

ROLE OF BASAL GANGLIA IN CONTROL OF INNATE MOVEMENTS, LEARNED BEHAVIOR AND COGNITION - A HYPOTHESIS

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INTRODUCTION

The progress of basal ganglia research has been rapid and fruitful. As is clear from articles in this book, we now know detailed neural circuits in the basal ganglia, heterogeneous distribution of chemically defined neuron groups, and the presence of various transmitter candidates and their intracellular actions. This accumulated knowledge allows us to provide reasonable interpretations for clinical symptoms of basal ganglia disorders and even to suggest novel surgical or drug treatments.

However, we still know little about how the basal ganglia work when we do something or think something. Such normal functions of the basal ganglia must be dynamic processes in which different parts of the basal ganglia work in a unique yet coordinated manner. Moreover, the basal ganglia system is only a part of the neural system that controls our behavior. Obviously we need to characterize the function of the basal ganglia in relation to such a global system. After a laborious task of investigating single cell activities, we now know that motor and non-motor signals are coded by basal ganglia neurons in various ways, frequently depending on the behavioral contexts. However, such signals are also found in other brain areas, especially in the frontal cortices.

What do all these data tell us after all? Where do such signals originate and how are they used? Are the signals merely circulating through the loop circuits formed by the cerebral cortex, basal ganglia and thalamus? What then is unique about the basal ganglia?

I think, in order to answer these questions or to figure out appropriate experimental paradigms to guide the answer, it is critical and urgent to set forth a working hypothesis. This paper is one such attempt.

DUAL MODE OF BASAL GANGLIA FUNCTION: DISINHIBITION AND ENHANCED SUPPRESSION

The two major outputs of the the basal ganglia, via the internal segment of the globus pallidus and the substantia nigra pars reticulata, are both GABAergic inhibitory and their levels are set extremely high by their tonic background discharges (DeLong and Georgopoulos, 1981) (Figure 1). Major inputs to these output areas originate from the striatum (putamen and caudate nucleus) which are also GABAergic and inhibitory (Carpenter, 1981). Here emerges a first mode of basal ganglia operation: an excitatory input from the cerebral cortex or the thalamus would lead to a disinhibition in the target structures of the basal ganglia (Penney and Young, 1983; Chevalier and Deniau, 1990).

areas also control autonomic functions, such as blood pressure and pupil dilation, and sensory functions, such as nociception (Bandler et al., 1991). These elementary behaviors, when grouped together, would constitute a purposive action, such as threat, aggression, and flight (Holstege, 1991).

The primary function of the basal ganglia would thus be schematized as follows. The lower brainstem and spinal cord contain generators of elementary movement patterns (Hepp et al., 1989; Pearson and Rossignol, 1991; Sillar, 1991). Each of the pattern generators is an intricate neural machine but would not function independently. Only when they are selectively and collectively controlled by the midbrain motor regions do the movement patterns become purposive.

During phylogenetic development animals obtained a variety of innate actions so that they could adapt to different conditions of environment. Here arose a new question: 'How can an appropriate action be selected?'. I propose that the basal ganglia evolved to play such a role of selection. The disinhibition and enhanced inhibition, which I mentioned above, are superb mechanisms for such a function. Selection is always based on some kind of evaluation and motivation. Such signals could be provided by the inputs from the limbic system (Ragsdale and Graybiel, 1988; Haber et al., 1990).

Clearly this is a very primitive form of motor control system. The actions and the constituent movement patterns are still basically innate. With the projections to the midbrain/pontine motor regions the basal ganglia can select innate actions (Figure 2). Thus, without the cerebral cortex, the animal might be able to walk, run, orient, feed, and vocalize. It would be amazing how integrated such an animal might look.

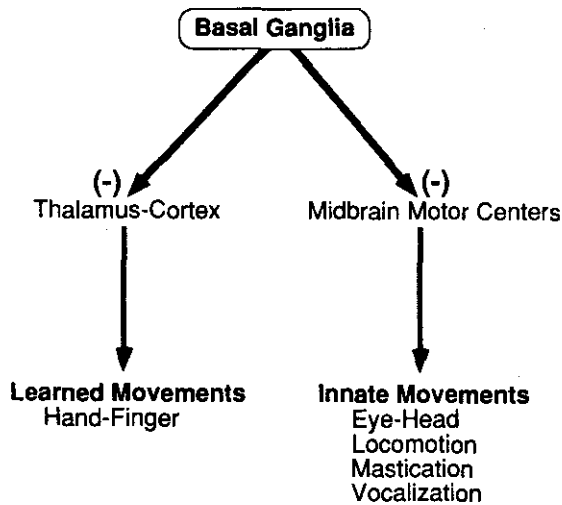


Figure 2. Basal ganglia control innate and learned movements.

