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ON THE FUNCTIONAL ORGANISATION OF THE FRONTAL LOBES IN DOG

BY

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During the last several years our laboratory was concerned with extensive studies of the effects of ablations of particular parts of frontal lobes upon various conditioned reactions in dogs. As test responses were used: classical and instrumental conditioned reflexes, reinforced either by food (3), (4), (10), (13), (14), (15), or water (17), or by noxious stimuli such as introduction of acid into the mouth, or electrical shock administered to the paw (2). The method of delayed responses was also used (11).

The most extensive studies were performed with alimentary instrumental conditioned reflexes (4), (7), (13), (14), (15). In these experiments the dogs were trained by means of food reinforcement to perform a relatively simple movement to a conditioned stimulus, namely that of putting the right foreleg on the foodtray situated in front of the animal. When such a conditioned response was firmly established, definite parts of frontal lobes were removed and the effects of lesions were studied. In such a way, a large experimental material was collected in which the testing response was always the same: the circumstance was favourable for the comparison of results obtained after different lesions.

The aim of this paper is to present briefly all this material and to try to elucidate the role played by various parts of the frontal lobes in performance of an instrumental conditioned reflex. Besides this the disturbances of general motor behaviour after each lesion are also described.

The whole frontal region may be subdivided into several areas, the boundaries of which are best determined, especially for surgical purposes, by some constant sulci. These areas roughly coincide with the areas defined on the basis of cyto-architectural (1) or myelo-architectural (8), (9) studies, as well as on the basis of electrophysiological investigations by using either evoked potentials technique (12), or electrical stimulation

of the cerebral cortex (5). They are represented in figure 1 and are usually designated as follows:

1. *Prefrontal area*, situated in front of the presylvian sulcus and its prolongation to the fissura magna. It includes the proreal gyrus except its laterocaudal part, subproreal gyrus and genual and pregenual gyri.

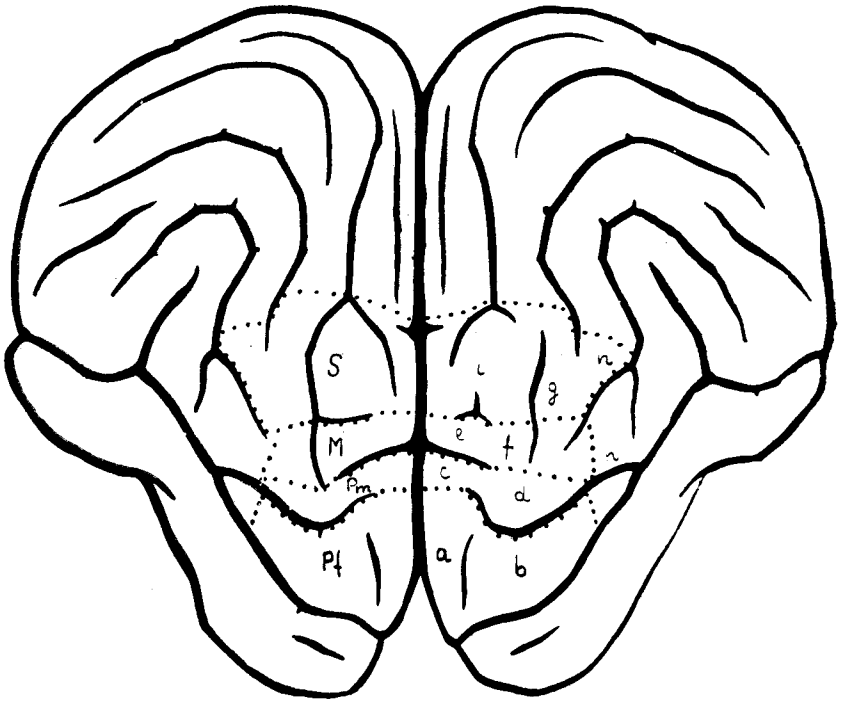

Fig. 1. — The cerebral cortex of the dog flattened on the plain.
Denotations: *a* — gyrus proreus, *b* — g. orbitalis, *c* — g. precruciatus, *d* — g. sigmoideus anterior, *e* — g. postcruciatus, *f* — g. sigmoideus posterior, *g* — g. coronalis, *h* — g. compositus anterior, *i* — g. postcentralis; *Pf* — prefrontal area, *Pm* — premotor area, *M* — motor area, *S* — sensory area.
Note that the designations of gyri accepted here are slightly different from those generally used.

