepared after several other experiments had been completed. The brains were fixed in 10 per cent formalin and dehydrated with various concentrations of alcohols; serial sections at 50 μ were then made of the entire brain and stained with anilinethionine, and from these at 2-mm intervals, orthogonal reconstructions of the site and area of lesions were produced. As there was no essential difference between brains or between the behavior of the monkeys in the various test situations, two reconstructions representative of each of the lesion groups are presented in Fig. 1.

Retrograde thalamic degeneration was restricted to the microcellular and perilammellar magnocellular portions of the nucleus medialis dorsalis in the frontally operated group. There was no significant difference between subjects in the extent or location of this degeneration which extended the length of the nucleus. All monkeys with inferotemporal resections showed spotty degeneration in the posterior portion of the nucleus pulvinaris restricted to the inferior half or third of the nucleus. One subject (No. 84) had a wedge-shaped area of degeneration in the lateral portion of the nucleus geniculatus lateralis dorsalis; this degeneration was evident only for approximately the posterior third of the nucleus. No other retrograde degeneration was noted in any of the monkeys' geniculate nuclei.

During the experiment reported here all twelve animals were given 50 trials a day for a total of 1200 trials on a nonspatial object alternation. For the first 500 trials, two objects, a tobacco tin and an ashtray, were presented on a board which contained two holes 1½ inches in diameter and 3 feet apart. For the remaining 700 trials these objects were presented on a board which contained six holes, each with a diameter of 1½ inches, arranged in a circle with a diameter of 2 feet. Each object could cover one hole completely and a peanut could therefore be concealed by the object. The holes were given numbers and on each trial the objects were placed over the holes according to a random number table. On successive trials, a peanut was placed alternately under one and then the other object irrespective of the placement of the object on the board. Trials were separated by the interposition of an opaque screen between the monkey and the test object. The animals were not allowed to correct if they made an error; that is, on any one trial, a

monkey was allowed to manipulate only one object and to uncover one hole to see if a peanut was there. On the next trial, the alternative object was baited and so on throughout the fifty alternations. Trials were spaced approximately 5 sec apart.
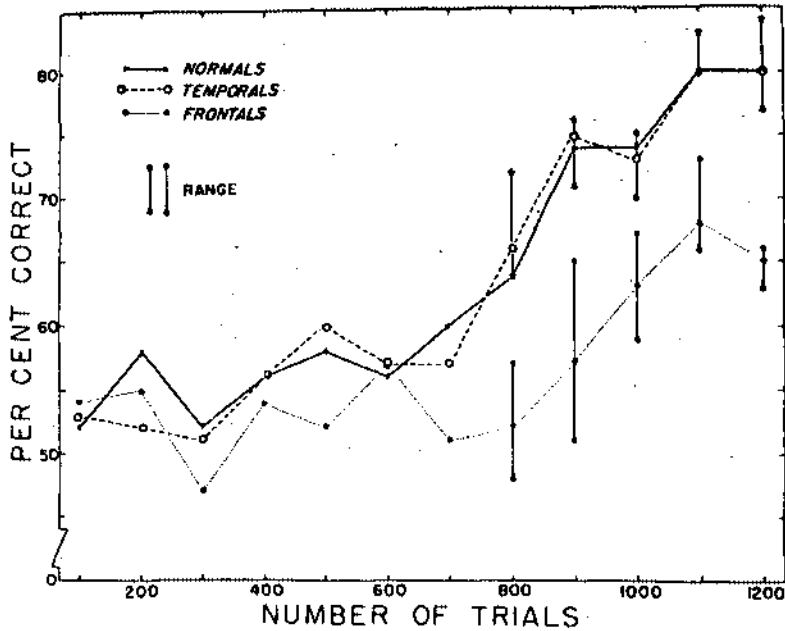


FIG. 2. Performance graph for monkeys in the nonspatial object alternation experiment.

*Results.* Figure 2 shows the performance curves of the three groups on object alternation. Inspection of the figure shows that the control operated and the unoperated control groups reached an average performance of approximately 80 per cent after 1200 trials, whereas the group with anterior frontal resections attained only a 65 per cent level of performance by the end of the training session. During the last 500 trials there is no overlap between the performance of any of the frontally operated animals and that of any of the monkeys in the two control groups. (The difference between all the performance scores of the frontally operated and those of each of the control groups is significant at the 0.03 level by the Fisher exact median test of a 2 × 2 contingency table.)

## Experiment II

*Procedure.* Eight new immature monkeys, two with anterior frontal resections, two with inferior temporal resections (control operation), and four unoperated controls were used in this experiment.

An abandoned icebox was modified to hold a training cage through one side of which a lever (a telephone switch key) extended into the cage. The monkey could press this lever down using very little force. The lever was attached to a spring which pulled it back to the upper position after each lever press. Just above the lever was a ground glass upon which a colored light could be projected. Below the lever was an opening in which was placed a cup. The lever was attached to a microswitch which activated a relay system so constructed that the color of the light on the ground glass and the delivery of peanuts into the cup was controlled in part by the pressing of the lever and in part by a program selected by the experimenter. The programs selected were those described by Ferster and Skinner (11) and called the multiple and mixed schedules of reinforcement. These consist of the following: Specifically after each monkey had been trained to press the lever so as to obtain a reward, a red light on the ground glass signified that he would receive a peanut whenever he had completed forty consecutive lever presses. As soon as he had received the peanut the light would change to green. This signaled that 4 min would elapse until another peanut could be obtained. Pressing during the 4-min interval was of no avail. As soon as the peanut was obtained under the 4-min condition, the red light again switched on. In other words, the red and green lights (and the reinforcement conditions they signified) alternated. The schedule signaled by the red light in this experiment is called a "fixed ratio." When this schedule is in force the animal is rewarded as soon as he has completed the required number of lever presses. The more quickly these presses are accomplished the sooner the animal obtains his peanut reward. The schedule signaled by the green light is called the "fixed interval." When this scedule is in force the animal is not rewarded for the number of lever presses which he performs. Rather, the peanut is delivered after a constant interval, fixed by the experimenter. Thus, the animal is rewarded as much for one lever press made at the appropriate time as for a hundred. The performance records of animals working under these two schedules have been reported repeatedly (11). A rapid but constant rate of lever pressing is generated

in the fixed ratio schedule; an exponentially increasing rate is generated during the fixed interval schedule.

In the present experiment, the eight monkeys were trained until consistent behavior was recorded. Since the two schedules were alternated, the training procedure took approximately 8 months to accomplish. At the end of this time, however, the records of each animal showed little variation from day to day, provided they were tested under constant conditions of food deprivation. In this experiment the monkeys were fed a sufficient amount of laboratory chow immediately after each training session to maintain them at approximately 80 per cent of the weight which they had attained after a 3-week period of *ad libitum* feeding. Daily weighing assured this 80 per cent figure. All animals were tested daily for 1 hour, 6 days of the week.

