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Corticothalamic Projections and Sensorimotor Activities
T. Frigyesi, E. Rinvik, and M.D. Yahr, editors. © 1972
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Association: Cortico-cortical and/or Cortico-subcortical

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I accepted the challenge presented by this Symposium because a body of work on the functional connections of the non-human primate association cortex is coming to fruition. The results of a long series of neuroanatomical, neurophysiological and neurobehavioral experiments have led me to revise the classical views on the functions of the association cortex which I had been taught. What are these views and what are the data that led to revision?

Webster's dictionary defines "association" as "the process of forming...connections or bonds between sensations, perceptions, ideas or feelings." The classical view of the functions of association cortex therefore implies that input from several primary sensory systems converges onto the association areas. And, in fact, a large number of electrophysiological studies on cats has delineated several cortical areas characterized by cells that can be stimulated through two or more sensory channels (45). These polysensory cortical areas are not the topic of the present paper. They have as yet been inadequately studied in primates although one fact relevant to this discussion has emerged. When the same techniques were used to delineate the polysensory cortical systems in cat and monkey, it became apparent that the primate precentral motor cortex is one of the major such polysensory areas (1). More of this later.

In primates, including man, an entirely different set of areas has been identified as "association cortex." Both clinical and experimental evidence shows these areas to be sensory specific rather than polysensory. It is this evidence, and that for the functions in behavior of this sensory specific association cortex and even what we have discovered about the anatomical substrate for these functions that have shaken my faith in the classical view.

THE CLINICAL EVIDENCE

In patients, damage to certain parts of the brain has been correlated with a loss of the ability to identify objects. This disability can be manifest in any one of the major sensory modes. For instance, when a visual deficit occurs, the subdominant

hemisphere is especially involved (24) approximately at the inferior junction of the occipital and temporal lobes. According to Henry Head (17), Sigmund Freud is responsible for the usage of the term agnosia to describe this syndrome, a term which epitomizes the problems posed by its occurrence.

Von Monakov (26) called attention to these problems in a thorough review of relevant data. The issues can be summarized in two related questions: 1. Is agnosia dependent on the occurrence of primary sensory difficulties? 2. Can agnosia occur in the absence of involvement of the primary sensory projection systems? Von Monakov's answer to the first question was an unequivocal "no", an opinion shared on the basis of more recently acquired and very carefully obtained data by Bay (5). With the negative answer to the behavioral question in mind, Von Monakov reviewed the anatomical data and also gave a tentative "no" in answer to the possible exclusion of sensory systems in agnosia. However, he was by no means completely convinced or convincing on this point.

THE NON-HUMAN PRIMATE

Because of the difficulty of obtaining evidence on precise and limited brain injury in man, I decided some years ago to attempt to produce animal models of the agnosias (and other disorders of psychological processes) produced by brain damage. Such animal models would allow long-term behavioral analysis and relatively complete specification of the brain locus and perhaps even of the brain mechanisms involved in cognition. The ensuing program of research has proved effective, and I wish today to share some of its critical experimental results with you.

The immediate problem in making animal models was to identify areas in the brain cortex of monkeys that were homologous to those of man in producing behavioral disturbances. To this end a series of anatomical (8, 11, 29-31), chemical, viz., neuronography (22, 32, 33), and electrophysiological (12, 18, 20, 23, 37, 46) studies were undertaken. The results of these experiments were then used as a guide to making resections of cortex in a series of experiments in which a battery of behavioral tests was administered (visual, auditory, somatosensory and gustatory discriminations; delayed response and alternation; locomotor activity; conditioned avoidance of foot shock).

But often the subsystems of forebrain determined by one technique did not match exactly those determined by another. Further, there was no guarantee that the dissection wrought by a particular anatomical or physiological technique would accord with the neurobehavioral classification I sought. Resections for testing behavioral effects were therefore made in any one experiment on the most logical basis of what was known at the time so that each experiment could stand on its own. However, when approximately half a hundred rhesus monkey models had been produced the results were collated by a method called "the intercept of sums technique" (27). Briefly, by this method, one adds together on a standardized brain diagram all of the areas of the resections that produced a particular behavioral deficit, then in a separate diagram adds together all of the areas of the resections that produced no deficit

on that test; and overlays the two summations. The extent of summed lesions producing deficit that lies beyond the margins of the non-deficit-producing sum is the area critically involved in producing the behavioral difficulty. That this area and only this area is so involved was then tested by limiting resections to the "intercept" area and reproducing the behavioral difficulty in its entirety.

MONKEY BEHAVIOR

What is the nature of this behavioral difficulty? First and critically, there is a correlation between locus of lesion in the posterior association cortex and agnosia in one or another sensory mode. (Frontal or limbic lesions do not produce sensory discrimination deficits.) Figures 1 and 2 summarize the results of these "intercept-of-sums" studies.

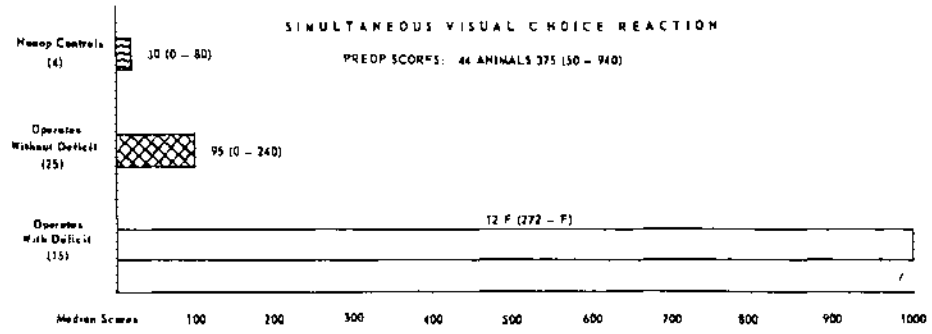


FIG. 1. Bar graph of median scores taken by monkeys to perform a visual discrimination task (the printed patterns + vs □). The number of animals per group is indicated below group name; the range from which median scores are taken appears in parentheses next to the median.

Second, a lesion producing a sensory specific deficit does not affect all behaviors in that mode equally. For instance, after resections of the inferior temporal gyrus, visual tracking was unaffected—monkeys could, despite severe visual discrimination deficits, catch gnats in midair with alacrity. But whenever a visually guided choice had to be made, monkeys with inferotemporal cortex resections showed impairment and this impairment was roughly proportional to the difficulty experienced by normal monkeys in learning the discrimination.

I want to limit discussion here to the brain area found to be homologous to that producing visual agnosia in man and to report only a few of a long series of experiments undertaken to determine the nature of this visual discrimination deficit. One

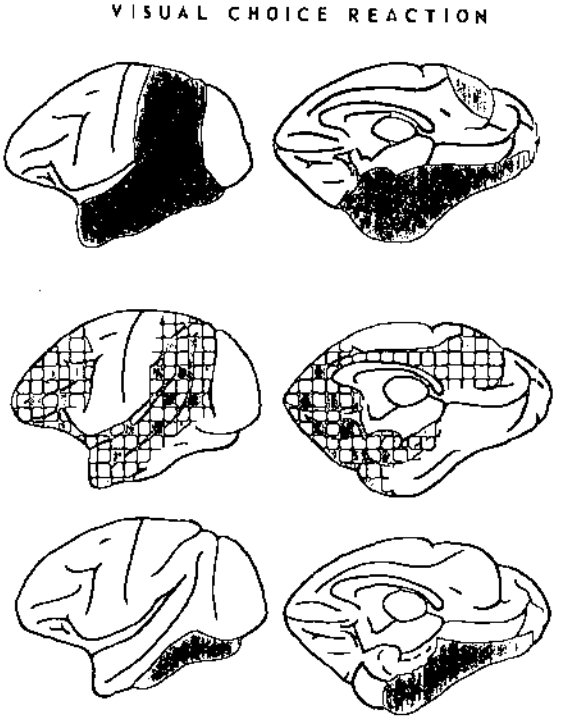


FIG. 2. The upper diagram A represents the sum of the areas of resection of all of the animals grouped as showing a deficit on the visual discrimination task noted in Figure 1. The middle diagram B represents the sum of the areas of resection of all of the animals grouped as showing no-deficit in Figure 1. The lower diagram C represents the intersect of the area shown in black in the upper diagram and that not checkerboarded in the middle diagram. This intersect represents the area invariably implicated in visual choice behavior in these experiments.

