Brain mechanisms for interleaving routine and creative action

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Abstract

In our system-level approach to brain modeling, we define creative action as that originating in the basic knowledge elaboration activity of the cortex. We argue that cortical areas, particularly frontal areas, will also be involved in the selection and control of routine action which originates in the basal ganglia. They initiate routine action, and monitor and terminate it.

We explain the anatomical connectivity of the basal ganglia which place them in loops from various source areas of the cortex and back to target areas. We relate these connections to the cortical perception-action hierarchy. We model routine action via the basal ganglia, which learn association connections among source areas and target areas.

Routine action is often but not always selected by goals, some of which may be set by frontal areas. Normally, there will be an interleaving of creative cortical action and routine action. We argue that the connections among the basal ganglia, thalamus and cortex provide a basis for real time control and monitoring of a stream of routine actions generated by the basal ganglia.

We outline examples of routinization and interleaving for the Tower of Hanoi problem, for routinization of motor control, of problem solving action, and of eye movement.

We suggest a role for the ventral group of thalamic nuclei in controlling the flow of routine action.

Key words: basal ganglia, neocortex, creative action, routinization, thalamus.

The routinization of mental action

There is a range of types of mental action, from completely novel action generated creatively by cortical planning, to more straightforward cortical action learned in the hip-

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pocampus, to routinized action learned in the basal ganglia.

In our system-level approach [4] [3] [2] [6], learned plans are stored in frontal areas, are activated by goals, and are elaborated through the perception-action cortical hierarchy to generate action. We argue that the cortical planning areas must be in control of all action and that streams of routine action descriptions from the basal ganglia will be selected, initiated, monitored and terminated by planning areas. Selection may be by triggering from the current mental state, however this can often involve goals set by planning areas. Further goals can be generated lower in the perception-action hierarchy, including perceptual goals which can trigger eye movement.

We cannot leave it up to simple competition between individual creative and routine actions; in general, the creative thought process will need to perform control decisions. However, in order to assess control decisions, the planning system will need a stream of information originating in the routine system. It seems that the creative system will require more resources, more energy, and more realtime, than the routine system, to generate an action. However, once initiated, the routine system should be able to send and receive information rapidly, leaving the planning system to monitor its progress and effects in parallel.

One issue is the variability of routine action from one situation to another. The inputs to the basal ganglia are not raw sensory data but from certain levels in perceptual hierarchies. Similiarly their outputs are not directly to motor areas but to planning or premotor areas.

The phenomenon of utilisation behavior [8] [11] suggests that, on weakening or ablation of the controlling area, the lower area defaults to automatic control driven by perceptual input.

The basal ganglia loops

Research by Garrett Alexander [1] has shown that the basal ganglia are not an intermediate level of motor control between cerebrum and thalamus, but instead participate in four loops starting in the cortex and ending in the cortex, see Figure 1, comprising (i) the sensory-motor loop, corresponding to routine motor action (ii) the oculomotor loop, corresponding to routine eye movement (iii) the association loop, corresponding to routine planning, and (iv) the limbic loop, corresponding to routine goal and context setting.

We will call the input areas to a loop *source areas*, which can be perception or action areas, and the output areas *target areas*. Thus, for the association loop, there is one perception source area namely posterior parietal cortex (7), and one action source area namely premotor cortex (6), and the target areas are prefrontal cortex (9,10). The source areas can arguably be seen as being involved in preparation of higher-level information to be sent to the target area of the loop.

Using our prior analysis of cortical neuroanatomy [4], it seems that, in general, for all four loops, for each connection from the cortex or other area to the basal ganglia there is a direct cortical connection to or from the target area. For example, areas 6 and 7 have direct cortical connections to 9 and 10, from perception source areas to the target area and from the target area to and from the action source areas. Thus each basal ganglia loop forms a connection system which runs parallel to part of the cortical connection system.

A theory of the action of the basal ganglia and cortex

We use our system-level brain modeling approach to develop a theory of what may be going on when routinized mental action occurs.