Following surgery, a 2-week rest period was given all animals. They were then retested for approximately 2 weeks until the preoperatively stable performance was again observed. There was no change in the behavior pattern of the operated and unoperated groups of animals with respect to the discrimination index used (see below); nor were any more subtle changes in behavior observed to follow surgery. Thereupon, the actual experiment was undertaken. The previous 1-hour sessions were extended to 1 hour and 20 min. During the first 20-min period of the session the conditions of testing were exactly the same as those used preoperatively during training and postoperatively during testing of retention of the trained performance. At the end of this 20-min period, a variation was instituted: The (colored) lights that signified which of the two schedules was in force were turned off. All other conditions remained the same; the schedules of reinforcement continued to alternate. Now, however, the alternation of schedules was the clue the animal had as to which of the two behavior patterns was appropriate at any particular time.

Testing was continued for 6 consecutive weeks or until an animal had reached an average performance for 1 whole week such that discrimination between the two schedules was made 85 % of the time. Discrimination was considered to have been made whenever a monkey took a longer period of time to complete the first forty lever presses while the interval schedule was in force than he took to complete the forty lever presses while the ratio schedule was in operation.

Anatomical controls for lesion site and extent, prepared in the same

manner as those in Experiment I, showed similar extent and location of degeneration and are reported in Fig. 3.

*Results.* On the basis of data previously obtained in other situations (23), the prediction was made that the monkeys with inferotemporal lesions would rely less on vision than would the normal group, that these monkeys would therefore perform the alternation in the absence of visual cues at least as well if not better than the unoperated group. The results are in accord with this prediction. Whereas the unoperated group of
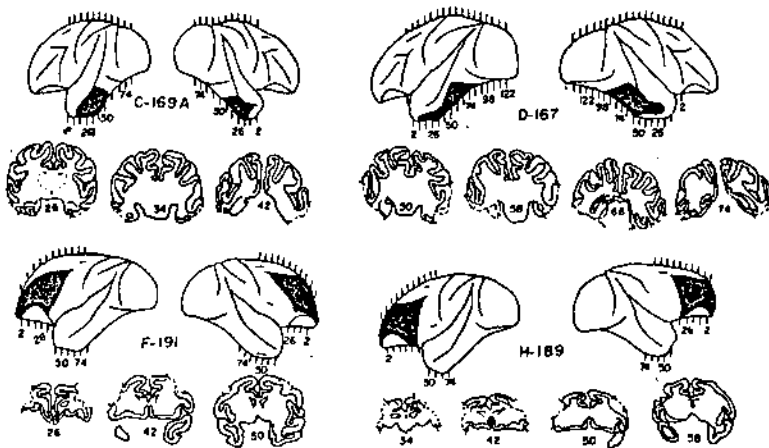


FIG. 3. Reconstructions of the extent and depth of lesions of the monkeys used in Experiment II.

animals took an average of 4 weeks to reach the discrimination criterion of 85 per cent, the animals with the inferotemporal resections reached this criterion in 2 weeks.

The further prediction was made that animals with frontal lesions would have difficulty with the alternation procedure once the visual cues that signified the schedules were eliminated. As can be seen from Table 1, the results obtained are in accord with this prediction as well. The animals with frontal lesions never achieved criterion in the 6 weeks of testing even though they occasionally performed well during a single day's session, and, of course, continued to alternate at criterion level during the first 20 min of each session when the red and green lights signaled the session. Figure 4 shows a typical record of the differences in the performance of the two operated groups. Note that the monkey

with the inferotemporal lesion occasionally fails to discriminate between two types of schedules. Note also that occasionally the frontally operated monkey makes the distinction appropriate to the two schedules. The difference in performance is that the monkeys with inferotemporal lesions and the unoperated monkeys repeatedly regain the cadence of alternation even after an occasional miss, whereas this happens rarely, and then only briefly, with the frontally operated monkeys.

TABLE 1

THE NUMERICAL RESULTS OF THE PERFORMANCES OF ALL OF THE ANIMALS REPORTED IN EXPERIMENT II

| Monkey[a] | No. days previously tested | Percentage discrimination | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Last 6 days tested | | | | | | (Average) |
| | | (1) | (2) | (3) | (4) | (5) | (6) | |
| Unoperated | | | | | | | | |
| A | 27 | 86 | 91 | 92 | 88 | 85 | 91 | 89 |
| B | 32 | 80 | 87 | 100 | 78 | 83 | 95 | 87 |
| E | 8 | 91 | 89 | 89 | 96 | 100 | 89 | 92 |
| G' | 24 | 84 | 100 | 78 | 78 | 88 | 95 | 87 |
| Average | 23 | 85 | 92 | 90 | 85 | 89 | 92 | 89 |
| Temporal | | | | | | | | |
| C' | 11 | 100 | 80 | 91 | 77 | 100 | 100 | 91 |
| D | 13 | 100 | 90 | 100 | 89 | 83 | 100 | 94 |
| Average | 12 | 100 | 85 | 95 | 83 | 91 | 100 | 92 |
| Frontals | | | | | | | | |
| F | 38 | 77 | 86 | 89 | 83 | 60 | 73 | 78 |
| H | 38 | 74 | 59 | 77 | 91 | 80 | 72 | 75 |
| Average | 38 | 75 | 72 | 83 | 87 | 70 | 70 | 76 |

[a] C' ≡ C169A; D ≡ D167; F ≡ F191; H ≡ H189.

## DISCUSSION OF EXPERIMENTS I AND II

The results of these two experiments support the conception that the deficit in behavior produced by frontal lesions is not due to a deficiency limited to one or another modality. In Experiment I, vision had to be relied on by the animals in order to solve the problem. Correct choice necessarily involved the visual appreciation of the sequence of rewarded cues. In the crucial portions of Experiment II, on the other hand, visual differences were unlikely as contributing to correct performance. In the

test portion of this experiment correct performance had to be based solely
on the sequence of occurrence of visually indistinguishable events: the
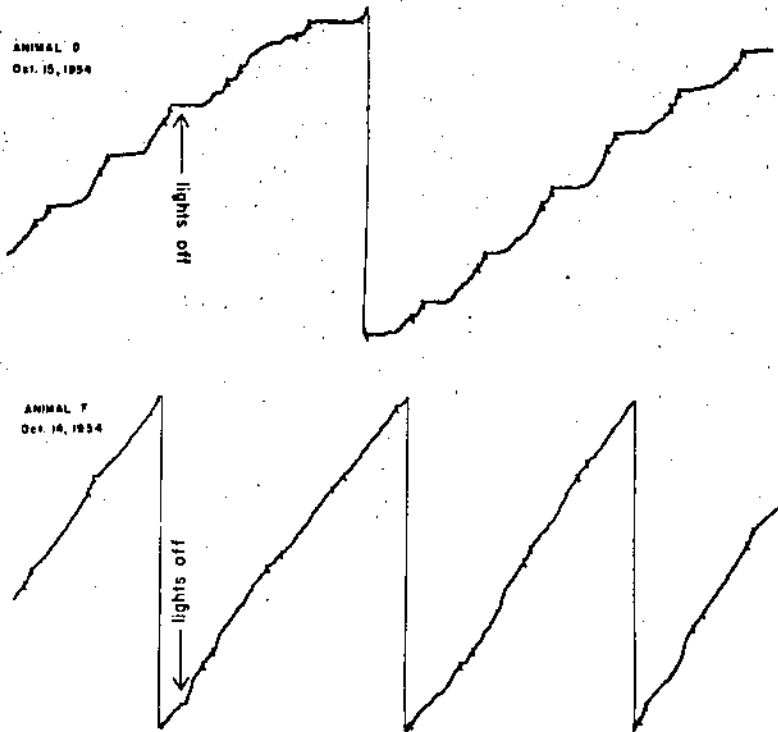events produced by the animal's own behavior.



