EFFECTS OF VENTRAL PUTAMEN LESIONS ON DISCRIMINATION LEARNING BY MONKEYS

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Inferotemporal cortex is necessary for normal visual discrimination learning.
Little is known, however, about the efferent mechanisms of this area.
Inferotemporal cortex projects to several structures, including the caudoventr putamen.
The effect of caudoventral putamen lesions on the postoperative retention of visual and auditory discriminations and on the postoperative acquisition of delayed alternation was studied.
Lesions in the caudoventral putamen and the adjacent white matter impaired performance of the visual but not the auditory and alternation tasks.
Thus this area appears to be part of the neural circuitry underlying visual discrimination.
However, the relative contribution to the deficit of the putamen damage and of the white matter damage could not be ascertained.

The inferotemporal cortex plays a crucial role in visual discrimination in the macaque.
Its removal produces a severe deficit in visual discrimination learning but does not affect either visual sensory functions or discrimination learning in other modalities (Gross, 1972, 1973).
Neurons in inferotemporal cortex receive visual information by way of a multisynaptic input from striate cortex and probably from the pulvinar as well (Gross, 1972; Gross, Bender, & Rocha-Miranda, 1973).
Inferotemporal neurons have very large receptive fields which always include the fovea and usually extend well into both visual half fields; many have specific and complex trigger features (Gross, Rocha-Miranda, & Bender, 1972).
Thus, inferotemporal cortex seems to have visual pattern recognition functions.
Whether this cortical region also has mnemonic functions.

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either alone or in association with other structures remains to be determined.
In any case, neurons in inferotemporal cortex can hardly move musculature and produce behavior; there must be efferents from this tissue that sustain visual learning.
However, damage to many of the structures to which inferotemporal cortex projects does not seem to produce the visual discrimination deficit that characteristically follows inferotemporal lesions (e.g., Anderson & Symmes, 1969; Bagshaw & Pribram, 1965; Chow, 1954; Mishkin, 1972; Rosvold, Mishkin, & Szwarcberg, 1958).
These structures include frontal cortex, the dorsomedial nucleus of the thalamus, the pulvinar, the amygdala, the superior colliculus, and the pretectum (Reitz & Pribram, 1969; Whitlock & Nauta, 1956).
The remaining major efferents from inferotemporal cortex project to the basal ganglia, specifically to the tail of the caudate nucleus and to the caudoventral putamen (Reitz & Pribram, 1969; Whitlock & Nauta, 1956).
Lesions of the tail of the caudate nucleus produce a mild visual discrimination deficit but no change in delayed alternation learning (Divac, Rosvold, & Szwarcberg, 1967).
Whether this discrimination deficit is a specifically visual one is not known.
The effects of lesions of the caudoventral putamen on visual
discrimination do not appear to have been investigated.

In this study, in order to elucidate further the efferent mechanisms of inferotemporal cortex we measured the effects of caudal-ventral putamen lesions on pattern discrimination. The monkeys were also tested on auditory discrimination and delayed alternation tasks in order to determine the specificity of any effect of the putamen lesions.

**METHOD**

**Subjects**

Nineteen adolescent *Macaca mulatta* with no previous experimental experience were used. Sixteen animals received bilateral stereotaxic lesions aimed at the caudal-ventral putamen, and 3 served as an unoperated control group.

**Overall Design**

Prior to operation, 11 animals (No. 6–16) were trained on a visual discrimination task and then on an auditory discrimination task. After surgery they were tested for retention of the visual and then the auditory task. Eight of these animals (No. 6, 7, and 9–14) were then trained on a delayed alternation task. The 3 unoperated control animals (No. 17–19) followed the same procedure except for surgery. The remaining 5 animals (No. 1–5) were trained on the visual discrimination task prior to surgery and tested for retention following surgery. They were never trained on either the auditory or delayed alternation tasks.

**Surgery**

The animals were anesthetized with sodium pentobarbital (36 mg/kg). Then, under aseptic conditions, skin and fascia were incised along the midline of the cranium and retracted to expose the temporal muscles; if necessary, the latter were reflected slightly. A small portion of the parietal bone was then removed. Electrolytic lesions were placed with a Grass Model LM-3 lesion maker, using a duration of 30 sec. and an intensity setting of 70–75, yielding a peak current of 7.1–1 ma.