of the critical experiments asked the question whether the monkeys with inferotemporal cortex resections had difficulty in distinguishing among visual cues or whether some other difficulty was responsible for their discrimination deficit (34). The monkeys were taught a very easy discrimination: to choose between a simultaneously presented ash tray and tobacco tin. Though the lesioned monkeys took significantly longer to acquire the discrimination than did the controls, the task was mastered by all monkeys. Then a change was made in the way in which the ash tray and tobacco tin were presented. Instead of a simultaneous discrimination, two forms of a successive discrimination task were instituted. In one—the go-no/go procedure—the monkey found a

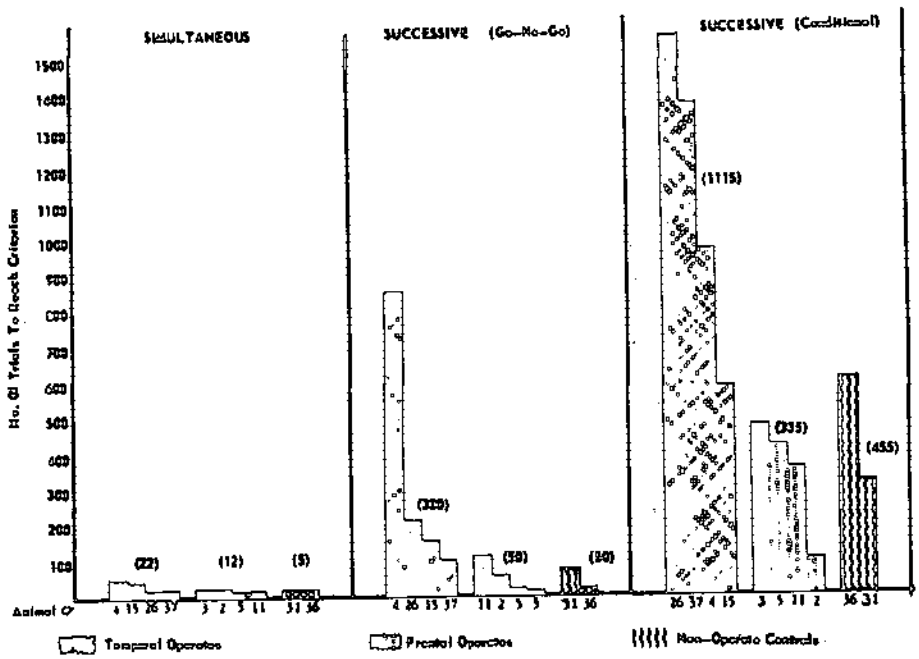


FIG. 3. Comparison of learning scores of three groups of animals (inferotemporal operates, anterofrontal operates, and non-operate controls) in a simultaneous task and two types of successive tasks in which the same cues were used. The increment of impairment of the inferotemporal group, as compared with controls, appears roughly proportional to the increasing difficulty of the task for controls.

peanut in a single box when the ash tray was present but no peanut when the tobacco tin adorned the top of the box. In the other, two boxes were present as in the simultaneous procedure but at this time the ash tray placed between them indicated that a peanut was located in the right hand box and the tobacco tin placed in the same position indicated that the peanut could be found in the left hand box. Compared with their controls, monkeys with inferotemporal cortex lesions showed severe difficulties in adjusting to the successive procedures. This, despite the fact that they could be shown on the same day in the simultaneous task to readily distinguish between ash tray and tobacco tin.

If the difficulty experienced by monkeys with inferotemporal resections—one is tempted to say, their agnosia—is not due to an inability to distinguish among objects, to what then is it attributable? Another change in the discrimination procedure provided a first clue to an answer to this question. In this modification several, rather than just two, cues were used (38). In this experiment the lesioned

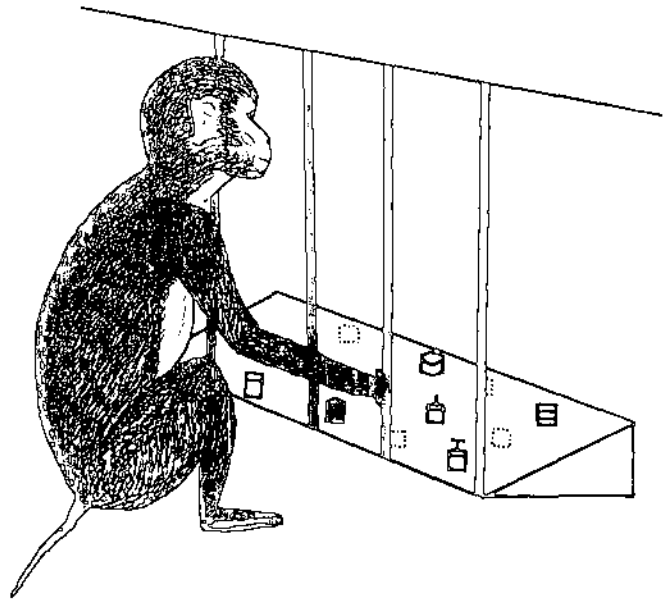


FIG. 4. Diagram of the multiple object problem showing an example of the seven object situation. Food wells are indicated by dashed circles, each of which is assigned a number. The placement of each object over a food well was shifted from trial to trial according to a random number table. A record was kept of the object moved by the monkey on each trial; only one move was allowed per trial. Trials were separated by lowering an opaque screen to hide from the monkey the objects as they were repositioned.

monkeys were shown to choose among fewer of the alternatives than their controls, suggesting a limitation on their ability to sample from an array of stimuli.

In another experiment Butter (7) showed that this limitation in sampling also occurred with respect to features within a particular cue. He taught monkeys to discriminate between two complex geometric designs and then dropped first one then another of the lines making up the designs. Normal subjects retained the ability to discriminate over a wide variety of such transformations of the cues. Monkeys with inferotemporal cortex resections began to fail after the initial transformations were undertaken.

These three experiments suggest that *selective* attention becomes impaired by the lesion, *i.e.*, the number of alternative stimulus features which can be attended

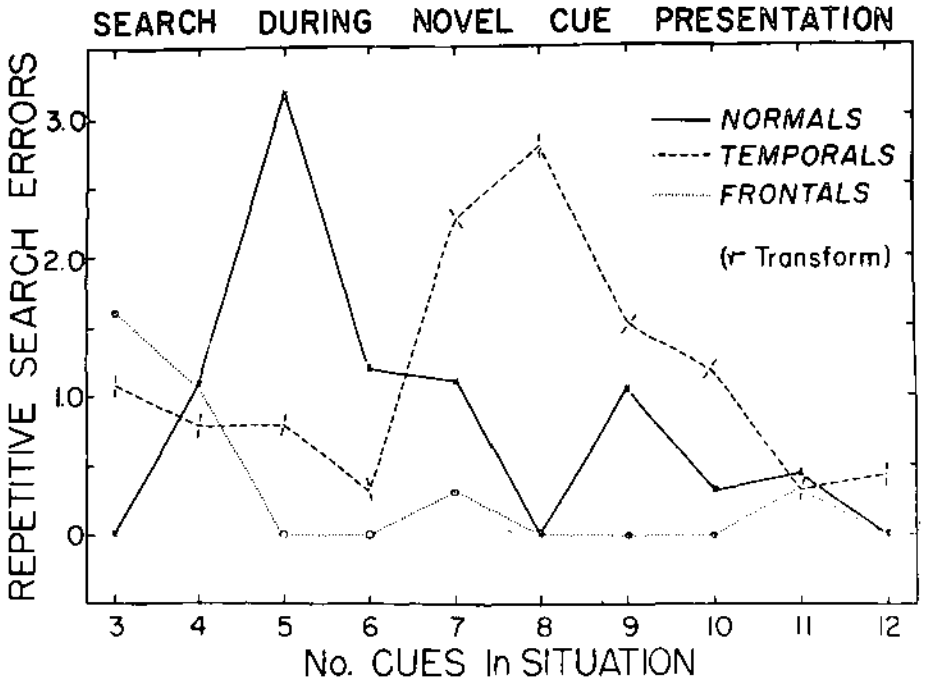


FIG. 5. Graph of the average of the number of repetitive errors made in the multiple object experiment during those search trials in each situation when the additional, i.e., the novel, cue is first added.