FIG. 4. Tracing of the actual records obtained on two animals in Experiment II.
Note the excellent performance of animal D with the inferotemporal lesion and the
indiscriminate performance of animal F with the frontal lesion. Time is marked as
the horizontal axis of the record; each response moves the pen in the vertical direc-
tion. Reinforcements are signified as short strokes perpendicular to the response
curve.

The argument can nonetheless be made that the impaired performance
of the group with frontal lesions resulted only from some general increase
in the difficulty of the task once the distinctive visual cues were removed—
an argument supported by the fact that in subsequent experiments monkeys
with frontal resections were shown defective in the fixed-interval situa-
tion per se. Arraigned against this supposition, however, stands the

markedly superior performance of the inferotemporal control group in the test portion of the experiment—a group shown to be visually impaired in a multitude of discrimination situations (1, 5, 6, 7, 18, 19, 20, 21). This result alone makes improbable the interpretation that vision per se plays a role in this increase in difficulty experienced by the frontal group.

The results of Experiment I confirm those previously reported in a similar experiment (28). In the earlier experiment, object alternation was accomplished by having the objects randomly placed in one of two positions on the board. The results of that experiment were not completely clear-cut: One of the animals with frontal lesions performed well in that situation; no unoperated control group was tested. The interpretation of the previously reported experiment had therefore been subject to some question. Though the spatial factor of placement of the object appeared adequately ruled out as decisive in that experiment, the remote possibility remained that, since only two cups were present, an animal might perseverate to one of the two places, or that some other obscure stereotyped performance based on the spatial aspect of the test could influence performance. The remote possibility that the operated control group would perform better than would an unoperated group of animals also had to be entertained. The results of the current experiment are clear-cut; the randomization among six positions leaves no doubt as to the efficacy of the procedure in eliminating nonvisual clues to the solution of the problem. All frontally injured monkeys performed more poorly than those in the operated and in the unoperated control groups.

In short, the experimental demonstration is complete, that spatial factors do not account for the deficit shown by animals with frontal lesions in alternation performance. From this it may be safely inferred that the deficiency in behavior which is observed in animals with such lesions cannot be attributed to a deficit in kinesthesis per se. Experiment I therefore provides evidence toward an answer in the negative to the first question posed in the Introduction: Is the impairment produced by frontal injury limited to kinesthesis?

Evidence that contributes to an answer to the second question posed in the Introduction is provided by Experiment II. This experiment demonstrates that when a deficit in the performance of an alternation problem results after frontal injury in monkeys, a change in visual capacity per se is unlikely to be responsible. Any interpretation of the alternation deficit in terms of defective visual performance will not hold up any more than

will an interpretation in terms of defective performance based on kinesthesis.

Thus, the experimental results reported tend to preclude an explanation of the behavior deficit that follows frontal injury in terms of specific sensory modes. Yet the deficit is a specific one. The question remains as to the nature of the specificity.

Clinical observations often give the illuminating description necessary to guide fruitful experimental analysis. One such clinical statement was quoted in the Introduction. To return to the summary sentence of the quotation: "It is this inability to visualize consequences which is the unique effect of leucotomy." Because of the proximity of the "frontal eye fields" to the eugranular frontal cortex, the visual aspect of the defect was emphasized by the author of the quotation. The results of Experiment II suggest that this emphasis is misplaced. What, then, is of importance in this perceptive statement? Should the inability to visualize *consequences* become the focus of our interest?

Denny-Brown (9), in his review of the functions of the frontal cortex from which the above quotation is taken, points out that to understand a defect produced by a neurological lesion often awaits determination of the stimulus variables that elicit the defective responses. Usually such stimuli are considered to be related to a specific sense modality. At best they could be "associative," i.e., made up of the interaction of two or even of several mode-specific "primary" sense data. Does this classical empiricist view cloud the issue?

A body of knowledge has been developed regarding the effects of the consequences of actions or "reinforcing stimuli" upon the subsequent behavior of the organism (10, 14, 34). This body of knowledge comes for the most part from the application of the techniques of experimental psychology; most systematic have been the efforts to examine the learning process. Of these experimental techniques, those used to investigate discrimination learning have been especially useful for the study of neuropsychological problems. Examples of two types of apparatus in current use and modified for primate behavioral testing have already been detailed. And the results reported suggest that the effect of frontal lobe lesions on the reinforcing properties of stimuli—on the organism's handling of the consequences of actions—be explored further.

Several types of variables have been found to affect the relationship between the consequence of one behavioral act and subsequent behavior.

For example, in the situation used in Experiment II, a monkey receives a peanut as a consequence of depressing a lever. Subsequently the monkey continues to depress the lever regularly either until he is sated or until the apparatus runs out of peanuts. Experiments III, IV, and V were undertaken simply to ask the questions: Do bilateral frontal lesions alter behavior much as do satiating or starving the monkey? Or, are the effects more evident when behavior is altered by a change in the presence or absence of the reinforcing stimuli, e.g., as when the aparatus runs out of peanuts?

### Experiment III

*Procedure.* Just how does a monkey react to variations in starvation or satiety? The subjects for Experiment III were twelve additional rhesus monkeys. These were not given any surgical procedure during the course of the experiment. The twelve monkeys were trained to press a lever in the situation described in Experiment II. In the present experiment, however, the food used for "reinforcement" was a specially prepared 0.5-mg pellet delivered at a constant interval of 2 min. No stimulus light or other "clock" signaled the time elapsed since the last reinforcing event. In this, and in the following experiment, this "fixed interval" schedule was the only one used. As in the previous experiment, the monkeys were fed a sufficient amount of laboratory chow immediately after each training session to maintain them at approximately 80 per cent of the weight which they had attained after a 3-week period of *ad libitum* feeding. Daily weighing assured this 80 per cent figure. All animals were tested every other day (except Sunday) for 2 hours until a stable level of performance was obtained.

In addition to the usual cumulative record obtained, as described in Experiment II, counters were so arranged as to sum the number of responses which an animal made during six equal periods into which the total 2-min interval was divided. From the numbers recorded on the counters, performance graphs were constructed. These graphs show the distribution of responses across as many of the 2-min intervals as desired. Thus the total performance of any monkey could be measured —an advantage not given by inspection of the ordinary representative cumulative curve. Also, in this way, averages of the responses of groups of animals could be taken and the variations between individual animals statistically analyzed.