2. *Premotor area*, situated roughly between the presylvian sulcus and the cruciate sulcus and its lateral prolongation. It includes the precruciate gyrus, anterior sigmoid gyrus[1] and the upper part of anterior composite gyrus.

3. *Motor area*, situated behind the premotor area caudally to the cruciate sulcus and its prolongation. Its posterior boundary is formed by

[1] In the course of our studies it appeared to be useful to separate the precruciate gyrus situated in front of the cruciate sulcus, and the anterior sigmoid gyrus situated laterally to it. Similarly we have separated the postcruciate gyrus lying behind the cruciate sulcus, and the posterior sigmoid gyrus lying laterally to it (cf. fig. 1).

the horizontal line drawn through the central sulcus. This area includes the postcruciate gyrus, posterior sigmoid gyrus and anterior part of the coronal gyrus.

4. *Sensory area* (I and II), situated behind the motor area and extending to the line of the ansate sulcus. It consists of the postcentral gyrus, posterior part of the coronal gyrus and rostral part of the anterior ectosylvian gyrus. Although this area belongs partly to the parietal lobe, its functional relation to the preceding area is so close that the effects of its ablations are also included in this paper.

As was already stated we do not believe that the boundaries determined above strictly correspond to those, dividing areas of different functional significance. But taking into account that the true boundaries between areas are never sharp, we think that they may serve as good landmarks allowing to reproduce analogous ablations in different animals.

In this paper only bilateral lesions will be described. In a series of experiments we have stated that the functions specific to each of these areas are represented in both hemispheres and that only after bilateral ablations the characteristic symptoms are fully developed.

RESULTS

1. *Ablations of prefrontal areas* (4)

When in a dog trained as described above the whole prefrontal area rostrally to the presylvian sulcus is bilaterally amputated, the recovery after surgery is prompt and uneventful, and after 4—5 days the animal may be brought again to the experimental chamber. Sometimes the animals display a more or less pronounced locomotor hyperactivity which, however, is rather shortlasting. In most cases hyperactivity is not observed and the behaviour of the animal hardly differs from that before operation. The dog perfectly recognizes people and surroundings familiar to him and his general attitude towards them is not changed.

When the dog is brought to the experimental situation and the positive conditioned stimulus is applied, it is at once seen that the conditioned response to it is unchanged : he raises his foreleg and puts it on the foodtray as promptly and skilfully as before operation. However, the further course of the experiment reveals that the conditioned reflex activity of the dog is not normal.

First, it is seen that the animal now and again performs the trained movement also in intervals between trials. Such intertrial movements had appeared at the beginning of training as an effect of a conditioned reflex to situation, but thereafter, not being reinforced, they completely disappeared. Their reappearance after operation may be considered as a sign of disinhibition of this situational conditioned reflex.