becomes restricted; the physiological studies suggest that the mechanism in this restriction is altered channel redundancy.

Confirmation of these hypotheses comes from an additional set of experiments. In this series the question was asked whether perhaps the difficulty in selective attention was due to a change in the way in which the lesioned monkeys observe cues. A Mackworth eye camera (21) was used to record the eye movements of monkeys (2) while they oriented to a change in one of a number of displayed cues. The course of habituation was also recorded and the distribution of eye movements was shown (4) to be indistinguishable from that of control subjects. (However, the monkeys with inferotemporal resections moved their eyes more often than did their controls.) When, on the other hand, I tried to train the monkeys to observe one of two cues by differentially reinforcing their looking at it, I failed with the lesioned group

though their unoperated controls responded readily (3). These results point up another aspect of the nature of the involvement of the inferotemporal cortex in selective attention. One of the ways attention can become selective is through differential reinforcement, and the inferotemporal cortex appears to be critically involved in this process.

THE EFFERENT HYPOTHESIS

The next questions to be answered concern the neural mechanism involved in selective attention and the relationship between selective attention and agnosia. As already noted, the classical view of the agnosias posits some association between "sensations, perceptions, ideas or feelings." These associations are assumed to occur via cortico-cortical connections between primary sensory receiving areas, connections which converge onto the association areas of the cortex. This hypothesis of the critical importance of cortico-cortical associations in the production of agnosias (and aphasias) is being actively pursued in man (14). But in monkey, a series of experimental results has led to an alternate view. The monkey brain appears not to be critically connected by its cortico-cortical pathways. In one experiment a comparison was made between the effects on visual discrimination of cross-hatching and undercutting the inferotemporal cortex. Cross-hatching, i.e., interrupting transcortical connections failed to impair visual discrimination learning. Undercutting the inferotemporal cortex on the other hand produced as much difficulty as does resection of this cortex (Figs. 6 and 7 and Table 1).

TABLE 1

	Animal	3 vs. 8	R vs. G	3 vs. 8
Crosshatch	158	380	82	0
	159	180	100	0
	161	580	50	0
	166	130	0	0
Undercut	163	(1014)	100	300
	164	(1030)	200	(500)
	167	704	50	0
	168	(1030)	150	(500)
Normal	160	280	100	0
	162	180	100	0
	165	280	100	0
	170	350	100	0

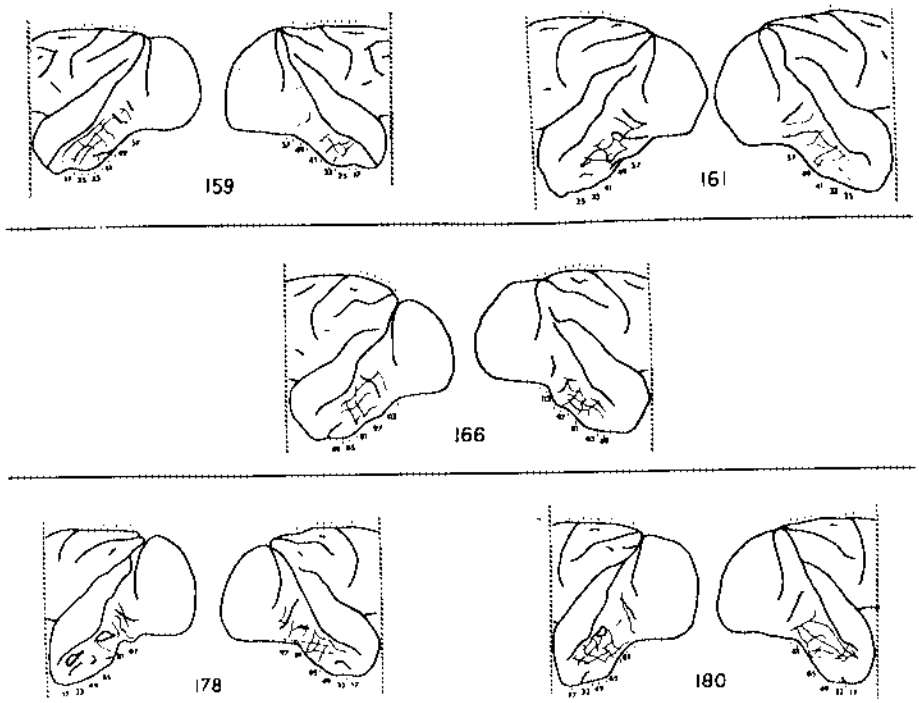


FIG. 6. Reconstructions of the cross-hatch lesions of Ss 159, 161, 166 (original learning), and 178 (retention). (Fine lines indicate the lesions.)

The question arises as to where the undercut fibers of the inferotemporal cortex connect. One possibility that must be considered is that the undercutting has severed U fibers originating in the striate area, the primary visual cortex. This possibility is ruled out by the fact that all known cortico-cortical connections of the striate area are with the peristriate cortex. There remains, of course, the possibility of a two-step indirect connection between visual projection and inferotemporal cortex via the peristriate area. To test this possibility, the striate and temporal cortex were radically disconnected from one another by making essentially complete resections of peristriate cortex and testing the effects on visual discrimination behavior. The results of this experiment confirmed those of earlier ones (9) in that monkeys could readily perform visual discriminations despite the radical disconnections (Fig. 8), (36).

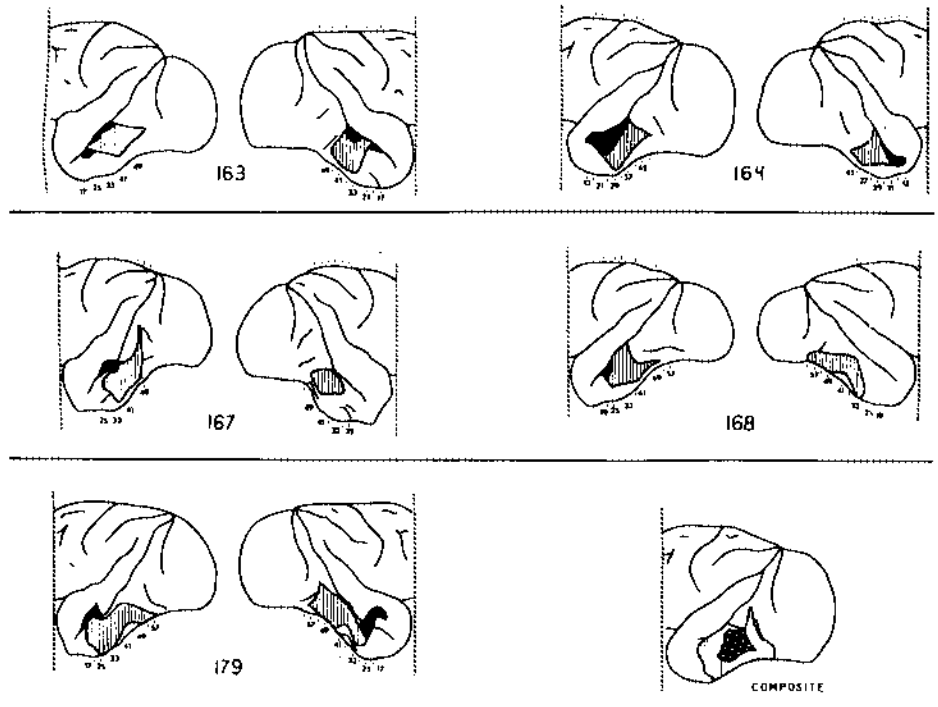


FIG. 7. Reconstructions of the undercut lesions of Ss 163, 164, 167, 168 (original learning), and 179 (retention). (Black indicates superficial cortical damage; stripes indicate the deep lesion.)

