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Some Subcortical Connections of the Inferotemporal Gyrus of Monkey

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Responses evoked by stimulating points along the inferotemporal gyrus of the macaque are found in the anterior commissure, amygdala, medial temporal cortex, the head and basal posterior portions of the putamen, the tail of the caudate nucleus, the pretectal tegmentum, just lateral to the central gray matter, and the superior colliculus. The superior colliculus projections come from the posterior part of the inferior gyrus only, and the amygdala receives fibers only from the anterior region. Interhemispheric connections of this gyrus go via the anterior commissure, with indications of a shift to corpus callosum crossing as inferotemporal cortex (area TE) blends into prestriate cortex (areas OA and OBO posteriorly). The importance of the various input and ouput connections to the inferotemporal area are considered with regard to visual discrimination performance, and the difference in projections of the anterior and posterior areas is related to findings of a functional difference between these regions.

Introduction

This study reports an electrophysiological mapping of the efferent projections of the inferior temporal gyrus of the monkey. These projections are of special interest today because of a paradox uncovered by experiments aimed at delineating the neural mechanisms involved in visual learning and recognition. Experimental ablation (8) or undercutting (13) of the inferior temporal cortex in nonhuman primates results in severe visual discrimination disabilities, and lesions in this region of the subdominant hemisphere of man produce disturbances in visual form recognition (7). The common assumption is that visual information reaches this cortex secondarily from the primary visual projections. However, the only known cortical connections of the primary visual (striate) cortex traverse the adjacent (peristriate) cortex and yet virtually complete resection of this territory fails to produce the visual impairments found to follow inferior temporal damage. Destruc-

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tion of the inferior pulvinar nucleus of the thalamus, which provides the only known direct subcortical input to the inferior temporal gyrus, has also failed to produce a detectable deficit (4). Pribram (11) suggested, therefore, that it would be profitable to consider the output from the inferior temporal cortex, which could be conceived to selectively modify activity in the primary visual pathway (via some subcortical connections) and thus account for the specifically visual function of this part of the temporal lobe.

Interest in the efferent projections is further generated by recent reports (Iwai and Mishkin) [2] that the anterior and posterior parts of the inferior temporal gyrus function differently in vision: that the anterior part of the gyrus is more involved in visual learning and the posterior part in visual recognition. Could this difference be based on differences in the termination of the projections originating along the anterior-posterior extent of the gyrus?

The present study maps the subcortical responses evoked by localized stimulation at points along the inferotemporal cortex. The map thus obtained yields information about subcortical structures which could be found important in visual learning and recognition and reveals something of the differences in distribution of projections from anterior and posterior segments, which may be relevant to understanding recent studies showing functional differences between these subdivisions.

Method

Eight adult monkeys (*Macaca mulatta*) were used. Under sodium pentothal anesthesia, they were cannulated intravenously for later injections, intubated for respiration, and then placed in the stereotaxic apparatus. A local anesthetic (procaine in oil suspension) was infused around the points of pressure and the edges of all wounds. In five of them the skull was exposed by a midline incision, the temporal muscle on the left was removed, and the stump was anesthetized. A rectangular opening was cut in the bone over the left inferior temporal gyrus and another over the area to be explored with the recording electrodes. After the dura in both areas was opened, the monkey was given Flaxedil (3 ml, iv), placed on a respirator, and maintained on the drug (2 ml/hour) throughout the experiment. For the last three animals the procedure was modified to minimize exposure of the cortex. For the recording electrodes a small midline incision was made as before, but now only burr holes were drilled at each site to be investigated. The dura was opened in each hole with a cutting needle and the holes were protected with moist Gelfoam until they were to be used.

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[2] Paper read at American Psychological Association, Washington, D.C., 1967.

The stimulating electrodes (two to three in each monkey) were inserted into the inferotemporal gyrus at an angle of about 45 deg from the vertical, lowered just to the bone, and then drawn back about 2 mm. These electrodes were left in place throughout the experiment. In the last three monkeys a small incision was made in the skin over the temporal region. The muscle was split and two small (1 mm) burr holes were drilled in the bone. Stimulating electrodes were inserted in the usual manner, but they were then cemented in place with dental acrylic. The muscle was sutured in anatomical layers and the skin closed, leaving only the electrode wires protruding.