Furthermore, when inhibitory conditioned stimuli established before operation are applied (differentiation, conditioned inhibition), the animal displays a more or less strong positive reaction to them, similar

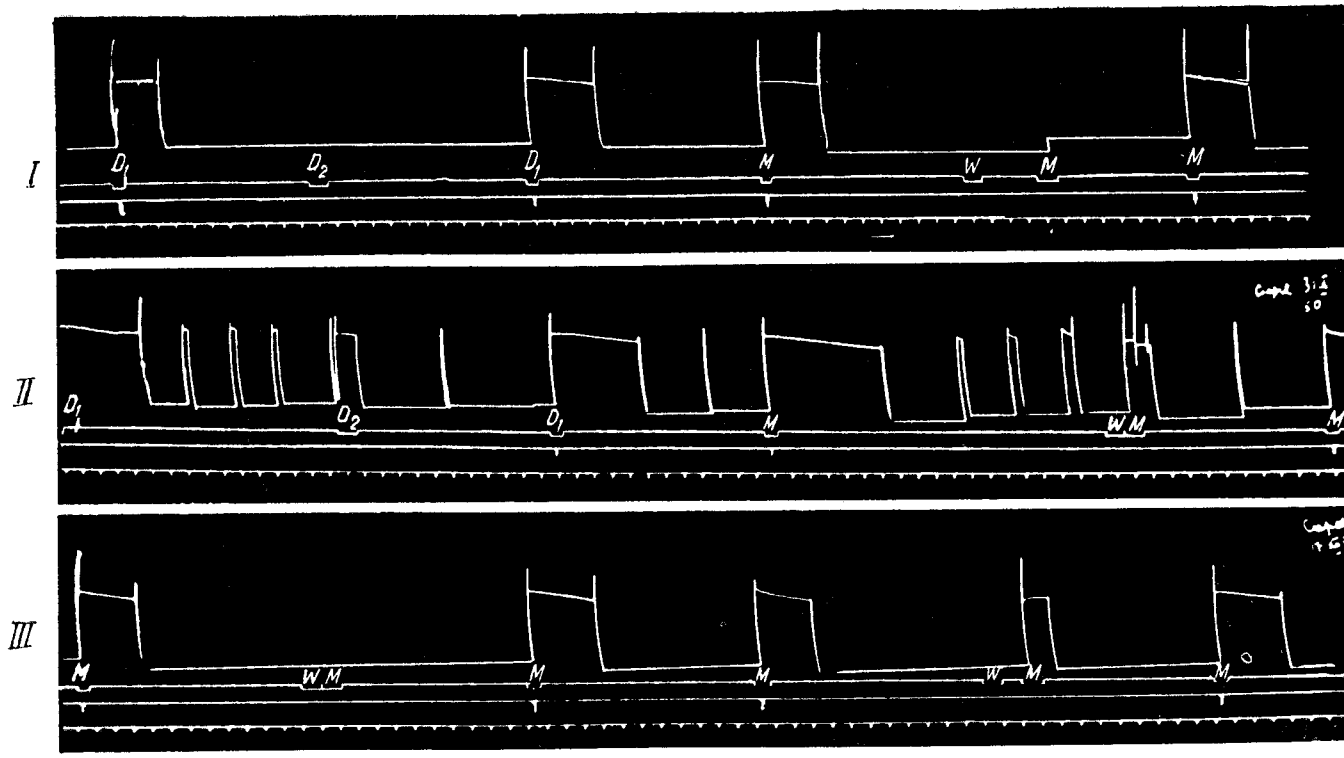

Fig. 2. — The effect of prefrontal lesion on the conditioned reflex activity of the dog.

I, an experiment before operation; II, an experiment just after prefrontal ablation; III, several weeks after prefrontal ablation. Each record represents from top to bottom: raising of the leg and putting it on the foodtray, conditioned stimulus, unconditioned stimulus (presentation of food), time (5 sec.). Positive conditioned stimuli: bell (D_1), metronome (M). Inhibitory stimuli: another bell (D_2), compound composed of toymill (W) and metronome (M).

Note that before operation to D_2 and WM there is no reaction, even when W precedes M by 10 sec. After operation the inhibitory reflex to D_2 is disinhibited as well as the inhibitory reflex to WM, even when M immediately follows W; several intertrial movements are seen. Several weeks after operation intertrial movements have disappeared; the compound WM produces inhibitory reaction when M immediately follows W, but M elicits positive reaction when the interval between W and M is 5 sec.

to that manifested in the first stages of preoperative training. The more difficult is the given inhibitory reflex, the stronger is its disinhibition.