The electrode was a 28-ga. stainless steel tube insulated except for the final 1.5 mm. Before the electrode was placed in the brain, an electrode guide of 20-ga. stainless steel tubing was stereotaxically inserted to within 3 mm. of the lesion site. The electrode was then slipped through the electrode guide until its final 3 mm. had passed beyond the tip of the electrode guide and arrived at the desired stereotaxic coordinates. Each animal received 4–6 lesions in each hemisphere intended for the caudal-ventral portion of the putamen (A10–A16). This region of the putamen receives the heaviest projection from inferotemporal cortex (Reitz & Pribram, 1969; Whitlock & Nauta, 1956). On completion of the lesions, the scalp wound was closed in anatomical layers and penicillin was administered (600,000 U im). Recovery was uneventful in all cases.

**Visual and Auditory Discriminations**

**Apparatus.** The animals were trained in a sound-insulated box. Two translucent Gerbrands keys (Ralph Gerbrands Co., Arlington, Massachusetts) 1½ in. in diameter and 12 in. apart were mounted on one wall of the box. The discriminanda were projected onto the keys by rear projection readout units (Series 10, Industrial Electronic Engineers, Inc., Hollywood, California) modified so that the keys were in the plane of the image of the stimulus. A Gerbrands liquid dispenser was mounted in the middle of the wall 21 in. below the midpoint of the 2 keys and a speaker was located 15 in. above it. The interior of the box was illuminated from above, and a masking noise was used during all visual problems. Stimulus presentation and reinforcement were programmed electronically.

**Procedure.** On both the visual and auditory tasks the animals were run water deprived. For the duration of the experiment the only fluid given was the orange juice reinforcement during training and, 15 min. after returning to their home cage, 100–300 cc of water.

On the visual tasks the right/left position of the stimuli was randomized. The intertrial interval was 5 sec., and any press during the intertrial interval reset the interval. Response to either or both keys turned the stimuli off. A correct response was followed by .5 cc of orange juice. Correction trials were not used.

The animals were first trained to respond to the keys when illuminated with a white square (Gra-son-Stadler Stimulus 156-4). Next they were trained to discriminate this white square (positive) from an unlighted blank key to a criterion of 90 correct responses in 100 trials. After this pretraining was completed the animals were trained to discriminate 2 horizontal white lines (positive stimulus, Gra-son-Stadler 154-5) from 2 vertical ones (Gra-son-Stadler 154-6) to a criterion of 90 correct responses in 100 trials. Immediately after reaching criterion on the visual tasks, 14 of the animals were trained on the auditory discrimination.

The auditory discrimination was between white noise and silence. At the end of the 5-sec. intertrial interval, both keys were lit and, on 50% of the trials according to a random schedule, the white noise was turned on. During the trial, responses to the right key were rewarded when the white noise was on, and responses to the left key were rewarded when it was not on. Responses to either key terminated the auditory stimulus and the illumination of the keys and started the intertrial interval. Responses during the intertrial interval reset the intertrial interval timer.
After reaching criterion on the auditory discrimination (or the visual discrimination for the animals that were not trained on the auditory discrimination) all the animals except for the unoperated group had free access to water for 6-9 days and then underwent surgery. Fourteen days later the animals were retrained to the same criteria with the identical procedure on the task or tasks (in the same order) that they had learned prior to operation.

Postoperative "savings" were measured by:

preoperative errors − postoperative errors
preoperative errors + postoperative errors

**Delayed Alternation**

**Apparatus.** A conventional Wisconsin General Testing Apparatus was used. The food wells were 12 in. apart and covered by 3 × 3 in. Bakelite plaques.

**Procedure.** After being trained to displace the plaques over the food wells, the animals were trained on a 7-sec. delayed alternation task. On the initial trial of each session both side food wells were baited, the plaques placed over the food wells, and the opaque screen raised. Immediately after the animal responded, the opaque screen was lowered, the plaques replaced, and after an interval of 7 sec. it was raised again. During each subsequent 7-sec interval, the food well opposite to the one which the monkey had selected on the previous trial was baited and both plaques replaced. Thus the monkey would receive a raisin each time it alternated its response from trial to trial. The animals were tested for 50 trials per day (excluding the initial trial on which they could not err) to a criterion of 90 correct responses in 100 trials.