To begin the evoked response mapping a recording electrode was first lowered stereotaxically to a point just medial to the stimulating electrodes to see if the stimulation was effective. Beginning at least 2 hours after the animal was placed on the respirator, the sites to be investigated were systematically mapped in 2-mm steps in an anteroposterior and mediolateral direction. Activity of the brain at the site was observed on an oscilloscope after each stimulus pulse. Each tract was mapped using either one stimulation site as the recording lead was lowered and one as it was raised, or by using the three sites in rotation at each point as the electrode advanced However, when any response evoked by one stimulation site was observed, all other sites were immediately checked to determine if they also evoked a response. An attempt was made to map each tract with at least one anterior and one posterior stimulation. In a number of the recording tracts in each experiment, iron was deposited at either the site of a response or at some specified level by passing current from a 9-v battery through the recording electrode for 6 sec.

Apparatus. Both the recording and stimulating electrodes (five monkeys) were concentric bipolar electrodes made by threading 300-μ-diameter enamel coated Nichrome wire through 20- or 22-gauge stainless steel spinal needles and coating both with vinyl. The tips protruded 1.5 mm beyond the barrel. A small ring was exposed around the tip and around the barrel. The impedance of the concentric electrodes in saline was about 4–5 kohms at 1 kHz. In the last three animals the stimulating electrodes consisted of pairs of adjacent enamel-coated Nichrome strands held together with vinyl. The tips were separated vertically by 1.5–2.0 mm.

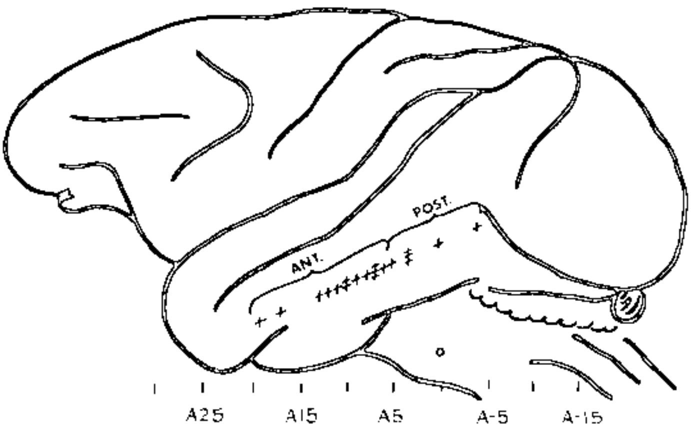
The output of the recording electrodes was amplified by a Tektronix preamplifier and again by a d-c amplifier (15,000 × total) and viewed on a storage oscilloscope. Data were preserved on Polaroid film.

Histology. At the end of the experiment the monkeys were given an overdose of barbiturate and perfused intracardially with normal saline solution followed by formalin containing potassium ferrocyanide. The brains were blocked in the stereotaxic plane, removed from the skull, and placed in formalin. Later they were removed to 20% alcohol. Frozen sections were cut at 50 μ, saving every fourth section. These were mounted and stained with thionine. In two brains every second section was saved around the electrode tracts and the additional sections were stained for fibers by the Weil method.

Results

The responses to stimulation between planes A19.0 and A6.0 along the inferotemporal gyrus were found to have a different distribution from the responses to stimulation between A5.0 and A-4.0. We will, therefore, discuss the projections of the anterior and posterior portions separately. All of the stimulation sites, anterior and posterior, are shown as plus signs (+) on the side view of the brain in Fig. 1.

Anterior Stimulation (A19.0–A6.0). Responses were observed in the cortex and fibers of the temporal lobe medial to the rhinal fissure (A26–A11), the "internal capsule" fibers just ahead of the anterior commissure (A24–A23), the far anterior part of the putamen adjacent to the head of the caudate nucleus (A26–A24), the amygdala (A23–A18), the base of the putamen from the level of its juncture with the amygdala to its caudal extreme (A20–A11), the tail of the caudate nucleus (A16–A5), and in the fibers between the putamen and tail of the caudate. The AP coordinates given here refer to the sections in Fig. 2. These are sections taken from a number of the brains on which have been superimposed tracts from corresponding planes in all eight of the monkeys. Responses were obtained from



Stimulation Sites

FIG. 1. Side view of the brain showing anterior and posterior stimulation sites.