In learning by doing, the basal ganglia "record" the activity of their source modules

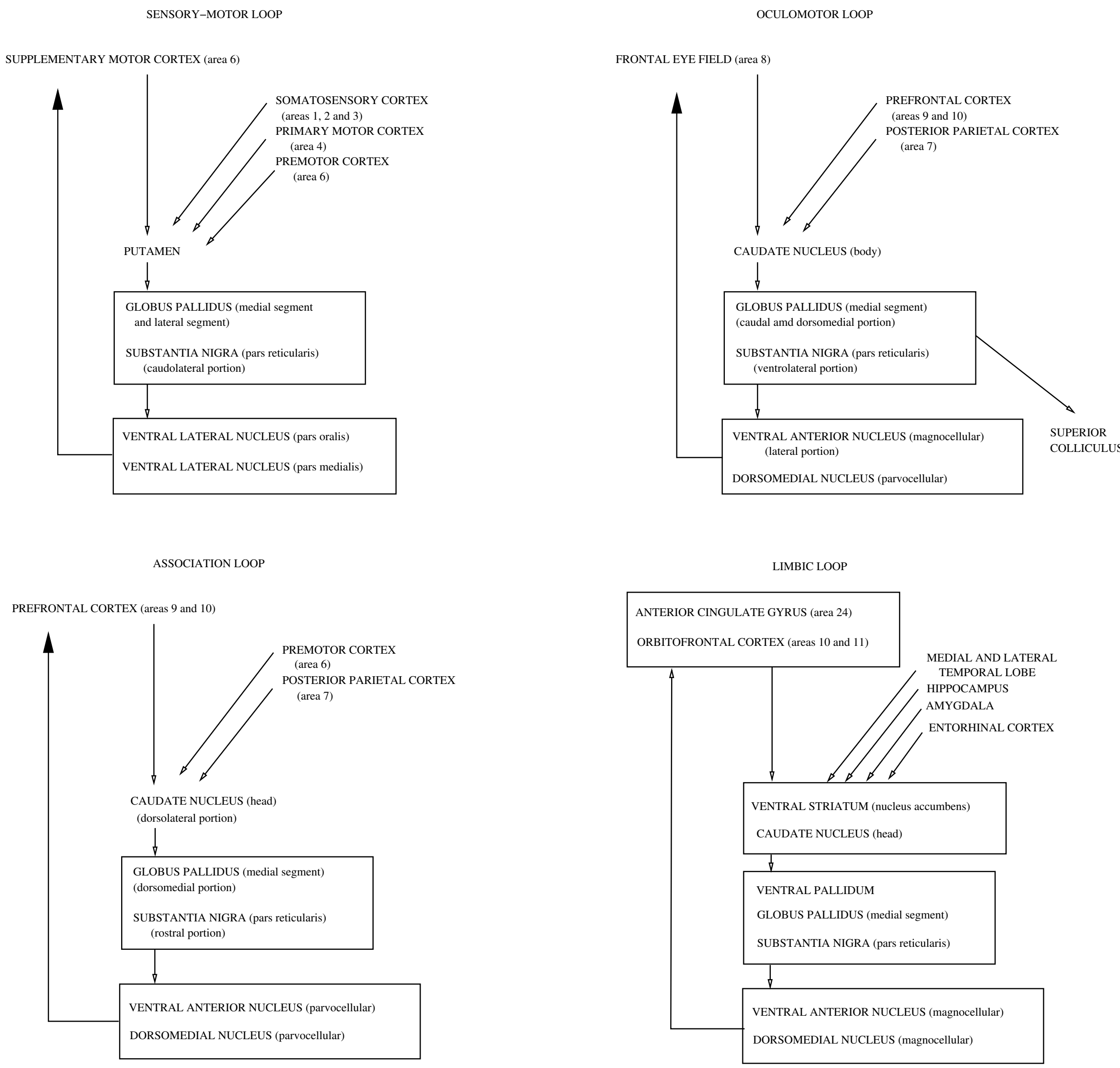

Figure 1: Loops involving the basal ganglia, from Noback et al. 1991 [9], pp. 385-388