When inhibitory conditioned reflexes are retrained, they gradually return in most cases to normal. First disappear intertrial movements, then reactions to easy differentiated stimuli, still later reactions to conditioned inhibition compound, especially when the interval between its components is protracted (fig. 2). However, in most dogs the inhibitory capacity is permanently impaired, which is best seen in the relative instability of inhibitory reflexes.

2. *Ablations of prefrontal and premotor cortex* (7) (15)

If the lesion is more extensive than that described above, and involves also the precruciate and anterior sigmoid gyri, the symptoms observed in the animals are much more spectacular. First the recovery period is more prolonged and lasts sometimes about two weeks. In the beginning the animals do not recognize either people or surroundings, do not react to call and do not manifest the usual investigatory behaviour in a room, so characteristic of normal dogs. When strong enough to stand and walk they manifest a very pronounced hyperactivity, pacing or running along the walls of the room for long periods of time. Very often they have a tendency to repeat again and again the same itinerary. Their head is usually bent beneath their body axis and they tend to pass below obstacles instead of jumping over them. If they enter the narrow corners of the room they are not able to withdraw from them. Very often they are unable to find their way to the experimental room, although they were perfectly familiar with it before operation. All these symptoms tend to disappear after a lapse of time.

On the other hand the dogs do not manifest any impairment in the performance of particular motor acts. They are as skilful as before operation, are able to jump onto high places, their placing and hopping reactions are undisturbed.

When brought to the experimental chamber they are at first disoriented and sometimes even cannot find the place from which they received food. To the conditioned stimulus they display a strong orientation reaction, as if it were quite new to them. No trained movement appears. If, despite the absence of instrumental reaction, the stimulus is several times reinforced by food, the direct alimentary reaction is manifested, consisting, however, not in awaiting the presentation of food, as is seen in normal animals, but rather in licking the empty bowl as if food were already offered.

Usually in the first experiments the trained movement does not appear at all. When, however, the animal starts to perform it (which usually occurs quite suddenly and unexpectedly, rather in intervals than to a conditioned stimulus), he performs it again and again hundreds of times during the whole experimental session. In this period conditioned stimuli rather inhibit the performance of the movement, as they elicit either orientation reaction, or direct alimentary reaction, or both.

Such a state of affairs may last for many weeks or even months. Sometimes the intertrial movements do not disappear at all through the whole period of observation. However, the motor conditioned reactions to the conditioned stimuli become more and more prompt and regular, although usually they are preceded by the orientation reaction.

The tendency to repeat again and again the same motor act is not only limited to the trained movement, but may be manifested by many other perseverative actions. Some dogs repeatedly climb the foodtray with two or even four legs, others make persistent oscillating movements with the head, still others gnaw the borders of the bowl and do so with such vehemence that they risk to destroy the whole apparatus.

The inhibitory capacity of the prefrontal-premotor dogs is much more impaired than that of the prefrontal dogs. Only after a very long time are they able to react inhibitorily to differentiated stimuli, but even then their inhibitory reflexes are unstable.

All these symptoms, and in particular perseverative movements, inadequate reactions, irregularity of both positive and inhibitory conditioned reflexes cause that the animal's behaviour makes the impression of "stupidity", which is in marked contrast with the skilful performance of particular motor acts.

3. *Ablations of the premotor area* (15)

Since the difference between the prefrontal and prefrontal-premotor dogs has proved to be so pronounced, it was necessary to see what would be the results of pure premotor lesions. Unfortunately we meet here the difficulty consisting in not knowing the exact rostral limit of the premotor area medially to the end of the presylvian sulcus[1]. Our findings obtained so far induce us to draw the following conclusions : If the lesions are restricted only to the premotor strip, no clear hypermotility is manifested, but there is a strong disturbance of the whole conditioned reflex activity. In the first period after operation the conditioned motor reaction to the stimuli fails to appear, although the animal is able to perform the trained movement and does so sometimes in intervals. Since there is no motor hyperactivity, the chance of spontaneous "reeducation" is even less than in those dogs in which the lesions extend more rostrally. When, however, the lesion encroaches on the medial parts of the prefrontal area (which is difficult to decide) the animal becomes hyperactive and all the symptoms described in the preceding section are manifest.