those regions of the tracts marked by short horizontal lines. Where more than one stimulation site was used within the region from A19 to A6, the results are indicated by plus and minus signs above those tracts. Thus, in the most medial tract at A26, the most anterior stimulation site (A19 in this case) gave a response at the horizontal marks, whereas stimulation at two, more posterior sites (A11 and A7) did not. The AP designations of each section in the figure were chosen to be representative of the actual coordinates of the tracts shown on it. These vary somewhat from

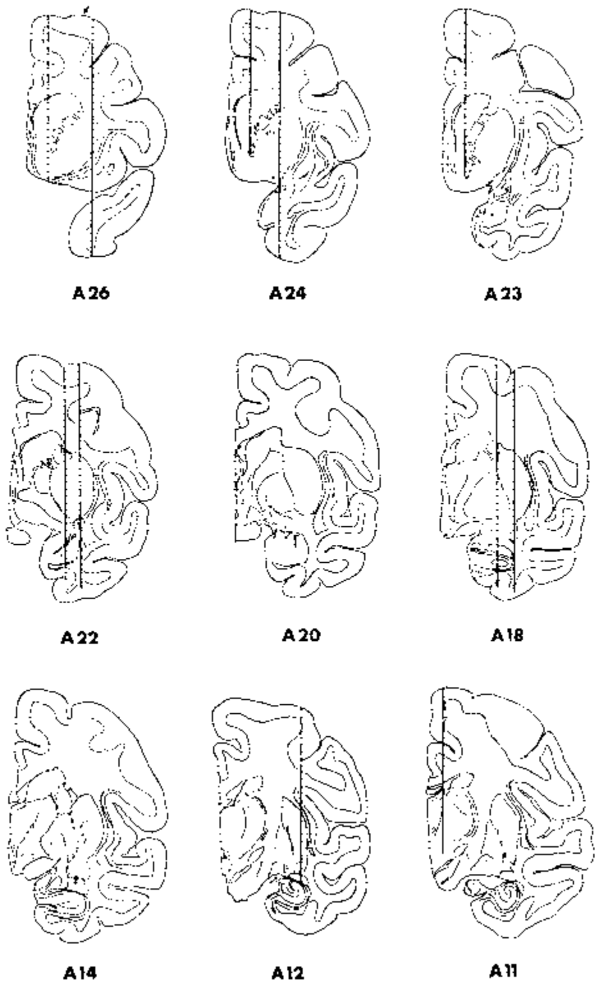
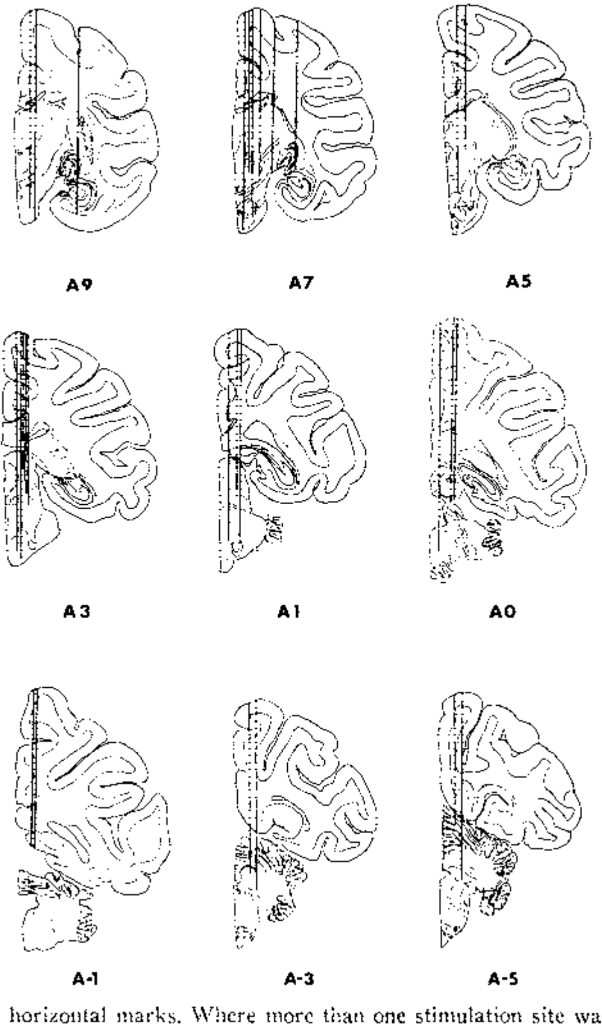