Where else could the undercut temporal lobe fibers critical to visual discrimination connect? A second possibility is that a second visual input system, in parallel with the primary projection system, has been interrupted. Such a second system has been described to exist in lower primates (16, 42), and there is a thalamic input to the inferotemporal cortex of the rhesus monkey from the pulvinar (6, 8) which could be the homologue of the second system of lower primates. However, experiments in which the pulvinar was destroyed failed to influence visual discrimination (10); in an as yet unpublished study (25), some 35 such lesions which destroyed the entire extent of the pulvinar and more, have left visual discrimination intact.

Because of results such as these, which have become ever more persuasive in recent years, I suggested some fifteen years ago yet a third alternative for the criti-

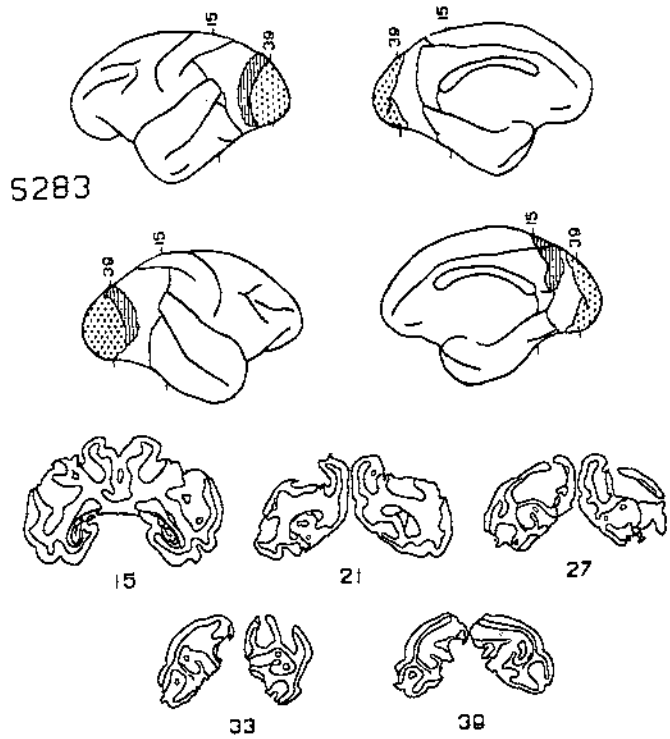


FIG. 8. Reconstruction of bilateral prestriate lesions after which monkey could still perform a visual discrimination (the numerals 3 vs. 8).

cal connections of the inferotemporal cortex: viz., that corticofugal, efferent fibers leave the temporal lobe to connect downstream with visual structures such as the superior colliculus to alter the functions of the primary visual projections. I specified the tegmental region of the brain stem rather than the thalamic because preliminary anatomical studies had shown no direct connections from the temporal cortex to the lateral geniculate nucleus (47). I want now to report a series of electrophysiological studies undertaken to test the hypothesis that the inferotemporal cortex

exerts control over visual input and to determine the pathways by which this control may be effected.

The clearest evidence that the temporal cortex can control the activity of visual input system comes from studies of the effects of electrical stimulation of the inferotemporal cortex on unit activity recorded from cells in the visual input system by microelectrodes. The results of a series of experiments demonstrating this corticofugal effect is shown in Figure 9 (43, 44).

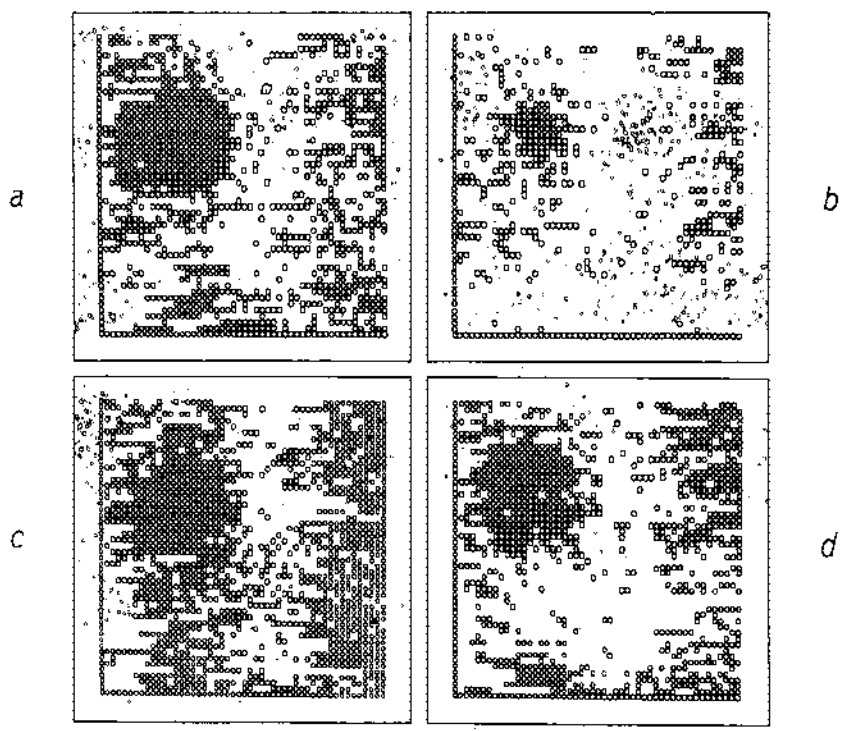


FIG. 9. Visual-receptive field maps show how information flowing through the primary visual pathway is altered by stimulation elsewhere in the brain. Map a is the normal response of a cell in the geniculate nucleus when a light source is moved through a raster-like pattern. Map b shows how the field is contracted by stimulation of the inferior temporal cortex. Map c shows the expansion produced by stimulation of the frontal cortex. Map d is a final control taken 55 minutes after recording a.

Two questions are immediately raised by this demonstration: 1. What are the efferent pathways to the visual input system from the temporal cortex, and 2. What is the functional significance of these pathways? The anatomical question had already been posed in the studies (of Whitlock and Nauta) referred to above and was reinvestigated by electrophysiological methods (38). Essentially four major corticofugal pathways have been shown to exist. 1. The connection from the temporal cortex to the superior colliculus, already mentioned, turns out to originate only in the posterior part of the inferotemporal cortex (and in the peristriate cortex). Therefore this connection by itself cannot account for the role of the inferotemporal cortex in vision. 2. A connection between inferotemporal cortex and amygdala which, however, arises only from the most anterior extremity of the cortex involved in vision. In view of the close connection between temporal pole and amygdala and the fact that resections of neither the pole nor amygdala produce visual impairment, I feel that these connections represent an overlap between inferotemporal and polar areas. These considerations plus the facts that there are no direct connections between inferotemporal cortex and other limbic structures (such as the hippocampus) and that resections of limbic structures do not lead to visual discrimination deficits tends to disconfirm hypotheses (14) which explain the functions of the association cortex of monkeys on the assumption that such connections are critical. 3. A connection between inferotemporal cortex and pulvinar. Interestingly, this connection is not with that part of the pulvinar (posterior inferior) which projects to the inferotemporal cortex but with a portion somewhat anterior and lateral. Thus a simple direct feedback loop appears precluded. The possible functional role of these connections therefore remains unexplained. 4. A connection between inferotemporal cortex and the basal ganglia: tail of the caudate nucleus and ventral putamen. The vast extent of this connection and the large size of the potentials evoked in the basal ganglia by inferotemporal stimulation came as a surprise in the electrophysiological experiments. Anatomical studies, however, have confirmed the stimulation data (Fig. 10) (19) and, in my opinion, these connections account fully for the results obtained by Rosvold and Szwarcbart (39) that stereotaxic lesions in the region of the tail of the caudate nucleus and ventral putamen drastically disrupt visual discriminations. What remains to be uncovered is the pathway by which the basal ganglia control visual input. Experiments to do this are now under way.