The actual experiment consisted of the following procedure: Ten 2-

hour sessions were given. Then each animal was subjected to a 72-hour fast and retested for one session, after which the usual feeding schedule was immediately resumed and testing continued as in the prefast period for ten sessions. The entire procedure was repeated another time with the interposition of 118 hours fasting before the critical test session.
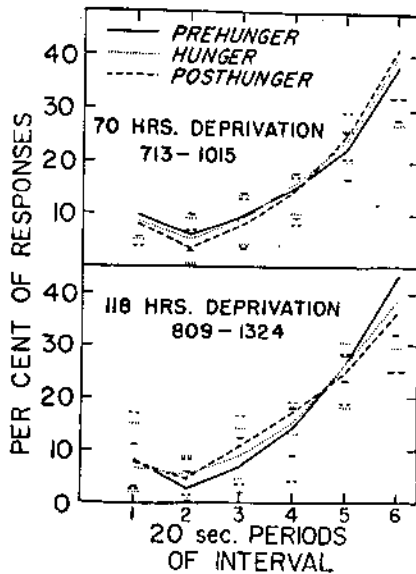


FIG. 5. Graph showing the effect of food deprivation on monkeys' rate of lever pressing response to food (a small pellet of laboratory chow) which became available every 2 min. The change in total rate is indicated by numbers under the deprivation label. The lack of change in the distribution responses is shown by the curves. Each curve represents the average of the responses of ten monkeys; each point represents the average rate during a period of the interval over 10 hours of testing. Variance is indicated by the short horizontal bars.

*Results.* The results are shown in Fig. 5. As can be clearly seen, the effect of food deprivation, i.e., of starvation, is upon the rate and not upon the distribution of monkeys' responses during an interval. The percentage of total responses made during any particular portion of the interval appears to remain remarkably constant despite marked changes in the total number of responses which an animal makes.[3] Note also

[3] There are similar changes observed when monkeys are sated. Fixed-interval performance when the animals are kept in an *ad libitum* feeding situation shows a lower

the consistency of results and the little variation between animals. When monkeys are starved for 3 to 5 days their total rate of response increases —but the way in which they distribute these responses during an interval does not change.

### Experiment IV

*Procedure.* The procedure used in this experiment was identical to that used in Experiment III, except instead of varying starvation, brain lesions were made. The same group of animals was used. Three of them were given ablations of the frontal eugranular isocortex and three others were given control lesions which consisted of resection of the inferior portion of the temporal isocortex. Four of the remaining animals served as unoperated controls.

After completion of the experiment, the six operated animals were sacrificed, their vascular systems perfused with isotonic saline and ten per cent formalin solution, the brains fixed, dehydrated in alcohols, and embedded in nitrocellulose and celloidin. The brains were sectioned at 50 μ, stained with thionine, and serial reconstructions made. The thalamic degeneration was essentially the same as in monkeys used in Experiment I except that there was no involvement of the lateral geniculate nucleus in any of the subjects. Representative reconstructions are presented in Fig. 6.

*Results.* Figure 7 graphs the results obtained following these procedures. When rate of response of the operated and control groups is compared, no differences are apparent. Note, however, that for the frontally operated group, the distribution of responses across the interval is markedly different, while that of the control monkeys remains unchanged. This effect of the frontal lesion is in direct contrast to the effect of starvation.

### Experiment V

*Procedure.* In this experiment, the same situation and the same animals were used as in Experiment II. The object of the procedure was to determine whether frontal ablations would alter the behavior of monkeys in response to the apparatus "running out of peanuts."

All monkeys were first tested, as in Experiment II, for 80 min after which everything in the situation continued unaltered except that

over-all rate and a somewhat steeper slope in the earlier part of the response curve. See Fig. 5, Schwartzbaum (32).
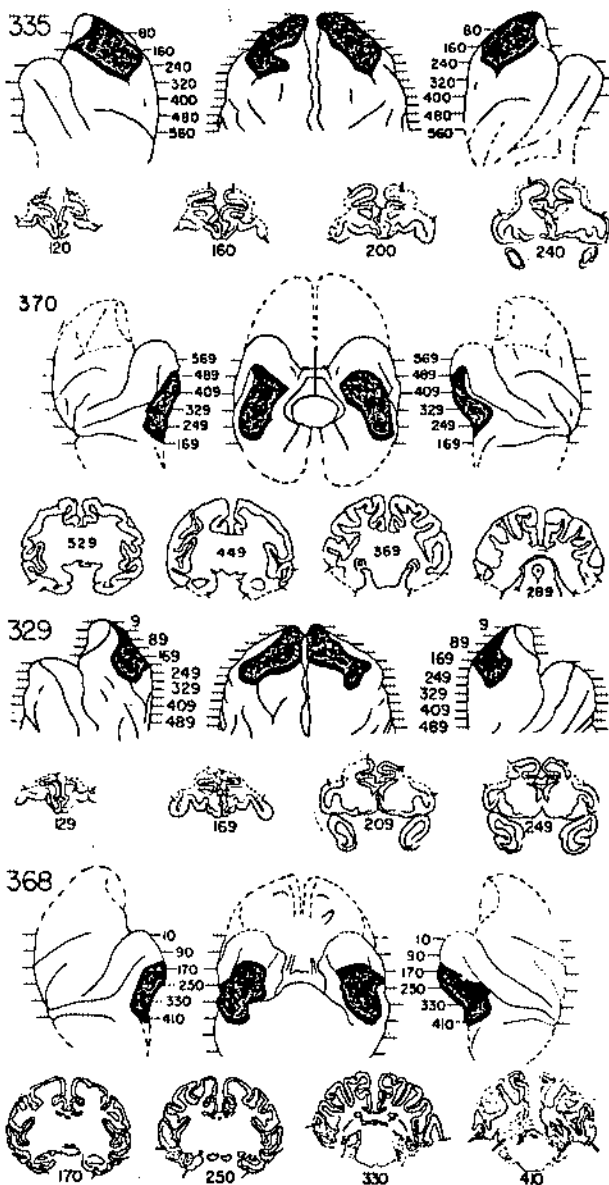
FIG. 6. Reconstructions of the extent and depth of lesions of the monkeys used in Experiment IV.

peanuts were no longer delivered. The monkeys were run under these "extinction" conditions for 4 additional continuous hours and the rate of response per hour recorded.
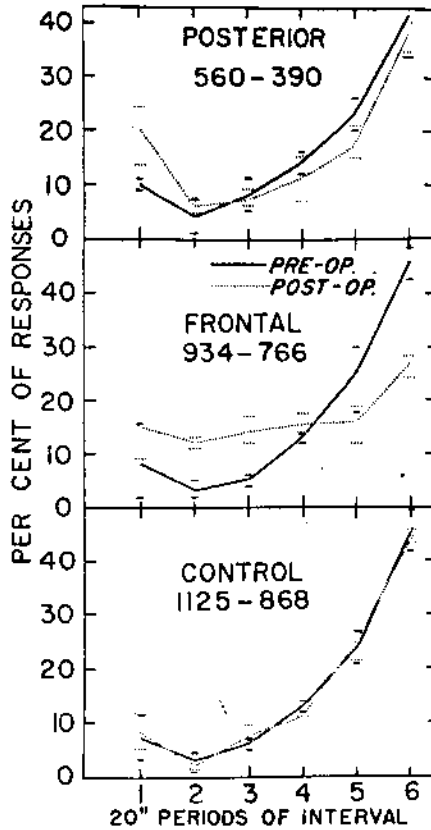


Fig. 7. Graph showing the change in distribution on monkeys' response rate following frontal ablation (three monkeys). Note that the distribution of rate over the interval is not affected in the controls (four monkeys) and after inferotemporal (posterior) ablations (three monkeys). Also note that the total rate of response did not increase; rather rate was somewhat decreased in all groups, probably due to the *ad libitum* feeding period which all groups were given prior to operation—approximately 2 weeks before postoperative testing.