FIG. 2. Anterior stimulation shown on this and facing page: Cross-sections showing all tracts explored with recording electrodes while stimulation was applied to sites between A19 and A6 along the inferotemporal gyrus. The location of clearcut responses

monkey to monkey, but center about the numbers given. These coordinates come from large monkeys and do not necessarily correspond with standard atlases such as Olzewski (9) and Snider and Lee (16). This is especially true of the anterior end of the gyrus. We have used them here to refer to 5 msec) after the stimulus artifact. They also include only responses which did not simply reverse their polarity when the polarity of the stimulus was reversed, although their shape was at times altered by the polarity reversal.



is indicated by horizontal marks. Where more than one stimulation site was tested, the occurrence or absence of a response is indicated by a plus sign or minus sign above the tract, the most anterior stimulation indicated at the bottom and the most posterior at the top.

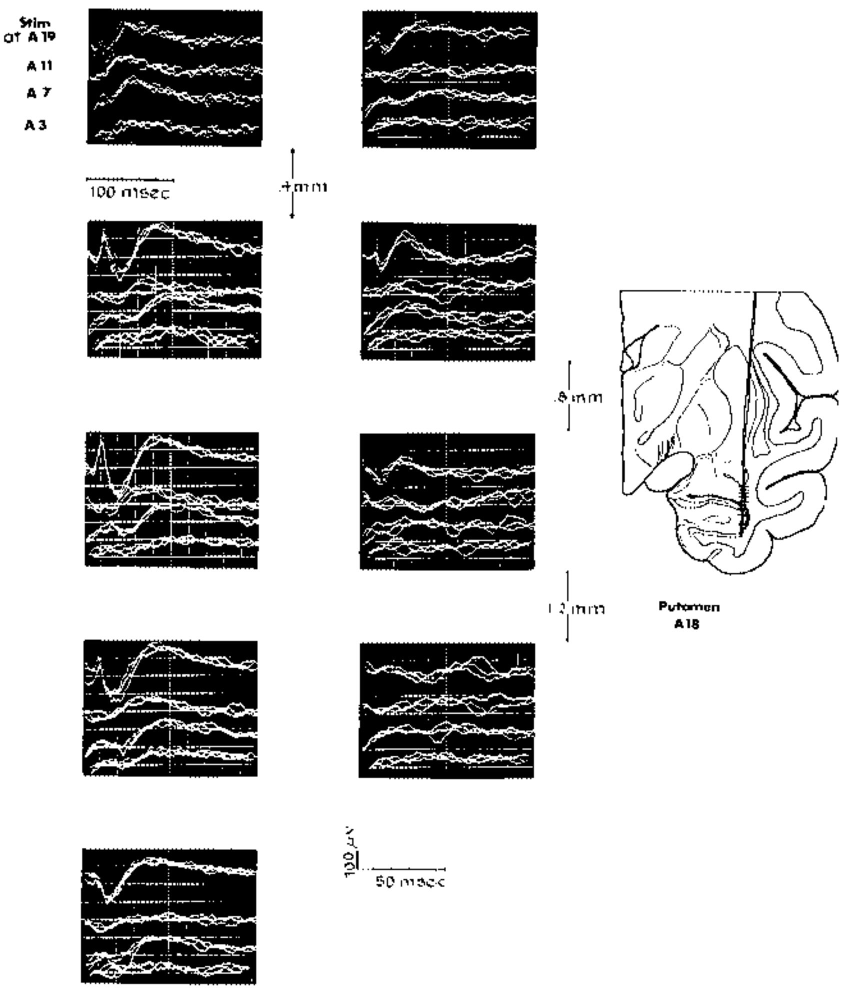


FIG. 3. Responses recorded from tracts passing through the putamen. Horizontal marks indicate the location of the tip of the recording electrode from which the response was photographed. The AP coordinates of the stimulation sites appear next to each set of multiple oscilloscope tracings. The voltage and the time scales applicable to the photos appear beneath them.

both recording and stimulating sites, with the hope of avoiding obscurity about the sites discussed.

All of the responses mentioned above satisfied the criteria that they be synchronized with the stimulus and that they begin shortly (not more than

Figure 3 shows an example of the type of record obtained by one pass through the putamen and tail of the caudate at A18. The response begins with a latency of about 2 msec. As the tip of the electrode passes through the base of the putamen the polarity of the response changes, and its form alters again as the caudate is entered. When both tips finally enter the hippocampus the response has disappeared. A typical response from the anterior commissure is also shown in Fig. 4.