In summary, neuroanatomical, neurophysiological and neurobehavioral experiments indicate that it is likely that the visual functions of the inferotemporal cortex depend on corticofugal efferents to the basal ganglia which influence the primary visual projection system by an as yet unspecified pathway.

CHANNEL REDUNDANCY AND ATTENTION

Given the probability that the brain's association areas work by way of corticofugal efferents that alter the functions of the primary projection system, the question arises as to how that efferent control is manifest. A clue toward an answer to this question has come from a series of electrophysiological experiments on the effects of

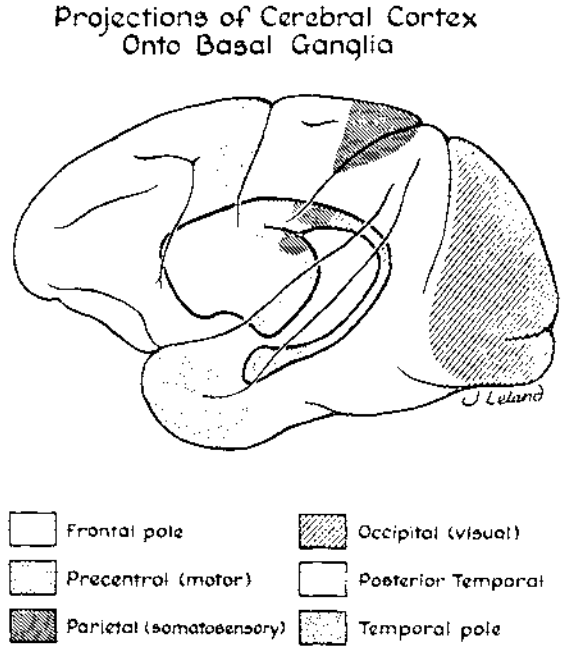


FIG. 10. Diagram of the projections of cerebral cortex onto the caudate nucleus and putamen. There is considerable overlap not shown in diagram.

electrical stimulation of the inferotemporal cortex on recovery cycles in the visual input system (43). In fully awake monkeys such recovery cycles were initiated by presenting double flashes separated by a varying interval of between 25 and 250 msec. The amplitude of the two responses evoked at the visual cortex was measured and the ratio of second to first plotted as a function of the interflash interval. The plot gave the recovery function of the system for a particular monkey and this remained stable over weeks of testing. Continuous electrical stimulation of the inferotemporal cortex was then begun and the recovery function obtained under the new condition. Figure 11 shows the effect of such stimulation: the recovery is slowed by stimulation of the inferotemporal cortex.

An interpretation of these results can be made in information processing terms: slowing of recovery indicates that a greater number of fibers of the input channel remain "busy" for longer during the stimulation condition. This effectively reduces

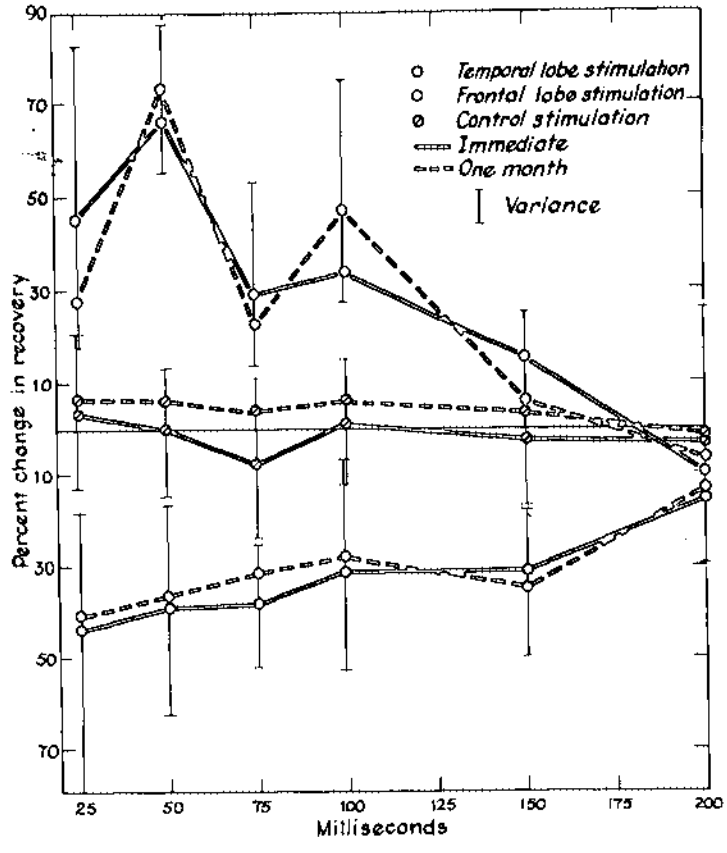


FIG. 11. The change produced by cortical stimulation in recovery of a response in an afferent channel. Cortical stimulation of 8 Hertz was maintained continuously for several months. Control stimulations were performed on the parietal cortex. Records were made immediately after the onset of stimulation and weekly thereafter. The initial recovery functions and those obtained after 1 month are shown. Vertical bars represent actual variability of the records obtained in each group of four monkeys.

the number of fibers carrying the signal evoked by the second flash and thus reduces redundancy in the channel whenever more than a single brief signal is processed. Redundancy reduction implies an enhanced information density in the channel, i.e., at any moment, the channel capacity for processing information becomes increased.

Because of the importance of these results to an understanding of the functions of the inferotemporal cortex, additional studies were undertaken. Very quickly we found that we had not specified all of the variables necessary for replication. Sometimes the effect on recovery function was seen clearly; in other experiments it was lacking. Finally a fortuitous accident pointed the direction our research must take. Because of the crowded condition of the laboratory, Lauren Gerbrandt, then a postdoctoral fellow, began to perform the recovery cycle experiments at night. His wife was pressed into service to help catch and place the monkey in a restraining chair. One evening, after good results had been pouring in nightly, she brought a friend along to help pass the waiting time while her husband was testing. She told her friend of the experiment and the usual wifely chatter continued for a time in the large room in which the experiment was conducted. And lo! the slowing of recovery previously obtained whenever the inferotemporal cortex had been stimulated now ceased. Gerbrandt called me and we quickly put his serendipitous observation to test. We took a record under normal quiet conditions and then opened the testing cage so the monkey could see me and took another record. The recovery function became slowed while the monkey attended me and this slowing was comparable to that produced by inferotemporal cortex stimulation in the inattentive condition. While the monkey was visually or auditorily attending, the temporal lobe stimulation had no further slowing effect. In short, behavioral attention and electrical stimulation of the inferotemporal cortex converged to produce the same effect on input channel redundancy.