*Results.* The results of this experiment are shown in Fig. 8 and Table 2. They demonstrate clearly a slower rate of extinction of lever pressing for the frontal group as compared with that of the control animals. The

monkeys with frontal ablations continue to depress the lever at a considerably higher rate for a considerably longer time when the apparatus has run out of peanuts.
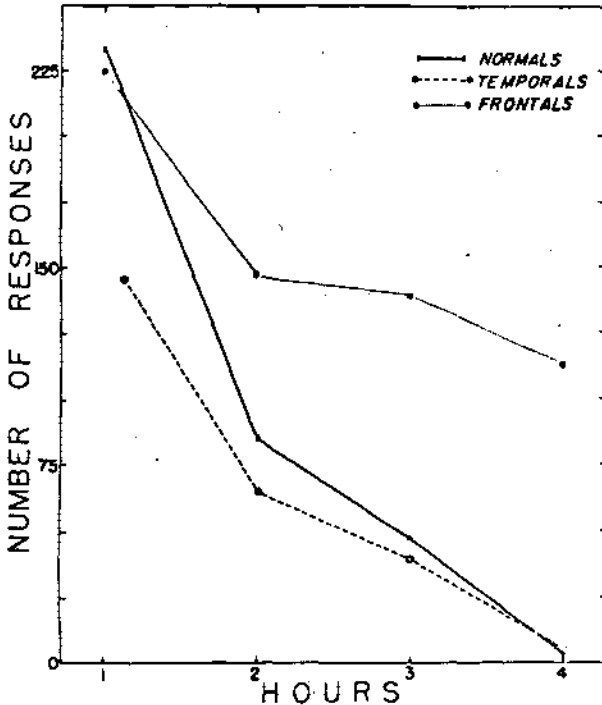


Fig. 8. Graph of performance under extinction conditions as reported in Experiment V.

## DISCUSSION OF EXPERIMENTS III, IV, AND V

The results of these three experiments are clear-cut. Bilateral removal of the frontal eugranular isocortex of monkeys changes behavior altered by the appearance or nonappearance of reinforcing stimuli—and not those aspects of behavior altered by starvation or satiation. In other words, frontal lesions affect the responses of monkeys to some property of reinforcement that is unrelated to how starved or how sated the organism may be. Can anything more be said about the nature of this property? Careful inspection of Fig. 7 (Experiment IV) does give a clue. The group of animals with frontal lesions does not behave completely

indiscriminately during the interval—there is an increase in the number
of responses toward the end of each interval. As also demonstrated by
Experiment V, the consequence (receiving a peanut) of the action
(pressing a lever) becomes a less effective stimulus in guiding behavior
as a result of the frontal surgery. The operated monkeys behave as if
they were less sensitive to the changes in reinforcing conditions. The
last two experiments (VI and VII) were undertaken, therefore, to

TABLE 2

THE SCORES OF THE INDIVIDUAL ANIMALS IN THE EXTINCTION CONDITION REPORTED
IN EXPERIMENT V

| | Extinction | | | | |
|---|---|---|---|---|---|
| | No. responses in hours | | | | |
| Monkey[a] | (1) | (2) | (3) | (4) | (Average) |
| Unoperated | | | | | |
| A | 205 | 110 | 70 | 8 | 98 |
| B | 305 | 75 | 55 | 0 | 109 |
| E | 230 | 20 | 10 | 0 | 65 |
| G' | 195 | 130 | 45 | 0 | 92 |
| Average | 234 | 84 | 45 | 2 | 91 |
| Temporals | | | | | |
| C' | 185 | 85 | 75 | 8 | 88 |
| D | 100 | 40 | 0 | 0 | 35 |
| Average | 143 | 63 | 38 | 4 | 62 |
| Frontals | | | | | |
| F | 195 | 85 | 120 | 100 | 125 |
| H | 250 | 205 | 155 | 122 | 183 |
| Average | 222 | 145 | 137 | 111 | 154 |

[a] Subjects are the same as in Table 1.

explore further the range of conditions over which this defect is evident.

Earlier analyses of the defective performance of monkeys with frontal
lesions suggest that the relation to consequences of action is a special
instance of a more general impairment. In the alternation situation it
is true that correct performance can be interpreted to depend on the
consequence of the monkey's actions on the trial prior to one currently
demanding choice. In the delayed reaction situation, however, correct
performance depends on the consequences of the monkey's behavior
(looking) at the time of the presentation of the cue, i.e., during the

predelay period. The more distinctive the cue, the less the deficit (21, 22). Here the consequence of behavior is "attention" to the cueing stimulus. The notion immediately presents itself that the effects of frontal lesions is on one important property of reinforcers—their attention-getting or instructional aspect. The theoretical implications of this notion have been pursued elsewhere (27). Here, the experimental analysis is aimed at defining more precisely the relation between the "frontal deficit" and this type of "attention."

The performance of monkeys with frontal lesions is unimpaired in a task when one of two choices is consistently reinforced. In this situation there is no evident inattention. When, however, irregularities in the recurrence of the reinforcement are introduced or when the complexity of the situation is increased by augmenting the number of choices available, the task becomes more ambiguous. This increase in ambiguity may account for the impairment in performance of monkeys with frontal lesions. Ambiguity is affected, among other things, by the number of alternatives from which choice is required and the amount of repetitive consistency with which the reinforcing event appears in the situation. If these are indeed critical factors for monkeys with frontal lesions then manipulation of the ambiguity of the task by these two methods should result in impaired choice performance. To this end, in Experiment VI the number of alternatives from which choice is required is progressively augmented; in Experiment VII the repetitive consistency of reinforcement is·progressively diminished.

### Experiment VI

*Procedure.* Twelve monkeys were used in this experiment, four with bilateral anterior frontal resections, four with bilateral inferior temporal resections (control operation), and four unoperated controls. The monkeys were those that had been used in Experiment I. The data for Experiment VI were obtained some 2½ years after surgery.