Posterior Stimulation (A5.0–A-4.0). Responses to stimulation within this region were observed in the base of the putamen (A14–A11), in the pretectal tegmentum, just lateral to the periaqueductal grey, the superior colliculus, and in the corpus callosum (A3–A1). Cross-sections showing the response sites are found in Fig. 5.

The major differences between the projections of the anterior and poste-

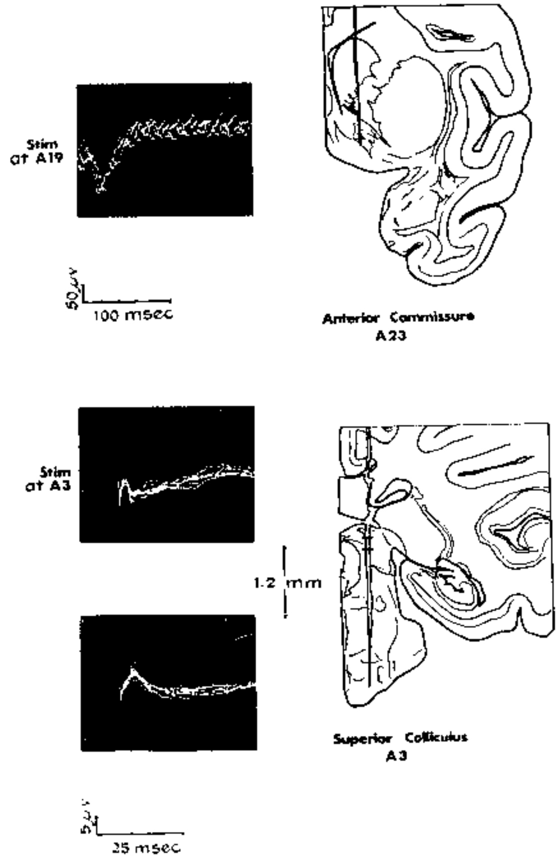


FIG. 4. Responses recorded from tracts passing through the anterior commissure and superior colliculus. Horizontal marks indicate the location of the tip of the recording electrode from which the response was photographed. The AP coordinates of the stimulation sites appear next to each set of multiple oscilloscope tracings. The voltage and time scales applicable to the photos appear beneath them.

rior regions lie in the observation that only the posterior region sends fibers to the superior colliculus; that the interhemispheric connections of the anterior segment pass via the anterior commissure, whereas those of the posterior cross via the corpus callosum; and that the anterior part sends projections to the polar and medial temporal cortex and the amygdala. Though the more anterior planes have not been mapped as thoroughly by posterior as by anterior stimulation, the available data suggest that projections from the posterior temporal cortex to the anterior putamen (adjacent

