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FUNCTIONS OF THE NEOSTRIATUM: CORTEX-DEPENDENT OR AUTONOMOUS?

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Abstract. Studies of animals with ablations of varying amounts of the neocortex, the neostriatum, or both, are reviewed in an attempt to establish to which extent functions of the neostriatum are dependent on its cortical input. Scarce and inconclusive evidence does not allow firm conclusions. It seems well established that the neostriatum shares some functions with the neocortex. In the rat and infant monkeys these striatal functions appear to be cortex-independent, whereas in cats and adult monkeys they seem to be more cortex-dependent. It is possible, and even likely, that the neostriatum also has functions which are not shared with the cortex and which are cortex-independent. The degree to which the neostriatum is able to contribute to the integration of behavior in the absence of its cortical input is species- and age-specific.

INTRODUCTION

The functions of the neostriatum (NS), divided in some species by the capsula interna into the caudate nucleus and the putamen, are most commonly described as motor or inhibitory and considered to be essentially unrelated to those of the neocortex (12). On the other hand, much evidence has accumulated showing a close anatomical and functional relation of the neocortex and NS (4, 5, 9, 26, 29). Some evidence even indicated that in the absence of the cortex, NS no longer mediates the

functions shared by the two formations (6, 39). The aim of this paper is to see whether the available evidence supports Fulton's (17 p. 491) suggestion that "once the cerebral cortex has been removed the basal ganglia cease to contribute significantly to functional integration", or whether the functions of NS are essentially independent from the neocortex as implicit in the writings of several authors (e.g., 1, 2, 23, 24). The possible role of NS in the organization of the prosencephalon has been discussed elsewhere (8) and will not be considered here.

DECORTICATE VS. "THALAMIC" PREPARATIONS

As early as 1924 Dresel (14) suggested that the functions of NS can be studied by comparing decorticated and "thalamic" preparations. (The quotation marks should serve as a reminder that after ablation of both the cortex and NS, the thalamus degenerates almost entirely and that consequently the highest grossly preserved part of the brain is the hypothalamus). Presumably the abilities found in decorticate, but not in "thalamic" preparations could be attributed to NS functioning. This idea at first appears attractive, but the results of such experiments are not easy to interpret. Perfect decortication, particularly in gyrencephalic brains, is a formidable task. In attempts to remove the cortex or the neostriatum, or both, it has been particularly difficult to preserve the so-called limbic system. In the past 50 years there have been a number of attempts to follow Dresel's paradigm, but only two studies, in which direct comparisons of the decorticate and "thalamic" preparations were made, provided satisfactory histological reports. In one of these experiments, cats in which NS was ablated together with the cortex, unlike decorticated animals, failed to eat spontaneously, to vocalize, and to clean themselves or other cats. On the other hand, "thalamic" cats were more active than the decorticated ones, and they showed both "obstinate progression" (a tendency to walk forward until an obstacle is encountered and then keep pushing against it as if attempting to go through) and sham rage (38). These results were partly confirmed in two other studies which furthermore demonstrated that "thalamic" cats do not mate (15), but can escape punishment (35). The latter authors found that extensive decortications alone also produced strong "obstinate progression".

A similar experiment performed on rats, provided similar results except that "thalamic" rats showed some elements of grooming, better coordination of locomotion, and an ability to gnaw, although they never ate spontaneously (32). Decorticated rats showed very little motor impairment (32, 34).

Thus, in both rats and cats, the decorticate preparation is more viable than the "thalamic" one, but rat preparations of either kind function better than comparable cat preparations. Unfortunately, the preserved functions in decorticated animals may have been mediated by parts of the limbic system which were damaged much more in "thalamic" animals than in decorticated ones. While the hippocampal contribution to the studied functions seems negligable (34), the amygdaloid nuclei may play some role. Nevertheless, these results may indicate that NS contributes at least something to the superior performance of decorticated animals as compared to the "thalamic" ones. Since these preparations have not been investigated with "cognitive" tasks, we do not know how their abilities for discrimination, learning and memory compare.