The Wisconsin General Testing Apparatus (13) was modified slightly for the experiment. Essentially the problem situation is a complex form of discrimination reversal: number of discriminanda is systematically varied; criterion to be attained is kept constant. The animals are initially confronted with two junk objects placed over two holes (on a board containing twelve holes in all) with a peanut under one of the objects. An opaque screen is lowered between the monkey and the objects as soon

as the monkey has displaced one of the objects from its hole (a trial).
When the screen is lowered, separating the monkey from the twelve-hole
board, the objects are moved (according to a random numbers table) to
two different holes on the board. The screen is then raised and the
animal again confronted with the problem. The peanut remains under
the same object until the animal finds the peanut five consecutive times
(criterion). After a monkey reaches criterion performance, the peanut
is shifted to the second object and testing continues (discrimination
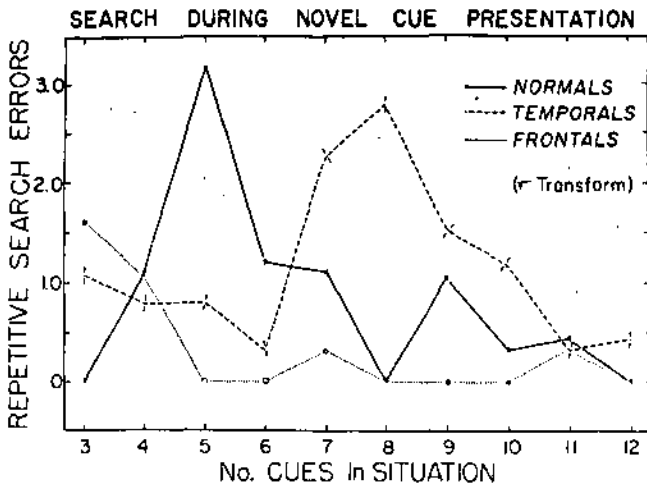


FIG. 9. Graph of the average of the number of repetitive errors made in the
multiple choice experiment during the search trials when the novel cue is presented.
Note that although records of the control groups show peaks that indicate confusion
between novel and familiar cues, the monkeys with frontal lesions are not confused.

reversal). After an animal again reaches criterion performance a third
object is added. Each of the three objects in turn becomes the positive
cue; testing proceeds as before—the screen separates the animal from
the twelve-hole board, the objects are placed randomly over three of the
twelve holes (with a peanut concealed under one of the objects), the
screen is raised, the animal allowed to pick an object (one response per
trial), the screen is lowered, and the objects moved to different holes.
The testing continues in this fashion until the animal reaches criterion
performance with each of the objects positive in turn. Then a fourth
object is added and the entire procedure repeated.

As the experiment progresses the number of objects is increased serially

through a total of twelve. The testing procedure is the same for all animals throughout the experiment; however, the order of the introduction of objects is balanced—the order being the same for only one monkey in each group.

*Results.* Data were analyzed to determine the differences in performance between the groups of monkeys during those trials necessary to find the peanut, and also on the trials taken after the peanut is found,
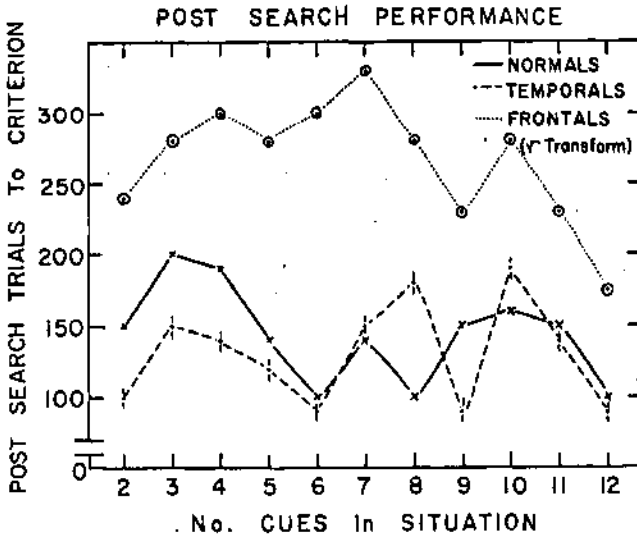


FIG. 10. Graph of the average of the number of trials to criterion taken in the multiple object experiment by each of the groups in each of the situations after search was completed, i.e., after the first correct response. Note the difference between the curves for controls and for the frontally operated group, a difference which is significant at the 0.05 level by an analysis of variance ($F = 8.19$ for 2 and 6 $df$) according to McNemar's (1955) procedure performed on normalized (by square root transformation) raw scores.

to reach criterion. Analysis of the "search" data proved especially relevant to the understanding of the effects of the inferotemporal lesions and is therefore reported separately (26). The effects of the frontal ablation are evident during search, however, each time a novel object is introduced into the situation (Fig. 9). The frontal group of monkeys responds immediately and uniformly to this object; control animals are more varied in their responses.

Figure 10 graphs the differences in the performance of the three groups

of monkeys during the "post-search" trials: i.e., during the trials that intervene between the trial on which the monkey finds which object conceals the peanut on any particular run and the attainment of the criterion of five consecutive correct responses on that run. Clearly, the frontally operated group takes a considerably greater number of trials to reach criterion throughout most of the experiment. This difference in performance is significant at the 0.05 level by an analysis of variance ($F = 8.19$ for 2 and 6 $df$) according to McNemar's procedure performed on normalized (by square root transformation) raw scores.

### Experiment VII

*Procedure.* For this experiment the same groups of monkeys were used. Four had received anterior frontal ablations, four "operated controls" had been given inferior temporal lesions, and four were unoperated controls. The experiment was carried out 3 years after surgery.

Essentially, the experiment consists of the usual discrimination reversal procedure in which the number of discriminanda is kept constant; however, criterion to be attained is systematically varied. A Wisconsin General Testing Apparatus was used. Two objects, a small tobacco tin and a flat ashtray, served as cues. All subjects were given approximately thirty trials a day and were initially rewarded only when they chose the tobacco tin. When, for ten consecutive responses the tobacco tin had been chosen, the reward (a peanut) was placed under the ashtray until ten consecutive correct responses were again obtained. Another reversal was then instituted. Reversals were continued to the "ten correct" criterion until 500 trials were accomplished. (If at the end of a day's run three consecutive correct responses were made, further trials were given until either the monkey made an error or reached criterion.) The procedure was then changed so that reversals were given after an animal had reached the criterion of only five consecutive correct responses; the reversals to the "five correct" criterion were continued until another 500 trials were completed. After this, the monkeys were run to criteria "four correct," "three correct," and "two correct," in that order. (The procedure when the reversals are made after two consecutive correct responses corresponds to a double alternation with corrections.) After completion of this and the previous experiment the animals were sacrificed, their brains subjected to anatomical analysis, as reported in Experiment I and as in Fig. 1.