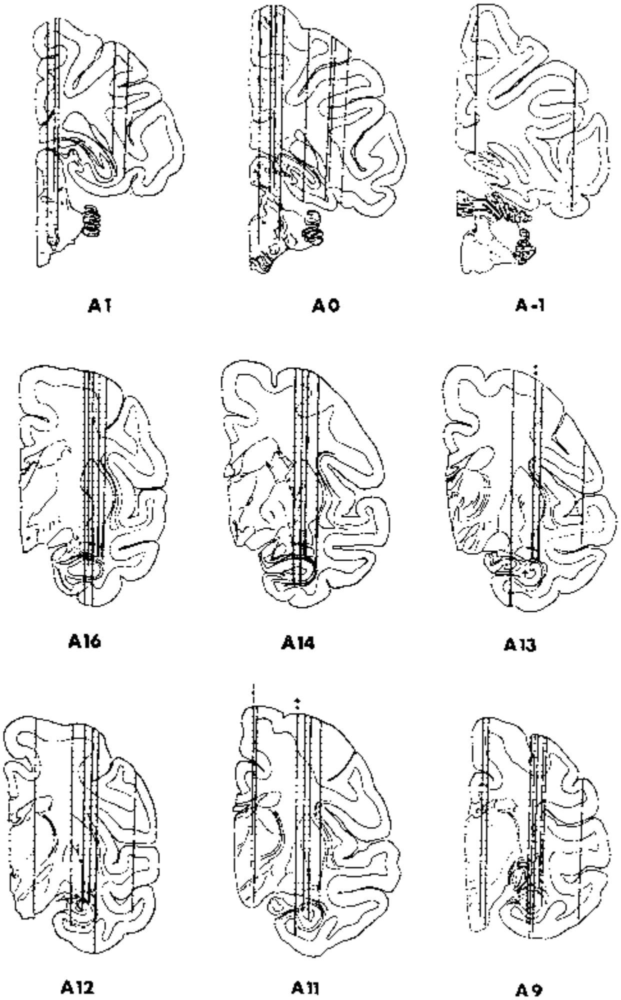
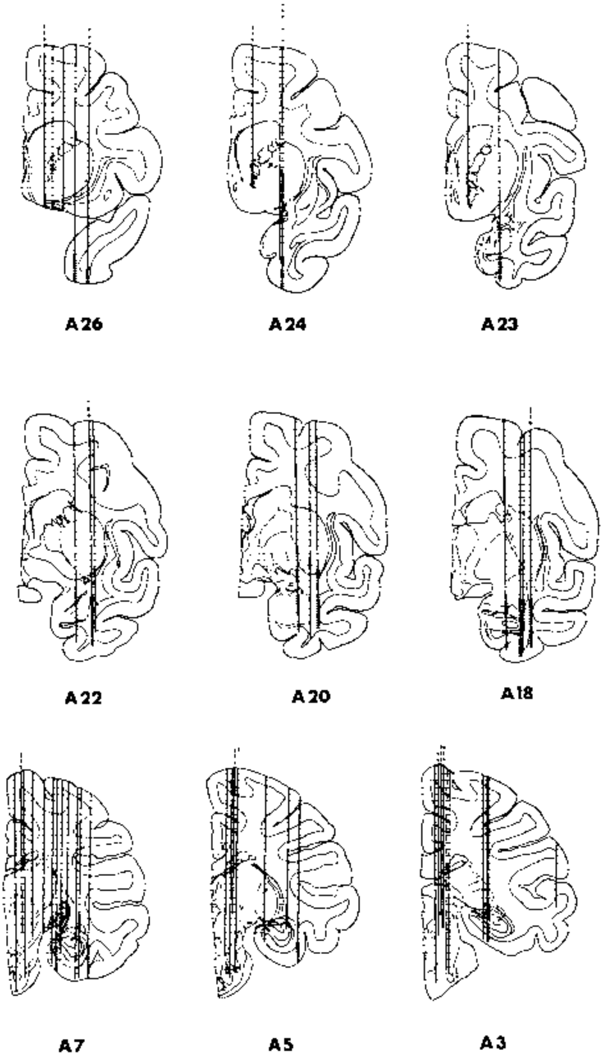


FIG 5. Posterior stimulation shown on this and facing page: Cross-sections showing all tracts explored with recording electrodes while stimulation was applied to sites be-

to the head of the caudate nucleus) and to its base (anterior to A14) are lacking, and that the fibers from the posterior cortex go only to the most posterior portion of the putamen.

Examples of a record from a tract passing through the putamen which was obtained with posterior stimulation (the fourth trace in each photo)



tween A5 and A-4 along the inferotemporal gyrus. Horizontal marks indicate the locations of the responses evoked. The plus and minus signs above the tracts have the same significance as in Fig. 2.

can be found in Fig. 3. Figure 4 shows an example of the collicular responses. Their latency was fairly short (1 msec or less) and their form was simpler than that of other responses with the exception of those from the corpus callosum.

Discussion

Reliability of Results. According to the experimental results obtained in the present study, the inferotemporal cortex projects to the putamen, tail of the caudate nucleus, amygdala, superior colliculus, anterior commissure, and corpus callosum. These data are in agreement with those of Whitlock and Nauta (19) who found, using silver staining techniques, what has been established as anterograde degeneration in all of these locations. The concurrence between these two techniques supports the assumption that the responses to electrical stimulation observed in our experiments are transmitted orthodromically and are therefore indicative of direct projections from the cortex.

The Anterior-Posterior Distinction. Our results show projections to the superior colliculus to be derived only from the region posterior to A5.0, which also agrees with Whitlock and Nauta, whose more anterior lesion on the inferior temporal gyrus did not yield degeneration in the superior colliculus, while the more posterior one did. Further, Whitlock and Nauta found that the amygdala received fibers from the anterior and not the posterior temporal cortex. We also found projections only from the anterior area. Finally, Whitlock and Nauta recorded projections from both regions to the pulvinar, which is the source of thalamic input to the inferotemporal gyrus, a result which we did not systematically explore in this study. Whether these anterior-posterior differences in connections are related to the differences in the effect of resections on visual behavior remains an open question.