A direct test of the importance of the attention variable in the recovery function experiment was then made. Other research (41) had shown that the potential evoked in the visual cortex of awake monkeys by an electrical pulse delivered to the lateral geniculate nucleus was sensitive to attentiveness. Using such a probe stimulus we first checked and confirmed the earlier observation and then used this phenomenon as a probe to gauge attentiveness in a recovery cycle experiment run during the day. Recovery functions obtained during periods of attention (e.g., when someone in high heels came down the hall) as gauged by the probe were separated by computer from those obtained during periods of inattention. Now beautiful records of slowing were again recorded consistently—but only during the periods when the monkeys were inattentive (13). Our initial experiments had taken much longer to perform than subsequent ones since we were still groping and so tested the monkeys daily with a large number of stimuli (e.g., single flash, double flash, single click, double click, click-flash and flash-click) repeated over and over. Not only the monkeys but the experimenters became inattentive; I remember many occasions when the monkey had to be prodded from time to time to keep him from falling asleep—a procedure which helped keep me from doing the same.

The results of these experiments suggest that the inferotemporal cortex is somehow involved in the process of visual attention, a suggestion supported by the findings of Gross et al.(15) that unit recordings from cells in this cortex register when the monkey is visually attending. The nature of this attentive process and its relation to recognition becomes evident from the results of yet another series of experiments,

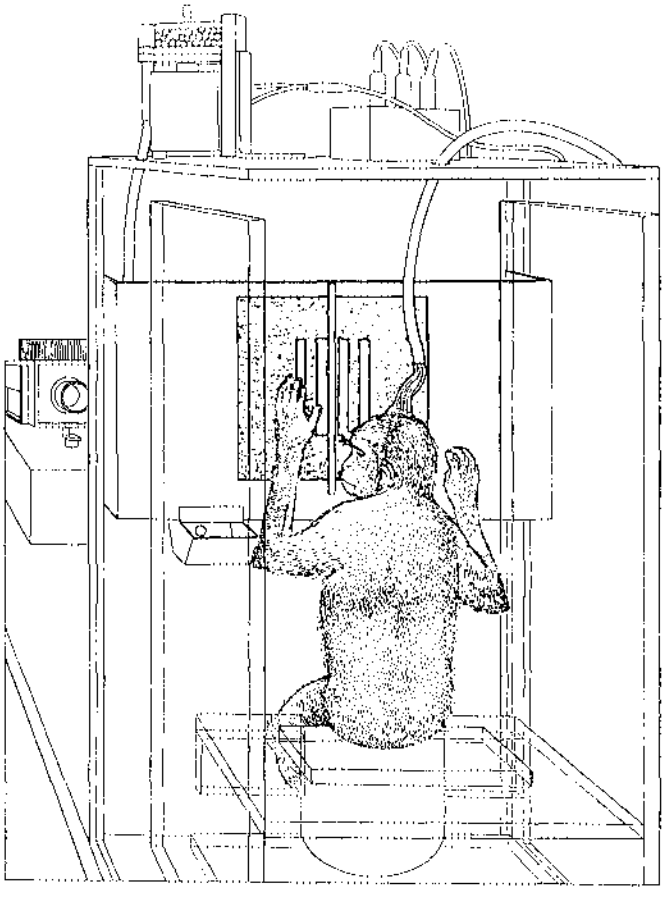


FIG. 12. On the translucent panel in front of him, the monkey sees either a circle or a series of vertical stripes, which have been projected from the rear. He is rewarded with a peanut, which drops into the receptable at his left elbow, if he presses the right half of the panel when he sees the circle or the left half when he sees the stripes. Electrodes record the wave forms that appear in the monkey's visual cortex as he develops skill at this task. Early in the experiments the wave forms show whether the monkey sees the circle or stripes. Eventually they reveal in advance which half of the panel the monkey will press.

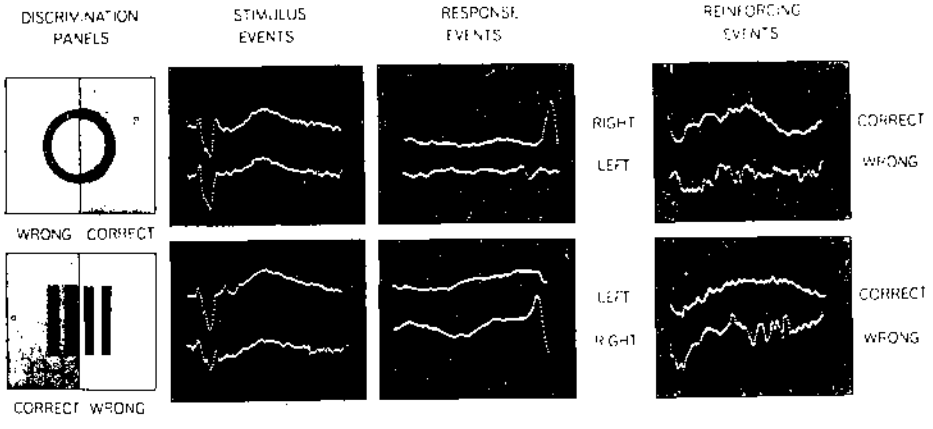


FIG. 13. Results of visual-discrimination experiment are shown in the wave forms recorded from the striate (visual) cortex of a monkey. The waves are those after he has learned the task illustrated in Figure 12. The records under "Stimulus events" are wave forms that appear immediately after the monkey has been shown a circle or stripes. The records under "Response events" were generated just prior to the moment when the monkey actually responded by pressing either the left or the right half of the panel. The records under "Reinforcing events" were produced when the monkey was rewarded with a peanut if he was correct or not rewarded if he was wrong. The correct response was to press the right half of the panel on seeing a circle, the left half on seeing stripes. A difference in the "stimulus" wave forms indicates whether the monkey has seen stripes or a circle. After he has learned his task well, sharp differences appear in the response and reinforcing records. The response wave forms, which are actually "intention" waves, show one pattern (the one with the sharp peak) whenever the monkey is about to press the right half of the panel, regardless of whether he has seen a circle or stripes. If he has actually seen stripes, of course, pressing the right half of the panel is the wrong response. Thus the wave forms reflect his intention to press a particular half of the panel. They could hardly reveal whether his response is going to be right or wrong because at this point he still "thinks" he is about to make the correct response.

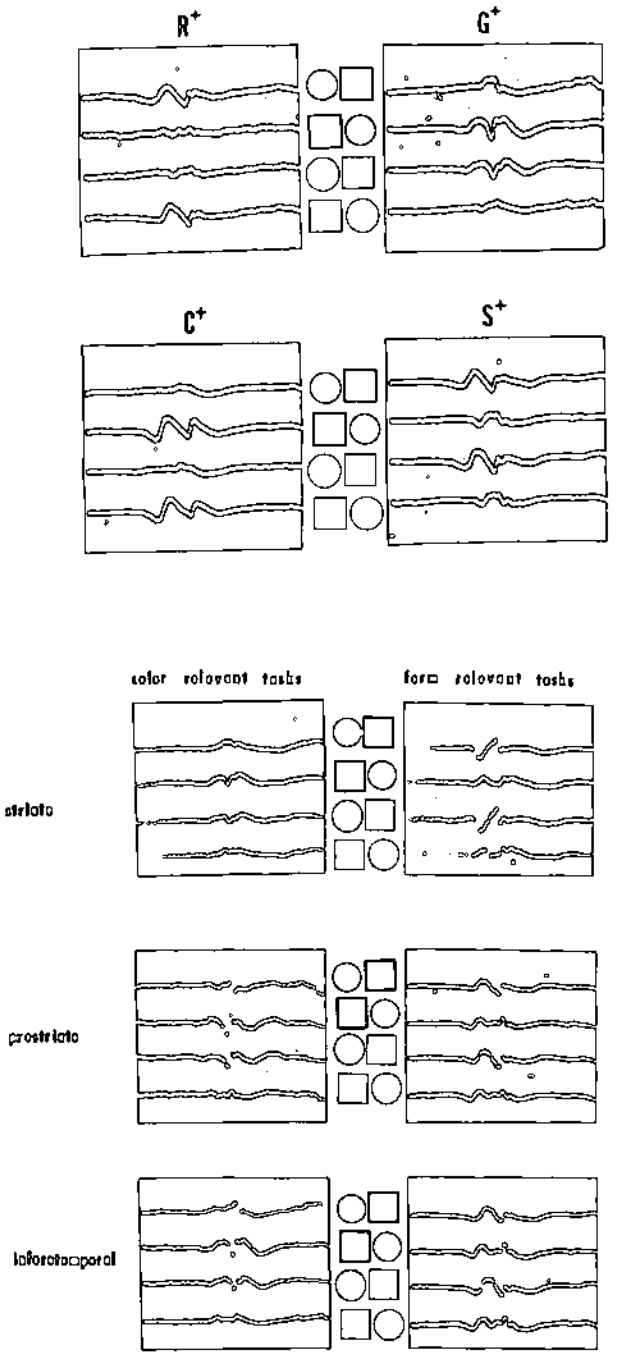
described below.