DECORTICATE VS. DENEOSTRIATE PREPARATIONS

Inferences about NS functions can be made from comparisons of the consequences of ablations of either NS or the cortex. This approach faces serious technical difficulties: ablation of the entire NS alone has not yet been achieved. The technique of kainic acid lesions (11) is promising but still imperfect (10). Mettler's group had tried to ablate the caudate nucleus, but extensive additional damage to nonstriatal formations such as the cortex, the centrum semiovale and the fundus striati (33) renders these studies virtually uninterpretable. Similar criticism can be levelled against the recent attempt of Denny-Brown and Yanagisawa (3) to destroy the putament in monkeys. Ablation of the entire caudate nucleus with sparing of the putamen and small damage to nonstriatal tissue has been achieved by Villablanca's group (35–37). In their experiments the caudate ablated cats were behaviorally compared to cats in which a large portion of the frontal cortex had been removed. It is not known, however, whether the ablated cortical area "corresponds" to the ablated neostriatal tissue (Fig. 1) and damage to the cingulum bundle must be considered in the interpretation of the results. Inspite of these difficulties, the experiments of Villablanca's group are valuable. They have shown that cats without the caudate nucleus do not necessarily die nor turn into "real vegetables" as had been claimed by Mettler's group. These cats do not have profound and lasting motor impairments. The only such persistent impairment is an absence of the placing reaction. The most striking symptoms of caudate ablation in cats are: (i) a transient "obstinate progression", less pronounced than after extensive neodecortications (35); the same symptom was found also after thalamectomy by Villablanca and Salinas-Zeballos

(37), (ii) a syndrome which was named the "compulsory approach" (stereotyped approaching and following persons, cats or objects, accompanied by signs of pleasant emotion: purring, kneading and rubbing against the followed object) and interpreted as caused by emotional changes (36), and (iii) impairments in a series of learning tasks such as bar pressing alternation and spatial reversal (27).

Thus, the cats without caudate nuclei did not have any "extrapyramidal" symptoms, but instead were incapable of mastering certain learning tasks, and appeared to have changed emotional reactions. These results agree with the hypothesis of NS as a stage of processing or cortical output (8), but not with the accepted notion of NS as a major component of the "extrapyramidal motor system". It should be noted that cats without caudate nucleus eat spontaneously about a week after surgery (36). The same is true for decorticated preparations, but not for "thalamic" animals (32, 38). These results suggest that permanent aphagia in the latter group may have resulted either from ablations in the posterolateral region of the hemisphere (of putamen or portions of the limbic system; e.g., amygdala (16), or nucleus basalis (7) or from the additive effects of cortical, limbic and NS ablations. The same may be said about sham rage and the absence of vocalization (see above).