But we do have learned types of movement. Here also the basal ganglia may play a role of selection. Underlying such a function may be the connection to the thalamus which is mutually connected with frontal cortical areas (Carpenter, 1981). In contrast to the midbrain projections, this pathway would control learned movements (Figure 2).

The motor control system can be viewed as a hierarchical organization (Figure 3). Central pattern generators in the spinal cord and the lower brainstem might be called 'fixed

pattern generators', which imply that they generate innate movement patterns. They are coordinated by the midbrain motor regions such that synergistic, purposive actions are generated. I would like to call them 'fixed action generators', implying that action is a synergistic complex of movement patterns. They are 'fixed' because their products are still innate. True adaptability to new environment was obtained by the evolution of the cerebral cortex. The basic function of the cerebral cortex would be to combine the available actions spatially and sequentially to create new action programs ('learned action generator').

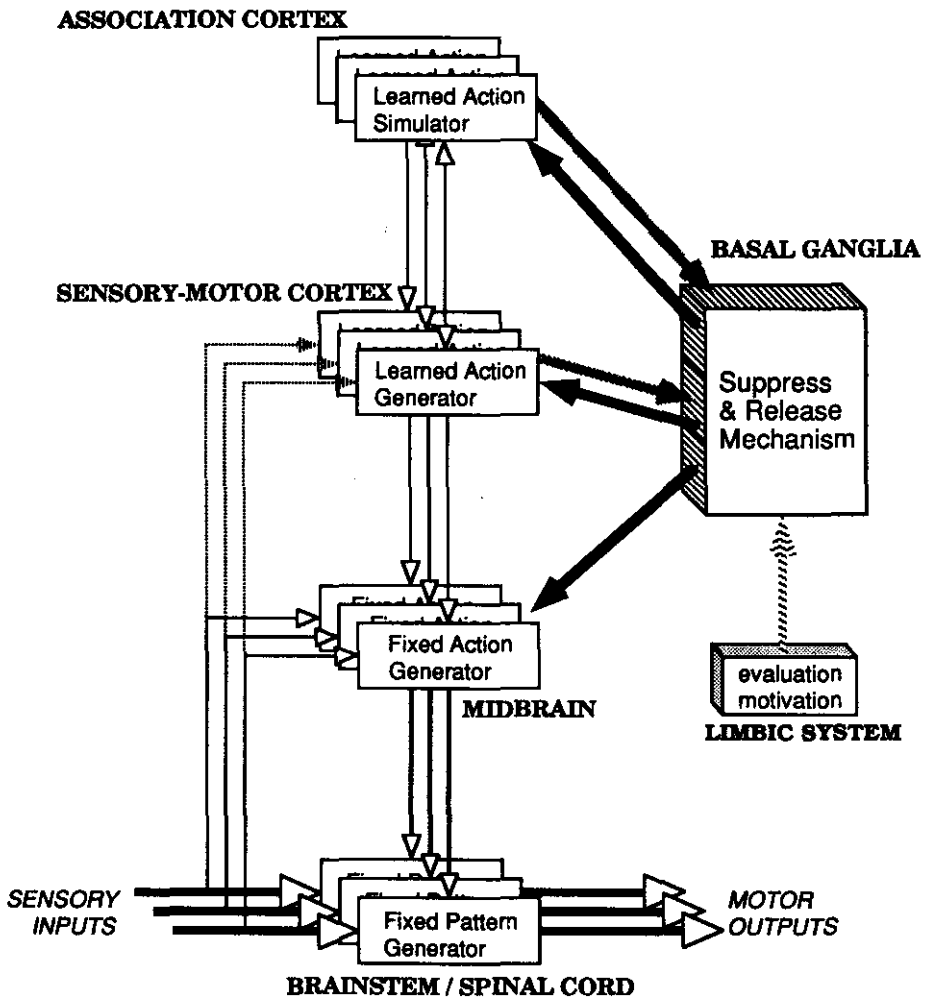


Figure 3. Hierarchical organization of motor control system and its relation to basal ganglia.

By the time an animal has grown up, many such action programs will have been accumulated in the motor-premotor cortices. Here arises the same question: 'Which action program should be selected?'. Again the basal ganglia should play a key role in the selection. This would be done by the connection through the thalamus (Schell and Strick, 1984; Nambu et al., 1991). But unlike in the case of innate actions, there is no fixed rule to be applied in terms of the algorithm of the selection. Perhaps for this reason, the basal ganglia need the information from the cerebral cortex (Kemp and Powell, 1970). In consequence, the relationship between the basal ganglia and the cerebral cortex is bound to be mutual.