To summarise it seems to be clear that after premotor ablations a disintegration of the motor conditioned reflex follows and the conditioned stimulus is no more capable to elicit the learned movement, although the performance of this movement per se is not at all lost. We have called such a status "conditioned disreflexia".

[1] According to Kreiner's morphological evidence (9), the premotor area extends on the medial surface of the hemispheres much more rostrally than the line of presylvian sulcus.

4. *Ablations of the motor cortex* (14)

If the lesion is made just caudally to the cruciate sulcus and comprises the narrow strip between this sulcus and the line of the central sulcus, quite a different picture of the animal's behaviour ensues. Immediately after operation the motor activity of the dog is strongly impaired. He is unable to get up and lies helplessly on his couch. Gradually he becomes able to stand and to walk but these movements are awkward and unskilful. Even after a long time when the dog already walks and runs quite well, his legs often slide apart on the smooth floor, particulary during the act of eating.

In contrast to these disabilities the motor conditioned reflex is often not lost even when the animal is brought for the first time to the experiment. It is true that the learned movement is performed with great difficulty being most awkward and readily fatiguable, but its general pattern is preserved. As a rule the animal performs the movement only to the conditioned stimuli and not in intervals. Inhibitory reflexes were not studied so far. Gradually the performance of the movement improves and may even hardly differ from the preoperative state.

However, the animals of this group manifest another striking symptom which is, as far as we know, characteristic only of this sort of lesion. It is that the dog performs the trained movement not only with his right but also with his left foreleg. This confusing of legs is all the more peculiar when we take into account that it neither happens in normal dogs, nor is observed after unilateral (left) hemispherectomy : even then the animal performs the trained movement with his disabled limb and does not try to do so with the unaffected one.

We have noticed that the dogs with motor ablations perform the trained movement with their right or left foreleg in dependance of the turn of their body in the moment of its performance. When the animal is turning left the right foreleg is put on the foodtray, when turning right the left foreleg is used.

Still another symptom observed in dogs with motor lesions is hyperkinesis (not hyperactivity) of the limbs, particularly of the forelegs. The animals incessantly perform with their legs small movements of a pedalling character, particularly well seen either when they are on the stand, or when they are lifted in the air. For this reason it is very difficult to test placing reaction in these dogs.

5. *Ablations of the sensory area* (13)

Still another picture of the animal's motor performances is seen when the lesion affects the somatic areas I and II. Just after operation the animals are as disabled motorically as after motor lesions. When after several days they are able to stand and walk, a number of characteristic symptoms appear, such as holding the limbs in unnatural positions (e.g. with dorsal side of the foot on the floor), disability to cross over the barriers and so on. Placing reaction is totally lost. No hyper-

kinesis is seen, on the contrary, when standing, or lifted in the air, the animal holds his legs even more motionless than before operation.

In spite of these disabilities the animal's general behaviour is strikingly sensible and adequate. From the first days after operation they are not at all disorientated and react properly to familiar people and surroundings.

When brought to the experimental chamber these animals again behave quite normally, they recognize the conditioned stimuli and display a normal general alimentary reaction to them. They are, however, not able to perform the trained movement: the foreleg remains motionless on the floor of the stand, sometimes slight muscular twitches are seen, but the proper movement does not appear. This state of affairs is not permanent; after several weeks or a few months the trained movement reappears either at once in a normal shape, or, rather more often, through a series of higher and higher abortive movements. This occurs nearly in the same time when the animal becomes able to cross over the barrier. Finally, the trained movement becomes quite skilful and does not differ from that before operation. What should be emphasized is, that in this period the animal is able to perform the given movement "voluntarily", but is not able to perform it as an effect of tactile placing reaction.