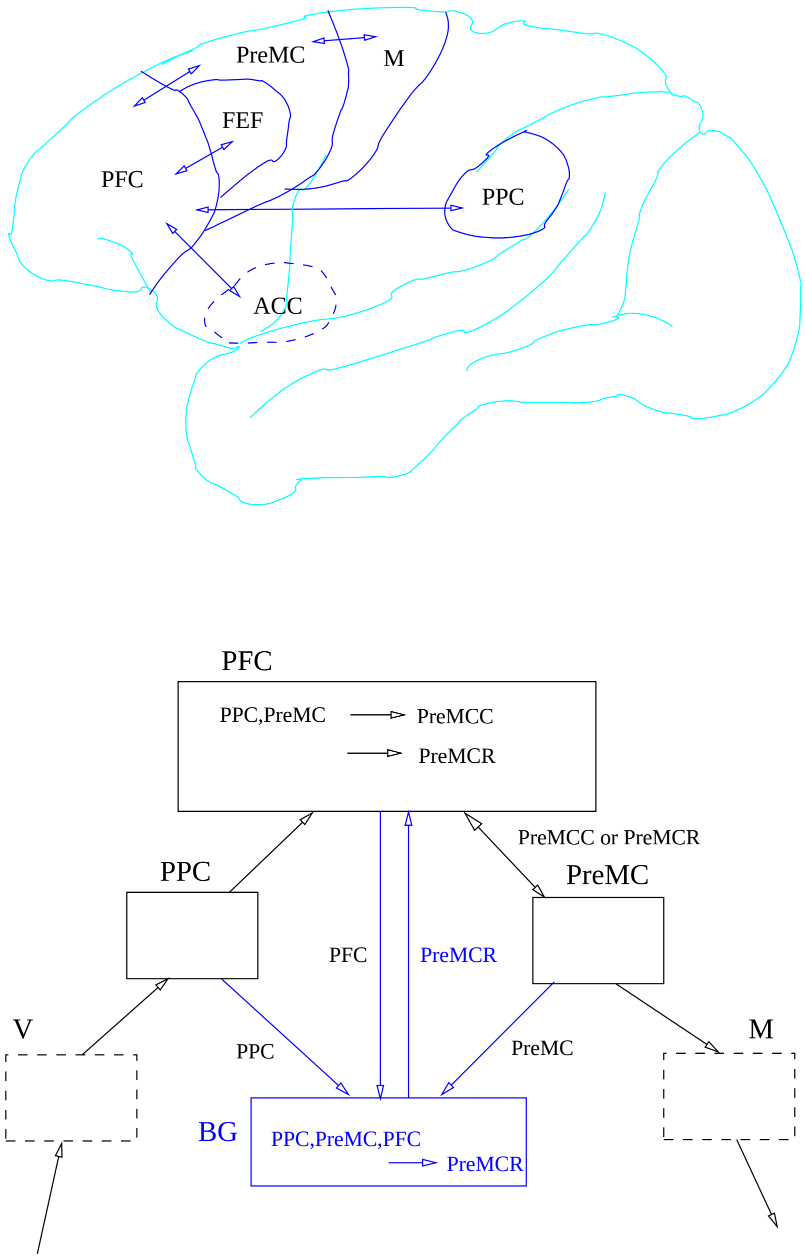

Figure 2: The association loop mapped onto the perception-action hierarchy

during the search for solution. Figure 2 shows Alexander et al.'s association loop mapped onto the perception-action hierarchy of our brain model.

So what are the members of the association loop typically doing?

(i) PPC, the posterior parietal cortex is concerned with visual perception to create nonegocentric maps.

(ii) PreMC, the premotor cortex generates descriptions of motor actions at the intention and coordinate level.

(iii) PFC, the prefrontal cortex, generates plans and actions at the relation level. One could write the association as:

if PPC and PreMC and PFC then PFC

so this assertion is upwards, from more concrete towards more abstract information.

Thus we conclude that the basal ganglia build a plan based on lower level inputs and outputs. The end result is rules in the basal ganglia and also for example PFC, of the general forms:

in the basal ganglia: if PPC and PreMC and PFC then PreMCR

and in PFC: PreMCR is a possible action.

What we intend by this notation is that the basal nuclei generate the suggested routine action PreMCR for PreMC, but they do not send it to PreMC, but instead to PFC for permission. PFC may have an alternative creative action PreMCC to send to PreMC, however it can also perform logic to make a decision between sending PreMCC or PreMCR to module PreMC. Figure 2 shows how the association loop might work. Thus according to this theory the upper module is the regulator or controller of the routine action. One main consideration is that, in situations warranting routine action, this can proceed quickly. Thus PFC would simply select PreMCR without doing any or much computation. This is to allow a rapid stream of actions to be generated by the basal ganglia and sent to module PreMC.