The same relationship is seen between the basal ganglia and the association cortices (Ilinsky et al., 1985), which I characterized as 'learned action simulator' as opposed to 'learned action generator'. The role of the basal ganglia here would be to select non-motor signals, such as memory, attention, and expectation.

So far I have suggested that the basal ganglia select available action programs in the midbrain or in the cerebral cortex. But the function of the basal ganglia system might go beyond this: it might play an important role in formation of the action programs.

FEATURE INTEGRATION VS PROCEDURE FORMATION

Perhaps the most important feature in learning is to associate independent signals. A notable example is classical conditioning in which a previously unrelated stimulus is associated with an innate reflex. I would suggest here that there are two conceptually different modes of association (Figure 4). In either case, neurons A and B at first are supposed to function independently; then there appears another neuron that associates A and B, but in two different ways. In the first case the new element receives signals from A and B; in the second case the element sends signals to A and B.

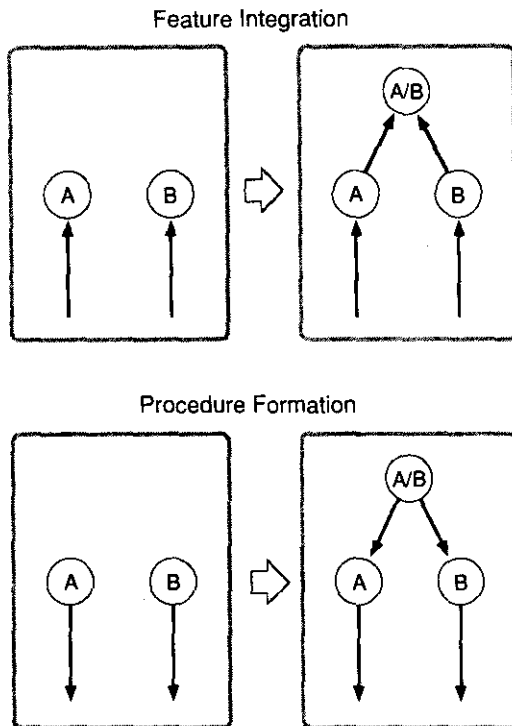


Figure 4. Two modes of association of neural signals.

The first mode (Figure 4, top) would be utilized mostly by the sensory systems. In the process that might be called 'feature integration', for example, we learn to recognize faces by combining signals of elementary features such as eye and mouth (Fujita et al., 1992). It is plausible to configure a neural mechanism underlying this process, mostly based on Hebbian or modified Hebbian type learning (Brown et al., 1990; Fregnac et al., 1992).

What seems important in the motor system is the second mode of learning (Figure 4, bottom). When we were babies we had a limited number of simple action programs or procedures. When we learned to do something, say, write our own names, the first thing we did was probably to combine the then available procedures (Newell, 1978). Such a process, which I call here 'procedure formation', may correspond to this type of neural organization. Unlike 'feature integration', it is difficult to imagine an underlying neural mechanism.

I would like to suggest that the basal ganglia may play an instructive role in procedure formation or procedural learning (Figure 5). Suppose there are neurons A and B in the cerebral cortex which send outputs independently (Figure 5, top). After mutual interplay with the basal ganglia a new set of cortical neurons that control both A and B emerges (Figure 5, bottom). The process would proceed as follows.

As already mentioned, the basic mode of basal ganglia action is inhibition and disinhibition. Before signals are fed into the basal ganglia, the outputs of the basal ganglia would continually suppress their targets, in this case, the thalamo-cortical circuits (Figure 5, top).

In the new environment, the animal may attempt to perform a motor act A simultaneously or sequentially with B, for example (Figure 5, top). It is known that there is

an extensive convergence in cortico-striatal connections (Parthasarathy et al., 1992). Thus it is conceivable that the signals A and B converge onto single neurons in the striatum. The neurons may at first not respond, because the striatum is probably one of the most quiet areas in the brain (Hikosaka et al., 1989). But if the combination of A & B is repeated and if the action produces reward, the combined signals may become able to activate the striatal neurons. The signals of the reward value may be transmitted by dopamine neurons in the substantia nigra pars compacta (SNc) (Romo and Schultz, 1990; Schultz and Romo, 1990; Ljungberg et al., 1992) which exert modulatory effects on striatal neurons (Gerfen et al., 1990; Garcia-Munoz et al., 1991; Calabresi et al., 1992).