With respect to this question, the cytoarchitectural identity of the posterior portion of the cortex we have investigated (and which has been involved in the anterior-posterior distinction) is somewhat unclear. All of our stimulating electrodes lie anterior to the inferior occipital sulcus and are in regions which von Bonin and Bailey (3) designated area TE. However, the distinction between TE and OA is virtually impossible to make in the region under the inferior occipital sulcus. Generally it has been asserted that the interhemispheric connections of TE go via the anterior commissure and those of OA (and OB) via the corpus callosum. As we have seen, responses in the corpus callosum but not in the anterior commissure are obtained to stimulation between A5.0 and A-4.0, which may indicate that the posterior part of the cortex stimulated in our experiments is better classified as OB than as TE. We have included this posterior-most section of the inferior cortex in our peristriate ablations (14), whereas Iwai and Mishkin (see footnote 2) centered their "posterior inferotemporal" ablations in this location.

Efferents and the Functions of the Inferotemporal Cortex. In various ways everyone studying the "association" areas has at one time or another wrestled with the question of the relationship between these areas and the "primary" cortices whose sensory modality they subserve; for vision, this question devolves upon the relationship between the inferotemporal and the striate cortex. As noted in the Introduction, the most commonly accepted hypothesis is that the important connections are transcortical, so that incoming visual information is successively processed by the striate, peristriate, and inferotemporal cortex, "associated" with other information, and passed on to eventually result in discriminative behavior. The connections which might link the areas in this fashion do exist, although there is a succession of studies in which drastic resections of prestriate cortex have failed to result in any severe impairment of visual discrimination performance (4, 14). This has led to the alternative hypothesis that the most crucial connection between the inferotemporal cortex and the primary pathways might be via efferents from the inferotemporal area to subcortical sites, which in turn would modify the activity in the primary pathways.

The results of the present study suggest additional tests of the efferent hypothesis. The effects on visual discrimination of lesions in several subcortical locations can now be investigated. It is already known that destruction of the amygdala, while having effects which are detectable within the performance of discrimination tasks [e.g., in successive reversals of a discrimination, etc (1)], produces results that are strikingly different from the sort of losses suffered after inferotemporal cortex ablation. Amygdalectomy simply does not produce the severe discrimination impairment which would be expected if the amygdala were a crucial waystation for an efferent effect on the visual system, or even if it were another step in some transcortical associative chain connecting sensory input to hypothalamic "reinforcement" sites, as Geshwind (6) has proposed.

This leaves three other loci receiving efferents—the superior colliculus, the tail of the caudate nucleus, and the putamen—whose involvement in complex visual processes remains to be considered. Discrepant reports plague our knowledge of collicular function. Rosvold, Mishkin and Szwarcbart (15) reported no effect on the visual discriminations of monkeys after partial stereotaxic lesions of the colliculi. Surgical removals of these structures in cats, however, was reported by Blake (2) to produce a visual defect similar to that found after inferior temporal cortex resection. Sprague (17) also implicated the colliculi of cats in visual discrimination. Further, Pasik and Bender (10) found in monkey a precollicular site important to visual discrimination, a locus which may be homologous to one shown by Thompson (18) to be involved in the rat.

With respect to the tail of the caudate nucleus, Divac, Rosvold, and Szwarcbart (5) found clear deficits in visual discrimination learning from a stereotaxic lesion restricted to this locus. Such lesions might involve as well the fibers of passage to the body of the putamen. Nonetheless, the result is especially suggestive in view of the similarities in effect on delayed response performance between lesions of the dorsolateral frontal "association" cortex and those in the head of the caudate nucleus (5). In fact, the intrinsic regions of the brain (12) seem to map from front to back and around into the temporal lobe onto the corpus striatum of the basal ganglia—the caudate nucleus and putamen—from head around to tail.

The importance of the putamen to visual function has yet to be investigated. Should it turn out that the basal ganglia of the forebrain serve functions similar to those handled by the intrinsic ("association") sectors of the cerebral cortex, a good deal will have been learned about both of these hitherto enigmatic parts of the central nervous system.

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