*Results.* No significant differences between groups of monkeys appears from a comparison of the over-all percentage of possible reversals the animals made per criterion block of trials (Fig. 11). There is, however, no overlap between the frontal and the unoperated control group in the number of errors made in the double (criterion 2 block) and the single (criterion 1 block) alternation situation when these are treated separately. There is only one overlap in error scores between the frontal and control groups in the criterion 3 block.[4]
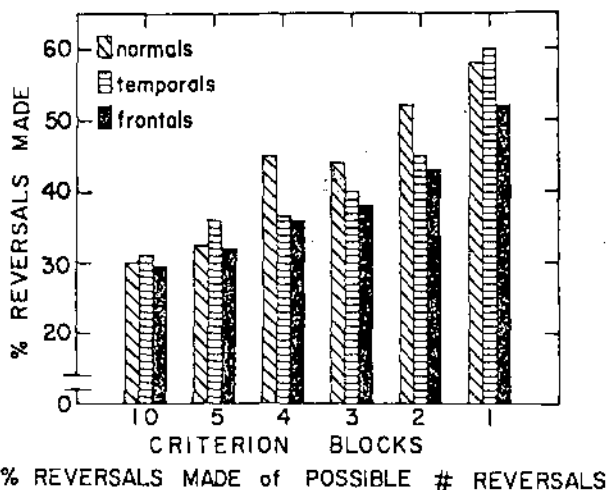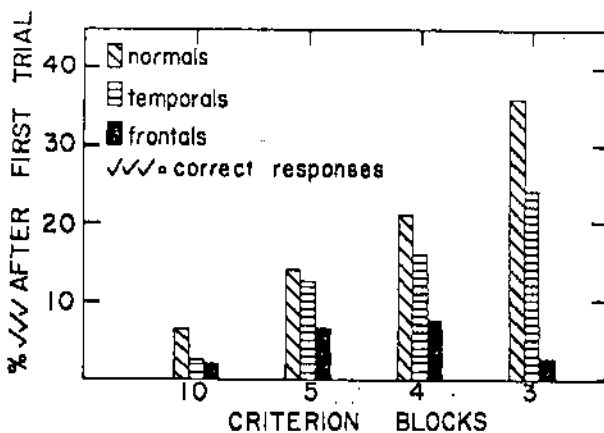


Fig. 11. Graph of the per cent of possible reversals made by the monkeys in each criterion block. There is no significant difference between groups except that at the criterion 2 level there was no overlap between the operated and the unoperated controls and at the criterion 1 level there was no overlap between the frontal and the other groups of animals.
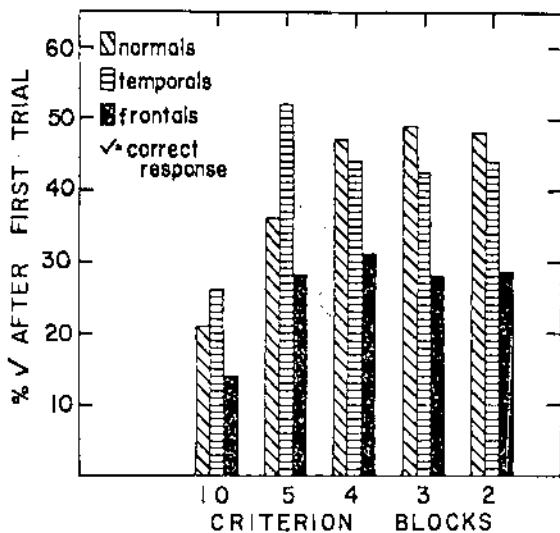
Further, marked differences appear when a comparison is made of responses on trials two, three, and four that immediately follow the one that signals each reversal. When performance between criterion blocks (Fig. 12) is compared, the control groups show progressively fewer initial errors as the reversals are given after progressively shorter criterion runs; the frontally operated group of monkeys shows no such

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[4] In the double alternation the inferotemporally operated group behaves as does the frontal; in single alternation the performance of the inferotemporal group is as that of the unoperated controls. These results confirm those obtained by Leary, Harlow, and Green (16).

TRIALS 2,3, and 4 of CRITERION BLOCKS

FIG. 12. Comparison of the performance of the groups of monkeys in each of the criterion blocks. The number of errorless performances on the three successive trials that follow the initial trial after reversal is plotted. Note the marked difference between the frontal and the other groups as criterion is shortened.



TRIAL 2 of CRITERION BLOCKS

FIG. 13. Graph of the performance of the groups on trial 2 after each reversal as a function of the length of criterion. Note that the frontally operated animals do not change performance, whereas both other groups do.

change in performance. This difference between groups is apparent on
trial two after each reversal (Fig. 13), and continues when trials two and
three (Fig. 14) are plotted, but disappears when performances on trial
five are included (figure not presented).

Since order of presentation of criterion blocks is confounded with
change in criterion, it can be argued that the improved performance of
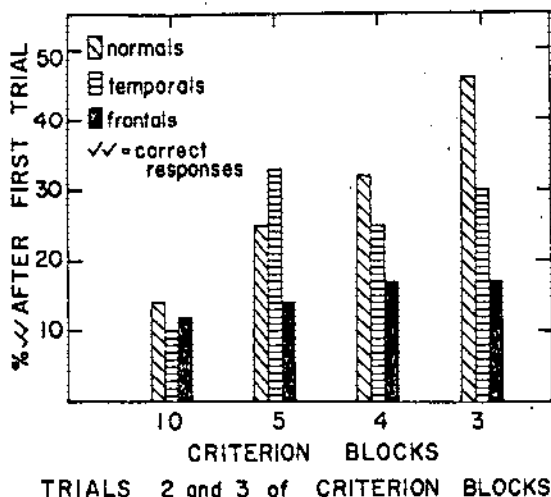


TRIALS 2 and 3 of CRITERION BLOCKS

Fig. 14. Same as Fig. 13 except that errorless performance on trials 2 and 3 is
graphed. Note again that control animals improve their performance as a function
of the shortened criterion while frontally operated animals do not change theirs. This
difference between groups is maintained through trial 4 as can be seen in Fig. 13.
However, when plots are made of successive errorless performances maintained
through trial 5 (no figure), the differences between groups disappear. There is some
improvement in the scores of the frontally operated animals and some deterioration
of the scores of the other groups.

the controls is due simply to learning the nature of the task in general.
This explanation is made unlikely by the analysis presented in Fig. 15.
Here a comparison is made of the performance of the groups on succes-
sive blocks of 100 consecutive trials within the 500 trials of the ten-
criterion and the 500 trials of the five-criterion blocks. (Averages of the
10- and 5-criterion scores are used; there was little difference between
them.) There is no change in the performance pattern on the initial
trials after reversal: All animals make about the same number of errors

in the last block as they did on the first. Thus, learning of some general factor applicable to test performance is unlikely to account for the improvement shown by the control groups when criterion blocks are compared.
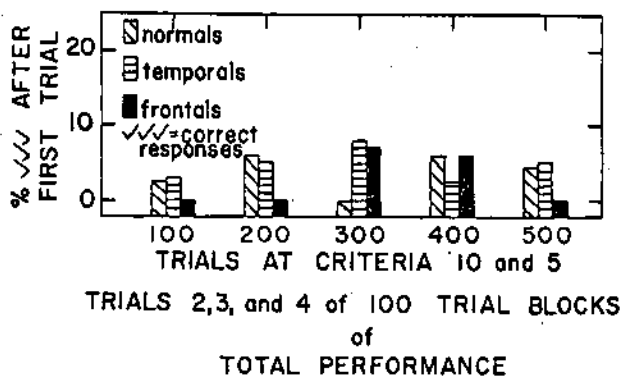


FIG. 15. Graph of the performance of the monkeys on successive blocks of 100 trials within each 500 trial performance. Note there is no essential difference between groups.