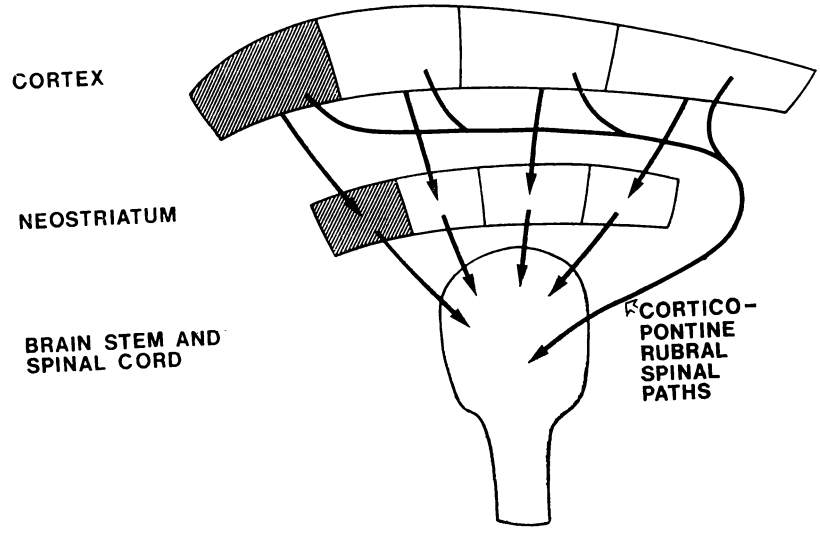

Fig. 1. Schematic illustration of the experimental paradigms reviewed in this paper. Either cortex, or the neostriatum, or both, at once or in sequence, are ablated. The ablation includes the whole formation or one of its parts. In the latter case, meaningful results are obtained if the cortical and neostriatal ablated regions "correspond" to each other (shaded areas).

The "compulsory approach" (different from "obstinate progression", see above), which is seen after large caudate lesions but not after ablations of frontal cortical area or of the entire cortex, may be taken to suggest that the neostriatum mediates functions which are not mediated by the cortex. It is, however, conceivable that the "compulsory approach" may result from a loss of a particular group of functions which could be eliminated also by removal of the cortical area which corresponds to the ablated portion of the neostriatum. This syndrome may alternatively be the expression of unrestrained control of the final common path by limbic and posterior cortical areas via the ventral striatum (21) or the putamen, respectively. Normally these mechanisms may be balanced by the output from the anterior cortex and the head of the caudate nucleus and hence only occasionally reach the final common path (Fig. 1). (Experiments can be easily designed to test the feasibility of these suggestions). In conclusion, the differences of effects of NS, and of neocortical ablations may be interpreted to indicate different functions of these two formations, but other interpretations are possible (Fig. 1).

ABLATIONS WITHIN A NEOCORTICO-NEOSTRIATAL COUPLE

The third approach in studying the degree of dependence of NS functions on the neocortex consists of manipulations of a restricted neocortical area and the related NS region (Fig. 1). Area-to-region coupling between the neocortex and NS has been extensively discussed elsewhere (4, 5, 9, 25, 29, 30). It suffices here to say that the evidence suggests a close relation between a neocortical area and a NS region. This relation is anatomical, neurobehavioral and metabolic-functional: each cortical area has one principal target region in NS, this target region shares at least some functions with the associated cortical area (11), and artificial activation of a cortical area produces coactivation in its principal target region in NS (9). If a NS region is associated anatomically and functionally with one cortical area (for a detailed discussion see Divac and Diemer 9), one can study cortico-NS relations concentrating only on one couple (Fig. 1). This approach is technically simpler and allows for more detailed analysis, but it is also not without methodological and interpretational difficulties and therefore cannot replace the already discussed paradigms. The most serious criticism is that even partial lesions aimed at NS produce accidental damage to the cortical connections. The evidence relevant for this problem is discussed in Öberg and Divac (26). Another criticism is that it is not exactly known which part of NS corresponds to a particular cortical area. This problem, however, seems possible to solve by the use of labelled 2-deoxyglucose

(9), unless the relation between the cortical and neostriatal regions changes with different functional requirements.

Lesions in the part of NS associated with the prefrontal cortex, if made in animals which mastered a delayed response-type task after prefrontal cortical ablations, produce different outcomes in different species. In Old World monkeys, ablations of either the prefrontal cortex (31) or NS (13) produce impairments in delayed response-type tasks. Since monkeys with total prefrontal cortical ablations acquired after infancy usually do not relearn these tasks, one must conclude that their NS is not capable of mediating their behavior in the absence of cortical input. Monkeys operated in infancy and tested in delayed response tasks at the age of 24 mo were not inferior to unoperated animals of the same age. At this age, however, all monkeys are less efficient than "young adults" (18). Lesions in infant monkeys involving the related neostriatal tissue alone (20) or along with the prefrontal ablation (22) do impair this performance. These and other results suggest that the neostriatum in the monkey is capable of mediating delayed response-type behavior before the related neocortex. The neostriatum never reaches the proficiency of the lateral prefrontal cortex, and moreover appears to loose its ability to independently organize delayed responding at an advanced age even if the prefrontal cortex had been removed in infancy (19).