**Histological Procedures**

At the completion of testing, monkeys were given an overdose of sodium pentobarbital and perfused through the aorta or left ventricle, first with normal saline and then with 10% Formalin. Part of the cranium was removed and the head placed in Formalin for three days, after which it was mounted in a stereotaxic instrument and blocked in coronal planes. The brain was then removed and placed for 7 days in sucrose Formalin (10% Formalin, 30% sucrose). The block containing the lesion was then embedded in an albumin-gelatin solution (18 gm. of gelatin, 600 cc of distilled water at 50° C, 180 gm. of albumin) and cut into 25-μm sections on a freezing microtome. Every tenth section was mounted and stained with cresyl violet. At 1-mm. intervals the amount of destruction was measured with a 1-mm. grid. The putamen and caudal part of the caudate were divided dorsoventrally into equal thirds (ventral, middle, dorsal), and damage to each third was computed separately.

In computing the amount of damage to white matter, 3 categories were used: anterior commissure, extreme capsule, and "external white matter." The external white matter was defined as including white matter lying between the putamen and the caudate, between the putamen and the amygdala, and between the putamen and the tail of the caudate nucleus. In computing damage to a particular structure for each animal, the area of the lesion to the least damaged side was used (as unilateral damage was assumed to be ineffective).

Upon examination of the histological results the animals were divided into 2 equal groups of 8 on the basis of the amount of damage to the ventral putamen at A = 13 (the intended center of the lesion). The large putamen lesion group consisted of Animals 1, 2, 6-9, 11, and 13. In this group the median size of the lesion to the ventral putamen (at A = 13) was .45 sq. in., and the interquartile points were .24 and .70 sq. in. The small putamen lesion group consisted of Animals 3-5, 10, 12, and 14-16. Although all the animals in this group sustained damage to the ventral putamen in both hemispheres, 6 of the animals had no damage in one hemisphere at A = 13, the damage for the other 2 being .06 (No. 10) and .09 (No. 3) sq. in. The lesions at A = 13.5 for each animal are shown in Figure 1.

**RESULTS**

**Visual Discrimination Retention**

The operated animals were impaired on retention of the pattern discrimination relative to the normal animals as measured both by postoperative savings and postoperative errors to criterion ($U = 8$, $p < .05$; $U = 6$, $p < .025$, respectively; all group comparisons are with a one-tailed Mann-Whitney test). When the operated animals were divided into 2 groups on the basis of the amount of damage to the ventral putamen at A = 13 (the intended center of the lesion), the large putamen lesion group had poorer retention on both measures than the small putamen lesion group ($U = 5$ and 3, $p = .001$) and the unoperated group ($U = 0$, $p = .006$). But the small putamen lesion group did not differ significantly from the unoperated group ($U = 8$ and 6). The median performance of the large putamen lesion group was .12 savings and 141 errors, that of the small putamen lesion group was .81 savings and 21 errors, and that of the unoperated group was 1.00 savings and zero errors.

Across both operated groups there was a
Figure 1. Cross sections through the lesions at A = 13.5 for each animal. (The lesions are shown in black.)
positive relation between retention performance and the amount of damage to the ventral putamen between $A = 10$ and $A = 16$, the region of the putamen that receives the most projections from inferotemporal cortex ($r_a = .50, p < .05$; all correlations are with the Spearman rank-order correlation coefficient). By contrast, there was no significant correlation between savings scores and the size of the ventral putamen lesion anterior to $A = 10$ and posterior to $A = 16$ ($r_a = .39$) or the total amount of putamen damage ($r_a = .22$). Furthermore, damage to other nuclear groups or subdivisions of nuclear groups was not associated with the degree of retention deficit.

However, all operated animals sustained damage to the white matter adjacent to the lateral and ventral borders of the ventral putamen. We have called this area “external white matter” (see Histological Procedures). The amount of external white matter damage was significantly correlated with the amount of ventral putamen damage both across the entire lesion ($r_a = .59, p < .05$) and between $A = 10$ and $A = 16$ ($r_a = .58, p < .05$). Retention performance was significantly correlated with the amount of damage to external white matter between Level $A = 10$ and $A = 16$ ($r_a = .73, p < .01$) but not with the amount of external white matter damage anterior and posterior to this region ($r_a = .12$). Finally, the total amount of destruction of gray and white matter, independent of site, was not correlated with retention performance ($r_a = .04$).

In summary, lesions that include the caudoventral putamen between $A = 10$ and $A = 16$ and the adjacent white matter impaired retention of the pattern discrimination; the larger the lesion in this area the greater the impairment. The results could not distinguish between the relative roles of putamen and external white matter lesions in producing the deficit.