DISCUSSION

The comparison of the effects of lesions of particular areas of the frontal lobes on the instrumental conditioned reflex tested in our studies, as well as on other motor performances, allows us to get a more or less distinct picture of the contribution of each of these areas to the animal's motor behaviour. The whole investigated region may be roughly divided into two parts, the line of the cruciate sulcus being their boundary. The lesions located behind this boundary produce a disorganisation of particular motor acts of the limbs, while the general patterns of motor behaviour remain normal. On the other hand, the lesions produced in front of the cruciate sulcus do not impair at all the particular motor acts of the limbs but disintegrate the more general patterns of behaviour.

The most vicious of all these lesions for the integrity of the instrumental conditioned reflex as such are undoubtedly those located in the premotor cortex and encroaching on some ill-defined caudal part of the prefrontal area.

The behaviour of dogs subjected to these lesions differs most strongly from that of normal dogs, even during long periods after operation. Their chief defect is, so to speak, the weakening of the bond between the conditioned stimulus and the conditioned reaction. This may be manifested either by the irregularity of conditioned reactions to conditioned stimuli (conditioned disreflexia) or else by incessant repetition of the trained movement independently of the stimuli applied. These defects are accompanied by the general inadequacy of animal's behaviour.

The lesions placed more rostrally also produce defects of the motor behaviour, but these defects are much more subtle and may be revealed only by special tests. The most prominent of them is the impairment of inhibitory reflexes and also of delayed responses (11); this last symptom was not dealt with in this paper. On the other hand, the more caudal is the lesion in respect to the premotor area, the more adequate is the general motor behaviour of the animal in spite of the heavy impairment of his discrete movements, or even, as is the case after sensory ablations, in spite of temporal loss of conditioned reflexes.

The serious defect of instrumental conditioned reflexes brought about by premotor lesions may be explained at least in two ways. On the one hand there is some evidence indicating that the so called premotor area is in fact the representation of the movements of eyes, head and trunk (16), and, one may add, it constitutes an "analyser" of these movements. Since in the perception of a given stimulus the orienting reaction towards it plays an important role, the destruction of the cortical area controlling eyes and head movements may disrupt the whole pattern of the instrumental reflex. On the other hand, according to the older views held by Jacobsen (6) and also by many neurologists, the premotor area represents a higher order integrative centre controlling the complex chains of motor reactions. Independently of which of these views will prove to be correct, one thing seems to be evident from our experiments. A normal alimentary instrumental conditioned reflex consists of a sequence of reactions passing smoothly one into another. They are: orienting reaction of eyes and head towards the stimulus → direct alimentary reaction towards the foodtray → putting the leg onto it. Now, although after premotor lesions these reactions, taken separately, are not at all lost, and may even be exaggerated, the bonds between them are somehow disrupted, and this disruption constitutes in fact the essential defect observed after these lesions.

SUMMARY

The effects of bilateral lesions of particular areas of the frontal lobes on a simple instrumental conditioned reflex (putting the leg on the foodtray in response to the conditioned stimulus) were examined in dogs. The following results were obtained:

1) The lesions of prefrontal areas leave the positive conditioned reflexes unchanged but produce an impairment of inhibitory reflexes.

2) The lesions situated in the premotor and partially in prefrontal area produce a disorganisation of positive conditioned reflexes and the tendency to perseverative movements.

3) The lesions of the motor area cause the awkwardness of movements of the legs combined with hyperkinesis ("pedalling") and confusing of legs in the performance of the trained movement.

4) The lesions placed in the sensory area produce atactic symptoms and temporary abolition of instrumental conditioned reflexes.

5) All these disturbances attenuate to a greater or lesser degree with a lapse of time.

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