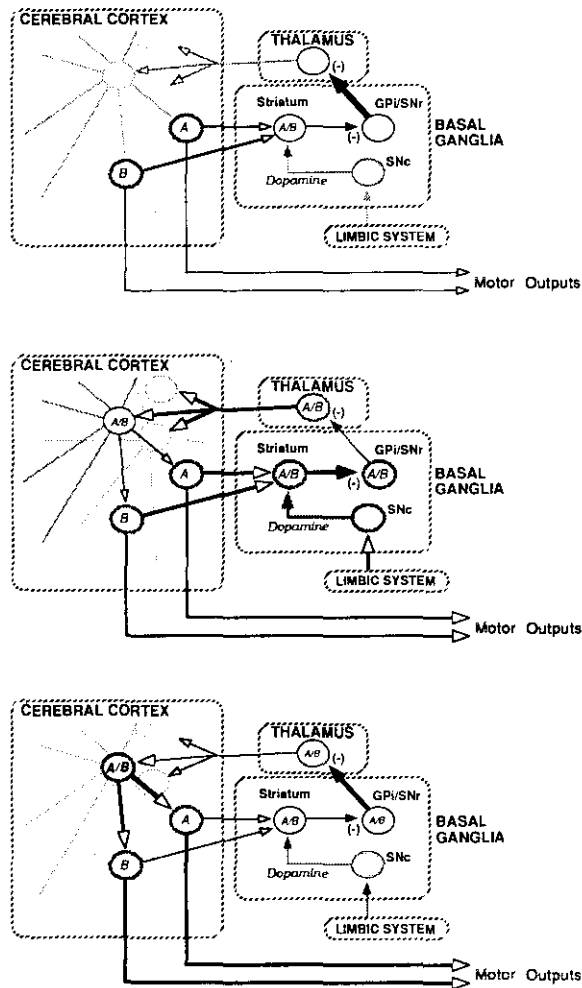


Figure 5. Hypothetical process of procedural learning.

Once the combined signal is put through the gateway of the basal ganglia, it would allow a limited portion of the thalamo-cortical circuits to be active (Figure 5, center). Note, however, that this selected set of cortical neurons are free to be active only under the condition of A/B. Let us assume that some (perhaps only a small fraction) of these neurons have already had weak and insignificant connections to the output neurons A and B. If the attempt of A/B is repeated, the efferent connections would be enhanced, perhaps based on the Hebbian rule. It may be possible that the combined cortical signals are again fed into the basal ganglia so that further complex combinations are created.

In short, the basal ganglia would temporarily retain the memory of behavioral procedures. The cerebral cortex would create motor or procedural memory based on such a neural template. An important feature is that the basal ganglia can not only combine different cortical signals but also test the validity of the combination through their outputs and the evaluating signals.

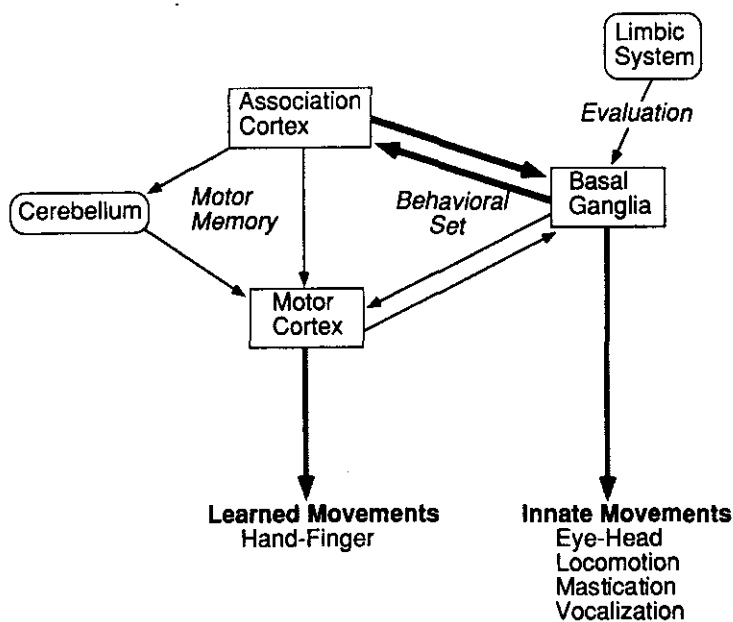


Figure 6. Differential roles of motor areas in learning.

CONCLUSION

Finally I would like to propose the hypothetical framework of the motor mechanisms (Figure 6). The basal ganglia system is a dominant structure in the lower species of animals. It would act to facilitate motor programs based on the reward-contingent inputs from the limbic system. The motor programs are still innate and thus their patterns are largely fixed. Such animals must learn, however, to associate particular environmental signals with particular motor programs. The attempted behavioral sets are first formed in the basal ganglia, and the cerebral cortex learns to create procedural memory based on the template. As the animal's behavior becomes more complex, the motor program itself must also be learned. Here again, the basal ganglia may play an instructive role so that motor memory is created efficiently in the motor cortical areas and probably also in the cerebellum.

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