In cats with prefrontal (gyrus proreus) ablations, the added NS lesion produced neither retention loss (39), nor appeared to play a role in relearning of delayed response type tasks (6). In two other studies the technique of sequential lesions showed some residual participation of the prefrontal neostriatal region deprived of its neocortical input in the prefrontal functions (28, 40). How delayed responding is mediated in cats with ablations of both the prefrontal cortex and the associated NS region is not known.

In rats without the critical part of the prefrontal cortex, the added NS lesion prouced a relapse of the impairment which lasted as long as the animals were tested (40).

These results suggest that the relation between the prefrontal cortex and the associated NS region, as well as the relation of this couple to the rest of the brain, differ among species. Thus, the "within-the-couple" relation is strictly serial in the adult monkey and apparently also in the cat. In both species, in the absence of the prefrontal cortex, the associated part of the NS no longer takes part or has a negligeable role in "prefrontal functions". (However, from this evidence it cannot be concluded that the "prefrontal region" of NS is left without any function when deprived of its principal cortical input). The cited results also

suggest a persisting involvement of the "prefrontal portion of the NS" in mediation of delayed alternation in rats with previous prefrontal cortical ablations.

DISCUSSION

The meager evidence available at present does not allow any firm conclusions about the degree of dependence of functions of the neostriatum on its neocortical input. *If* the data discussed in the first two sections are interpreted as showing, respectively, that the neostriatum remains partly functioning after decortication and that it subserves some functions which are not mediated by the cortex, then the following picture about neocortico-neostriatal relations, based also on the review in the third section, can be sketched: [1] The neostriatum has certain functions which it shares with the neocortex. Possibly, the neostriatum normally processes cortical input and sends the resulting computation further toward the final common path (8). In addition, the neostriatum may have functions which do not require cortical input. (The roles of other inputs to NS in functions of this formation will not be discussed here). The hypothetical cortex-independent functions of NS may belong to a category quite different from the cognitive functions which are mentioned in Section 3 and were extensively discussed in Öberg and Divac (26). However, in the rat at least, some cognitive functions of NS, normally shared with the neocortex, seem to be cortex-independent. Data reviewed in Sections 1 and 3 do not allow even tentative conclusions of whether cortex-independent functions of NS are qualitatively different from the cortical functions, but the presence of "compulsory approach syndrome" (Section 2), which has not been produced by cortical ablations, may indicate the presence of such NS functions.

Any description of NS functions, both cortex-dependent and cortex-independent, would be premature at present, except in the form of rephrazing the syndrome (see also 26).

One conclusion of this review seems unquestionable: the rat and the cat clearly differ both in the viability of "thalamic" preparations and in the behavioral repertoire following decortications; in each case the rat is superior to the cat. In other words, both the neostriatum and

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[1] Functions of NS may be dependent or independent on the cortical input, and on the other hand, they can be cortex related or unrelated. These classifications are independent of each other. In the first instance the criterion is preservation of NS functions in the absence of its cortical input; in the second instance it is qualitative similarity of cortical nad NS functions.

the brain stem seem to be more independent from the more rostral regions of the brain in the rat than in the cat and adult monkey. One remains wondering whether the lower brain mechanisms, capable of mediating rather complex behavior in simpler brains, have to be suppressed or undone in order to permit control from even more sophisticated higher mechanisms in more complex brains. Anyhow, it appears that the neostriatum has more cortex-independent functions in the rat than in the cat or monkey.

It seems necessary to emphasize again that although both the cortex and neostriatum participate in the mediation of some common functions, they need not be — and most likely are not — equipotential. Judging from their respective architectures and connections, they almost certainly contribute different operations towards the same goal. In the rat, however, the neostriatal mechanism can be sufficient to maintain correct behavior in the situations which normally require participation of the prefrontal cortex.

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