The most recent set of experiments performed in my laboratories demonstrates this relationship directly. Electrical recordings were made from the primary visual (35) and inferotemporal (40) cortices during visual discrimination performances. In order to generate analyzable transients in the brain, the cues were flashed briefly (1 microsec.) onto a translucent divided panel each side of which could be pressed in order to obtain reinforcement (Fig. 12). In the primary visual cortex, wave forms could be distinguished that reflected the differences between the cues presented to the monkey's retina (Fig. 13). In the inferotemporal cortex no such distinction could be made out. When, however, a somewhat more complicated task was presented—cues that differed in two dimensions, i.e., both in color and shape—the electrical activity recorded from the inferotemporal cortex correlated with the dimension responded to by the monkey. Specifically (but somewhat oversimply) monkeys were trained to discriminate color (e.g., green was rewarded, reinforced) until stable criterion performance was reached when recordings were made. Then they were taught the shape dimension (e.g., circle was reinforced), and again when stable performance was reached, recordings were made (Figs. 14 and 15). The records were then compared by computer analysis and differences were demonstrated. Note that the stimulus configuration displayed to the monkey's retina is identical in the two situations: only the reinforcing contingencies and therefore the responses generated are different. This is demonstrated by the fact that in this situation the brain electrical records anchored to the time of stimulus presentation do not reflect the dimension attended—only when the records are analyzed using the moment of response (panel pressing) do these differences in brain record show up.

CONCLUSION

These penultimate experiments demonstrate once again that the inferotemporal cortex is primarily involved in the "motor" function of responding to, rather than the "sensory" process of distinguishing between, visual cues. Thus if association does take place by virtue of the association cortex, it is not association between cues but between cue and the outcome of response, i.e., between cue and reinforcer. The system of which association cortex is a part and which apparently includes the basal ganglia is involved in establishing a motor set which reinforces discrimination learning through enhancing the process of selective attention. This is accomplished in part at least by increasing the capability of input channels to simultaneously transmit and select among different signals. Recognition, making identifications in the sensory world, depends on this motor process. When lesions of the association cortex of the brain impair identification, agnosias result.

Thus, an answer to Von Monakov's questions has been obtained, at least for the monkey. Agnosia does involve sensory (channel) capacity. Lesions of the association cortex affect sensory processing because the critical connections of the association cortex are the efferents to the input systems, not the afferents from them. But the input systems per se need not be anatomically disrupted in order that agnosia



Figures 14 and 15

FIGS. 14 and 15. Results of an experiment demonstrating the functions of the inferotemporal cortex by behavioral electrophysiological techniques. The experiment is similar to the one described in Figs. 12 and 13. A monkey initiates a flashed stimulus display and responds by pressing either the right or left half of the display panel to receive a reward while electrical brain recordings are made on line with a small general purpose computer (PDP-8). In this experiment the flashed stimulus consisted of colored (red and green) stripes and circles. Reinforcing contingencies determined whether the monkeys were to attend and respond to the pattern (circle vs stripes) or color (red vs green) dimension of the stimulus. As in the earlier experiment, stimulus, response, and reinforcement variables were found to be encoded in the primary visual cortex. In addition, this experiment showed that the association between stimulus dimension (pattern or color and the outcome of the response occurs first in the inferotemporal cortex. This is presented in recording 3 of Fig. 14 where the electrophysiological data averaged from the time of response (forward for 250 msec and backward 250 msec from center of record) show clear differences in waveform depending on whether pattern or color is being reinforced. Note that this difference occurs despite the fact that the retinal image formed by the flashed stimulus is identical in the pattern and color problems. Once the monkeys have been overtrained, this reinforcement produced attentional association between a stimulus dimension and response and also becomes encoded in the primary visual cortex as shown in Fig. 15.

be produced. The inability to recognize, to selectively attend to and identify the objective world, can be the result of lesions restricted to the association cortex. This cortex is not involved in association among inputs, nor in distinguishing between them, but in establishing, on the basis of reinforcement, a motor set that determines attentive selection among alternatives.

REFERENCES

1 ALBE-FESSARD, D. Activites de projection et d'association du neocortex cerebral des mammiferes. Extrait du Journal de Physiologie, 49 (1957) 521-588.

2 BAGSHAW, M.H., MACKWORTH, N.H. and PRIBRAM, K.H. Method for recording and analyzing visual fixations in the unrestrained monkey. Perceptual and Motor Skills, 31 (1970) 219-222.

3 BAGSHAW, M.H., MACKWORTH, N.H. and PRIBRAM, K.H. The effect of inferotemporal cortex ablations on eye movements of monkeys during discrimination training. Int. J. Neuroscience, 1 (1970) 153-158.

4 BAGSHAW, M.H., MACKWORTH, N.H. and PRIBRAM, K.H. The effect of resections of inferotemporal cortex on the amygdala on visual orienting and habituation (in preparation).

5 BAY, E. Principles of classification and their influence on our concepts of aphasia. In: Disorders of Language, edited by A.V.S. de Reuck and M. O'Connor. Little Brown and Company, Boston, 1964, pp. 122-142.
6 BLUM, J.S., CHOW, K.L.,and PRIBRAM, K.H. A behavioral analysis of the organization of the parieto-temporo-preoccipital cortex. J. comp. Neurol., 93 (1950) 53-100.
7 BUTTER, C.M. The effect of discrimination training on pattern equivalence in monkeys with inferotemporal and lateral striate lesions. Neuropsychologia, 6 (1968) 27-40.
8 CHOW, K.L. A retrograde cell degeneration study of the cortical projection field of the pulvinar in the monkey. J. comp. Neurol., 93 (1950) 313-339.
9 CHOW, K.L. Further studies on selective ablation of associative cortex in relation to visually mediated behavior. J. comp. physiol. Psychol., 45 (1952) 109-118.
10 CHOW, K.L. Lack of behavioral effects following destruction of some thalamic association nuclei in monkey. Arch. Neurol. Psychiat., 71 (1954) 762-771.
11 CHOW, K.L., and PRIBRAM, K.H. Cortical projection of the thalamic ventrolateral nuclear group in monkeys. J. comp. Neurol., 104 (1956) 57-75.
12 FULTON, J.F., PRIBRAM, K.H., STEVENSON, J.A.F., and WALL, P.D. Interrelations between orbital gyrus, insula, temporal tip and anterior cingulate. Trans. Amer. Neurol. Assoc., 175 (149).
13 GERBRANDT, L.K., SPINELLI, D.N., and PRIBRAM, K.H. The interaction of visual attention and temporal cortex stimulation on electrical activity evoked in the striate cortex. Electroenceph. clin. Neurophysiol., 29 (1970) 146-155.
14 GESCHWIND, N. Disconnexion syndromes in animals and man: Part I. Brain, 88 (1965) 237-294.
15 GROSS, C.G., BENDER, D.B., and ROCHA-MIRANDA, C.E. Visual receptive fields of neurons in inferotemporal cortex of the monkey. Science, 166 (1969) 1303-1305.
16 HALL, W.C., and DIAMOND, I.T. Organization and function of the visual cortex in hedgehog. I. Cortical cytoarchitecture and thalamic retrograde degeneration. Brain, Behav. Evol. 1 (1968) 181-214.
17 HEAD, H. Studies in Neurology. Medical Publications, Oxford, 1920.
18 KAADA, B.R., PRIBRAM, K.H., and EPSTEIN, J.A. Respiratory and vascular responses in monkeys from temporal pole, insula, orbital surface and cingulate gyrus. A preliminary report. J. Neurophysiol., 12 (1949) 347-356.
19 KEMP, J.M., and POWELL, T.P.S. The cortico-striate projection in the monkey. Brain, 93 (1970) 525-546.
20 LENNOX, M.A., DUNSMORE, R.H., EPSTEIN, J.A., and PRIBRAM, K.H. Electrocorticographic effects of stimulation of posterior orbital, temporal and cinguiate areas of Macaca mulatta. J. Neurophysiol., 13 (1950) 383-388.
21 MACKWORTH, N.H. A stand camera for line-of-sight recording. Perception & Psychophysics, 2 (1967) 119-127.