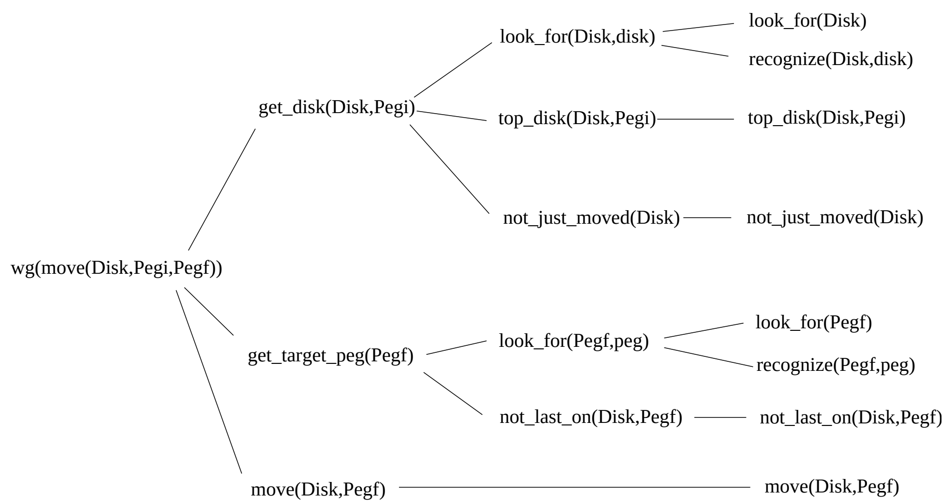

Figure 3: An example of a plan, for the selective search strategy

Tower of Hanoi example

We show in Figure 3 the plan for the selective search strategy for solving the Tower of Hanoi problem, which tends to be used initially by naive subjects.

This is actually represented [5] in the associative memory of the planning module as a set of descriptions (or codes):

(wg(move(Disk,Pegi,Pegf)),[get_disk(Disk,Pegi),get_target_peg(Pegf),move(Disk,Pegf)])

(get_disk(Disk,Pegi),[look_for(Disk,disk),top_disk(Disk,Pegi),not_just_moved(Disk)])

(get_target_peg(Pegf),[look_for(Pegf,peg),not_last_on(Disk,Pegf)])

(move(Disk,Pegf),[move(Disk,Pegf)])

and so on. We are thus assuming that the planning module has (i) descriptions (or codes) representing the information in each plan component, (ii) a neural circuit mechanism for association, given a key, to activate the corresponding plan description, and (iii) a neural circuit mechanism sequencing through a list of descriptions, activating one, waiting for completion, then activating the next. When a description is generated, it may be sent to another module, such as premotor cortex, frontal eye fields, or the hippocampus.

Initially, a search would take place, resulting in moving disk1 from peg1 to peg2. If this is repeated and reinforced, then a routine form could be developed by the basal ganglia:
move(Disk,Pegi,Pegf) → [get_disk(disk1,peg1),get_target(peg2), move_disk(disk1,peg2)]
This notation indicates that if the goal move(Disk,Pegi,Pegf) is received by the the basal ganglia then it would generate the sequence of codes [get_disk(disk1,peg1),get_target(peg2),move_disk(disk1,peg2)] in turn and send them to the planning module.

There could also be oculomotor routines:
look_for(Disk,disk) → [look_for(disk1),recognize(disk1,disk)]
top_disk(Disk,Pegi) → [top_disk(disk1,peg1)]
look_for(Pegf,peg) → [look_for(peg2),recognize(peg2,peg)]
By look_for(Disk,disk) we mean a description which is sent to parietal and FEF areas to generate a saccade to a given object, look_for(disk1) to saccade to disk1, recognize(disk1,disk) to recognize if disk1 is a disk or not, and top_disk(disk1,peg1) to check that disk1 is the top disk on peg1. Thus the variable Disk is replaced by the constant disk1, Pegi by peg1, and Pegf by peg2. There could also be a sensorimotor routine:
move(Disk,Pegf) → [move(disk1,peg2)]
By move(Disk,Pegf) we mean a description to be sent to premotor cortex to generate a physical movement.

Then when the working goal wg(move(Disk,Pegi,Pegf)) is activated in the initial context, the basal ganglia would generate the sequence. The cortical mechanism would compare the two possible choices, get_disk(Disk,Pegi) (creative) and get_disk(disk1,peg1) (routine), and would choose the latter. When the latter is complete, the cortical mechanism would sequence to the next action, i.e., get_target_peg(Pegf) or get_target_peg(peg2), and so on.