Auditory Discrimination Retention

There were no significant differences between the operated animals and the unoperated animals on retention of the auditory discrimination. The median performance of the large putamen lesion group was .73 savings and 65 errors, that of the small putamen lesion group .88 savings and 13 errors, and that of the unoperated group .93 savings and 23 errors.

Although no group comparisons even approached statistical significance, the 4 operated animals with the poorest savings scores on the auditory discrimination were also the 4 animals with the largest total brain destruction (No. 6, 8, 11, and 12). These animals could not be distinguished from the other operated animals in terms of damage to a specific structure, but only in terms of the total size of the lesion. These 4 animals did not appear to suffer from some “nonspecific” deficit since their visual discrimination retention performance was not significantly different from that of the other operated animals ($U = 10$). A relationship between auditory retention and the total size of lesion was further suggested by a significant correlation among all the operated animals between total amount of damage and auditory savings ($r_a = .69, p < .01$). Such a correlation was not found on the visual retention task.

Preoperative acquisition of the auditory discrimination was more difficult than that of the visual discrimination as measured by errors to criterion ($p = .012$, 2-tailed sign test). Thus the impairment on retention of the visual task after the putamen – white matter lesions was probably not a supramodality discrimination deficit. Further support for this was the absence of significant correlation between retention performance on the 2 tasks ($r_a = .47$).

Delayed Alternation

There were no significant or suggestive differences among any of the groups on the delayed alternation task nor did any individual animal seem impaired on this task. The median performance of the large putamen lesion group was 179 errors, of the small putamen lesion group 205 errors, and of the unoperated group 234 errors.

Discussion

Lesions of the caudoventral putamen and the adjacent white matter impaired reten-
tion of a pattern discrimination task. They did not impair acquisition of a delayed alternation task, indicating that the deficit on the pattern discrimination did not reflect some nonspecific deterioration. The lesions also did not impair retention of an auditory discrimination, suggesting that the deficit was indeed one of visual discrimination.

The magnitude of the deficit in most of the animals in this study was less than that usually seen after inferotemporal lesions (e.g., Cowey & Gross, 1970, who used the same visual discrimination task as the one used in the present study). Perhaps more complete lesions would have produced a more severe deficit, as suggested by the relation between size of the putamen—white matter lesion and the degree of deficit.

The critical lesions included the lateral and ventral portions of the caudoventral putamen and the adjacent white matter. Both the amount of caudoventral putamen damage and the amount of damage to the adjacent white matter were positively related to the degree of deficit. As there were no animals with equivalent damage to either the putamen alone or the adjacent white matter alone, our results are insufficient to determine if damage to either site alone would have been effective.

Where do the fibers in the white matter adjacent to the caudoventral putamen go? Of those that come from inferotemporal cortex, some terminate in the putamen and some in the ventral claustrum; some enter the anterior commissure, some travel on to the dorsomedial nucleus, and others go, by way of the extreme capsule, to the frontal lobe (Whitlock & Nauta, 1956). Analysis of the present results failed to show any relation of damage to the ventral claustrum, the anterior commissure, or the extreme capsule to the degree of deficit on the visual task. Previous studies have failed to show any impairment in visual learning after dorsomedial nucleus or frontal cortex lesions (Chow, 1954). Thus, one interpretation of our findings is that damage to the putamen or its input from inferotemporal cortex was the basis of the deficits we found.

Another possibility is that lesions confined to the caudoventral putamen would not impair visual learning themselves. Rather, it may be necessary to destroy or section the inferotemporal efferents to some set of the structures that the fibers in the external white matter terminate in. Since our effective lesions invariably included both this white matter and the caudoventral putamen, it is possible that this set could include, for example, the ventral claustrum and the dorsomedial nucleus as well as the caudoventral putamen.

In either case it is clear that the present lesions and lesions of the tail of the caudate nucleus (Divac et al., 1967) impair visual discrimination performance. Since both sites receive efferents from inferotemporal cortex, both are presumably important mechanisms through which inferotemporal cortex mediates visual discrimination behavior.

Further study is required to determine if the visual discrimination deficits following these two lesions are identical to each other and to the inferotemporal deficit. Qualitatively different visual discrimination deficits might follow destruction of different target organs of inferotemporal efferents (Gross, 1973).

Finally, the auditory retention deficit in a few animals with particularly large lesions might have an explanation analogous to that for the visual deficit. The superior temporal gyrus, which is involved in auditory discrimination learning, also sends fibers to the putamen (Whitlock & Nauta, 1956), and the larger lesions may have encroached on their termination fields.

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