22 MACLEAN, P.D., and PRIBRAM, K.H. A neuronographic analysis of the medial and basal cerebral cortex. I. cat. J. Neurophysiol., 16 (1953) 312-323.

23 MALIS, L.I., PRIBRAM, K.H., and KRUGER, L. Action potentials in "motor" cortex evoked by peripheral nerve stimulation. J. Neurophysiol., 16, (1953) 161-167.

24 MILNER, B. Psychological defects produced by temporal lobe excision. In: The Brain and Human Behavior (Proc. Assoc. for Res. in Nerv. & Ment. Dis., Vol XXXVI), Williams & Wilkins Co., Baltimore, 1958, pp. 244-257.

25 MISHKIN, M., and ROSVOLD, H.E. (unpublished study).

26 MONAKOV, C. VON. Die Lokalisation im Grosshien und der Abbau der Funktion Durch Korticale Herde. J.F. Bergmann, Wiesbaden, 1914.

27 PRIBRAM, K.H. Toward a science of neuropsychology: (Method and data). In: Current Trends in Psychology and the Behavioral Sciences, Ed. R.A. Patton, University of Pittsburgh Press, Pittsburgh, 1954, pp. 115-142.

28 PRIBRAM, K.H. On the neurology of thinking. Behav. Sci., 4 (1959) 265-287.

29 PRIBRAM, K.H., and BAGSHAW, M.H. Further analysis of the temporal lobe syndrome utilizing frontotemporal ablations in monkeys. J. comp. Neurol., 99 (1953) 347-375.

30 PRIBRAM, K.H., CHOW, K.L., and SEMMES, J. Limit and organization of the cortical projection from the medial thalamic nucleus in monkeys. J. comp. Neurol., 95 (1953) 433-448.

31 PRIBRAM, K.H., and FULTON, J.F. An experimental critique of the effects of anterior cingulate ablations in monkeys. Brain, 77 (1954) 34-44.

32 PRIBRAM, K.H., LENNOX, M.A., and DUNSMORE, R.H. Some connections of the orbito-fronto-temporal, limbic and hippocampal areas of Macaca mulatta. J. Neurophysiol., 13 (1950) 127-135.

33 PRIBRAM, K.H., and MACLEAN, P.D. A neuronographic analysis of the medial and basal cerebral cortex: II. Monkey. J. Neurophysiol., 16 (1953) 324-340.

34 PRIBRAM, K.H., and MISHKIN, M. Simultaneous and successive visual discrimination by monkeys with inferotemporal lesions. J. comp. physiol. Psychol., 48 (1955) 198-202.

35 PRIBRAM, K.H., SPINELLI, D.N., and KAMBACK, M.C. Electrocortical correlates of stimulus response and reinforcement. Science, 157 (1967) 94-96.

36 PRIBRAM, K.H., SPINELLI, D.N., and REITZ, S.L. Effects of radical disconnexion of occipital and temporal cortex on visual behavior of monkeys. Brain, 92 (1969) 301-312.

37 PRIBRAM, K.H., ROSNER, B.S., and ROSENBLITH, W.A. Electrical responses to acoustic clicks in monkey: extent of neocortex activated. J. Neurophysiol., 17 (1954) 336-344.

38 REITZ, S.L., and PRIBRAM, K.H. Some subcortical connections of the inferotemporal gyrus of monkey. Exp. Neurol., 25 (1969) 632-645.

39 ROSVOLD, H.E., and SZWARCBART, M.K. Neural structures involved in delayed-response performance. In: The Frontal Granular Cortex and Behavior. Eds. J.M. Warren and K. Akert, McGraw Hill, New York, 1964, pp. 1-15.
40 ROTHBLAT, L., and PRIBRAM, K.H. Selective attention: an electrophysiological analysis of monkey (submitted to Brain Research).
41 SCHOOLMAN, A., and EVARTS, E.V. Responses to lateral geniculate radiation stimulation in cats with implanted electrodes. J. Neurophysiol., 22 (1959) 112-129.
42 SNYDER, M., and DIAMOND, I.T. The organization and function of the visual cortex in the tree shrew. Brain, Behav. Evol. 1 (1968) 244-288.
43 SPINELLI, D.N., and PRIBRAM, K.H. Changes in visual recovery functions produced by temporal lobe stimulation in monkeys. Electroenceph. clin. Neurophysiol., 20 (1966) 44-49.
44 SPINELLI, D.N., and PRIBRAM, K.H. Changes in visual recovery function and unit activity produced by frontal cortex stimulation. Electroenceph. clin. Neurophysiol., 22 (1967) 143-149.
45 THOMPSON, R.F., JOHNSON, R.H., and HOOPES, J.J. Organization of auditory somatic sensory, and visual projection to association fields of cerebral cortex in the cat. J. Neurophysiol., 26 (1963) 343-364.
46 WALL, P.D., and PRIBRAM, K.H. Trigeminal neurotomy and blood pressure responses from stimulation of lateral cerebral cortex of Macaca mulatta. J. Neurophysiol., 13 (1950) 409-412.
47 WHITLOCK, D.G., and NAUTA, W.J. Subcortical projections from the temporal neocortex in Macaca mulatta. J. comp. Neurol., 106 (1956) 183-212.

DISCUSSION

METTLER: I don't think we should be deluded by the rather casual way that Karl presented this material. This is an elegant display of experimental techniques in an area which is extremely difficult to handle, and I congratulate you, Karl. What he has just shown you throws into relief the importance of two systems concerning which we have so far had only a few hints during the presentations of the last two days. He has opened the way to a new symposium, dealing with the interconnections of the cortex and striatum and pallidum, on the one hand, and between the striatum and pallidum with the thalamus, on the other. What is the difference between the functions of the cortex and extrapyramidal systems insofar as peak performance in sensory, motor and associative functions are concerned? The difference he has shown you is one of power, from the point of view of what we may call the associational handling of sensory experience. Without the striatum the animal is quite unable to relate itself to its environment at a satisfactory level of self-maintenance. Without its cortex it is unable to relate itself accurately to its environment but it still can do it. The cat, maligned feline though it may be, is able to get along reasonably well without much

cortex but if you add a sizeable striatal deficit to this, the animal looks at you with vacuous eyes and, in an uncomprehending manner, will walk out of a third floor window with complete unconcern.