There will be different levels of routinization. The one illustrated here is the choice of a subset or a single individual from alternatives. A further level is to eliminate checks, so get_disk(disk1,peg1) would not be visually checked, or checked in episodic memory as not just moved. Eventually, one could reach a fully routinized form move(Disk,Pegi,Pegf) → move(disk1,peg2) without any checks.

Neural mechanisms of interleaving

Interleaving. The planning module has to retain *supervisory control* [12] over routinized action. In situations requiring full evaluation of the proposed course of action, the system might have to reach a viable state, which could take 300 milliseconds. Routine action, on the other hand, can be used for faster actions such as steering a bike. The phenomena of action slips [10] show how action breaks at the boundaries between these two modes of action.

The connections and circuits involved. We can perhaps relate our ideas to neuroanatomy and the thalamus, by suggesting a possible role for the thalamus. Most of the thalamus is concerned with receiving a wide range of sensory, subcortical and cortical inputs and sending outputs to the cortex. It is only the limited parts, mainly the ventral group of thalamic nuclei, that are involved in the basal ganglia loops and receive inputs from the globus pallidus and substantia nigra.

The connections from cortical layers 5 and 6 to the thalamus have been described by Sherman and Guillery [13] [7]. They described two types of thalamic input, drivers and modulators. Driver inputs to the thalamus come from layer 5 and there are outputs from the thalamus back to layer 5. Modulators on the other hand appear to use layer 6, again reciprocally connected. We can now diagram in Figure 4 the cortical layers and the connections involved in our scheme.

A possible role for the thalamus. A possible role for the thalamus is that it could help regulate the rapid flow of routine action, so that once a routine course of action

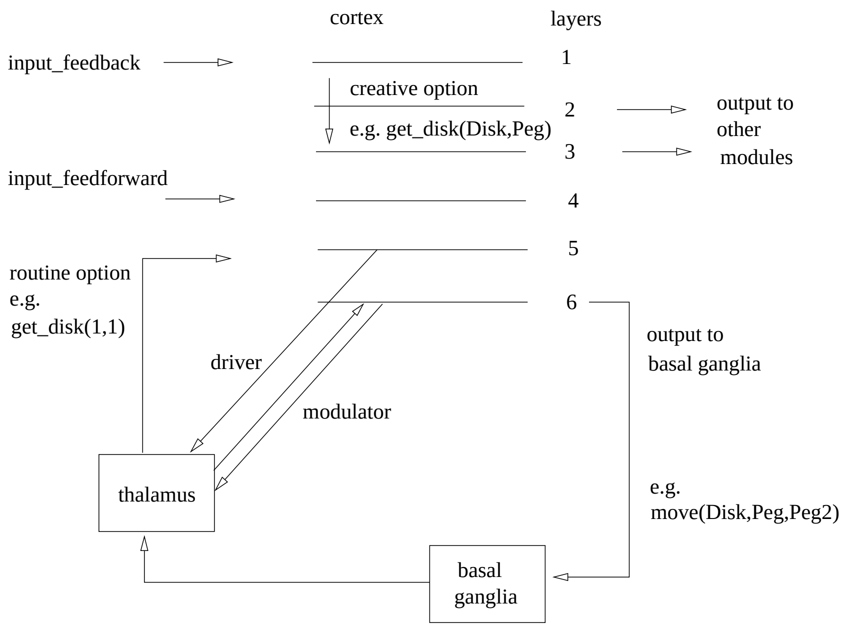

Figure 4: Composite diagram of cortex, thalamus and basal ganglia

is selected by the neocortex, the stream of routine actions can flow faster than cortical decision speeds. While the cortex is monitoring and deciding on selecting a routine action, a modulator message would be sent to the thalamus which would prevent rapid flow of information from the basal ganglia. Once the routine action is selected, the cortex would send a modulator message to the thalamus allowing it to let this rapid information stream through. During routine action, the cortex would monitor its effects and could stop it at any time by sending a modulator message to the thalamus.

Summary and conclusion

In this paper, we first discussed the nature of routine and creative mental action, and that control decisions should be made in cortical planning modules. We then discussed the basal ganglia loops and mapped these onto our system-level brain model. We then discussed how initiation, monitoring and control of routine action could be achieved by providing the planning module with the ability to monitor a stream of routine action descriptions, and to allow this to flow or else to instead make creative actions. We finally outlined in a neural level of description how different cortical layers and the thalamus might be involved in routinized action.

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