### DISCUSSION OF EXPERIMENTS VI AND VII

When a situation is unambiguous, as in the usual form of the two-choice discrimination experiment, monkeys with frontal lesions show no impairment. The results of Experiments VI and VII show, however, that when the ambiguity of a choice task is increased, such animals do show deficient performance. Furthermore, the defect shown in Experiment VI is not related to the uncertainty in choice produced by the increase in the number of alternatives in the situation: the impaired post-search performance is uniform throughout the experiment and does not vary as a function of the number of alternatives in the situation. The impairment occurs when the consequences of decision have already been indicated to the animal, i.e., during criterion run. This result is supplemented by the results of Experiment VII. Here, after repeated reversals, the first trial after reversal serves as a signal that reversal has taken place. In their performance, the monkeys with frontal lesions make less use of this signal than do the controls.

These experiments show, therefore, that the performance of monkeys with frontal lesions is altered in a choice situation provided the situation is made ambiguous. More specifically, the change in behavior is related

to ambiguity produced by changes in the repetitive reliability of the situation; changes in uncertainty that result from an increased number of choice alternatives have little effect.

When we observe that behavior is guided by the reliable repetitions of events in a situation, we must suppose that certain processes must be going on in the organism to make the observed regularities possible: (a) the events must be monitored, i.e., continuous attention must be maintained; (b) something that is produced by each of the events in question must be stored; (c) the stored process must be accessible to guide action. How, on the basis of currently available evidence, can one or another of these processes be selected as the critical intersection between the reliability of a situation and the neural mechanism of which the anterior frontal cortex is a part?

The major differences between the simple choice situation and the ambiguous ones in Experiments VI and VII point to the answer of this question. The accessibility of the stored process appears to be as necessary for performance in the simple choice as in the more ambiguous one. Furthermore, accessibility is not likely disturbed by frontal lesions: the complexity of choice (as determined by the number of alternatives in the situation) has little bearing on the impaired performance (Fig. 10), and the over-all performance of the "frontal" group in the complex situation of Experiment VI, and even in the relatively unreliable situation of Experiment VII, is superb. If this analysis is correct, the frontal impairment is centered about the first two processes listed: monitoring of the shifting events, or of the storage process. This placement is in agreement with that derived from several earlier experimental analyses already referred to: in these studies the defect was in each instance related to occurrences related in time to the cueing or reinforcing stimulus, and not to those events present at the time of response (20, 21).

Can the definition of the impairment by frontal lesions be narrowed further? Is the impairment one of monitoring or of storage? Is the defect one of maintenance of attention or of its immediate consequence in memory? Here the currently available experimental evidence does not allow a clear-cut choice, perhaps because the question is improperly phrased.

Could it be that the maintenance of attention itself intricately involves a memory process? Recent neurophysiological and psychophysiological experiments on the habituation of orientation to a stimulus situation

suggest an affirmative answer to this question (33). Re-evocation of orientation is immediate when a disparity occurs between the situation and this memory process (35). Here the process involved in attention is intricately bound to the memory process. Indeed, one could say that habituation and orientation are manifestations of attention that depend on a particular sort of memory. Perhaps reaction to the reliability of a situation is to be fruitfully analyzed in a similar fashion.

Thus the evidence from these experiments supports the idea that frontal lesions interfere with some organizational process that takes place in a relatively unreliable situation in the presence of stimulus events that must serve subsequently as guides to action. These stimulus events may appear as the consequences of the organism's own behavior, e.g., as reinforcing stimuli in the alternation situation. Or, they may be stimuli even more directly provided by an experimenter, i.e., as instructions, in the delayed reaction task. The organizational process is conceived to assure stability to the organism's actions in those situations that, though unreliable, nevertheless present some recurrent regularities.

This hypothesis can be tested further by experiments in which the performance of animals with frontal lesions is compared with that of controls on tasks in which risk is varied systematically. In addition, some clear-cut identifying physiological measures of the concomitants of this organizational process can be attempted.

## Conclusion

The functions of the frontal eugranular isocortex of primates have been the subject of much study and speculation. Yet, precise definition of the behavioral defect that follows injury to this cortex continues to be elusive. Seven experiments were undertaken to examine specific questions left unsettled by observations made in the clinic and by earlier primate researches.

The first two of these experiments deal with the problem of modal specificity. One experiment investigates the notion that damage to the frontal eugranular cortex disrupts only performances guided by the placement of cues; the second experiment is concerned with the relation between the primate frontal lobe and the visual mode. The results of the experiments demonstrate clearly that the defect in behavior that follows frontal injury cannot be attributed either to an impaired sense of place (proprioception) or to an impaired visual performance. Nonethe-

less, the behavioral deficit is specific and a suggestion can be made about the nature of the specificity.

Experiments III, IV, and V of the series examine the suggestion that the behavioral deficit that follows frontal injury results from an abnormality in the way in which these animals respond to the consequences of their own actions: i.e., to the reinforcing properties of stimuli. Further, the experiments were designed to detail more specifically the nature of the altered reaction to reinforcements. Experiments III and IV were addressed to the question: Do frontal eugranular lesions alter behavior in a manner similar to satiating or starving the monkey? The results show that they do not. Experiment V was therefore accomplished to test whether the frontal ablation affects behavior·altered by a change in occurrence of the reinforcing events—the results encouraged exploration in this direction. Experiments VI and VII were then undertaken to examine further the range of such conditions over which the frontal deficit is evident.

The results reported are analyzed to show that injury to the frontal cortex alters monkeys' behavior in situation that are relatively ambiguous. However, ambiguity per se is not a sufficient condition to evoke the impairment—an increase in the uncertainty of choice because of an augmented number of alternatives fails to affect the performance of monkeys with frontal lesions. On the other hand, a marked effect is produced by changes in situations to make them less reliable; changes, accomplished by altering reliability, affect the performance of monkeys with frontal lesions to a greater extent than they affect the behavior of controls. Thus, frontal lesions apparently interfere with the organizational process that must take place in normal subjects when the stimulus events that serve as guides to subsequent actions occur in relatively unreliable situations. Some experiments are proposed to delineate further the effects of frontal injury on this process.

Seven more experiments were performed, and complete specification of the behavioral defect that follows frontal injury continues elusive. Yet, definition is more precise than heretofore. The words of Denny-Brown take on new meaning: Patients with frontal lesions can "visualize objects or scenes" but cannot "visualize the consequences of the actual (i.e., act-guiding) situation." "Interest and hence sustained attention and initiative" are defective—in unreliable situations only. The neural nature of the process injured remains an experimental challenge.

The key to the problem may be found in the relations between the frontal eugranular isocortex and the limbic formations on the medial and basal surface of the forebrain and between these formations and the reticular core of the brain stem. Insight into method of approach has already been gained through studies that combine electrophysiological and behavioral techniques (3, 4, 35).

So, step by step, the knotty and resistant "frontal lobe problem" should yield a few more of its secrets during the next decade.

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