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Complementary roles of basal ganglia and cerebellum in learning and motor control

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Summary:

The classical notion that the basal ganglia and the cerebellum are dedicated to motor control has been challenged by a growing evidence showing their involvement in non-motor, cognitive functions. From computational viewpoints, it has been suggested that the cerebellum, the basal ganglia, and the cerebral cortex are specialized for different types of learning, namely, supervised learning, reinforcement learning, and unsupervised learning, respectively. This idea of learning-oriented specialization is helpful in understanding the complementary roles of the basal ganglia and the cerebellum in motor control and cognitive functions.

Introduction

The basal ganglia and the cerebellum have been known to be involved in motor control because of the marked motor deficits associated with their damages. However, it has not been clear what aspects of motor control they are involved in under normal conditions. Traditionally, the cerebellum was supposed to be involved in real-time, fine tuning of movement[1,2], while the basal ganglia were supposed to be involved in selection and inhibition of action commands [3]. However, these distinctions were by no means clear cut[4]. Furthermore, an ever increasing number of brain imaging studies show that the basal ganglia and the cerebellum are involved in non-motor tasks, such as mental imagery[5,6], sensory processing[7-9], planning[10-12], attention[13], and language[14-17].

Both the basal ganglia and the cerebellum have recurrent connections with the cerebral cortex[1,3]. Anatomical studies using transneuronally transported viruses[18-21] have clearly shown that the projections from the basal ganglia and the cerebellum through the thalamus to the cortex constitute multiple `parallel' channels. The diversity of the target cortical areas, not only the motor and premotor cortices but also the prefrontal[18], temporal[22], and parietal cortices[19], is in agreement with their involvement in diverse functions. However, the neural activity tuning and the lesion effects of a subpart of the basal ganglia or the cerebellum tends to be similar to that of the cortical area it projects to[21]. This makes it difficult to distinguish the specific roles of the basal ganglia and the cerebellum simply from recording or lesion results.

Is it then impossible to characterize the specific information processing in the basal ganglia and the cerebellum? Despite their diverse, overlapping target cortical areas, the basal ganglia and the cerebellum have unique local circuit architectures and synaptic mechanisms. This strongly suggests that each structure is specialized for a particular type of information processing.

Specialization by Learning Paradigms

Theoretical models of learning in different parts of the brain suggest that the cerebellum, the basal ganglia, and the cerebral cortex are specialized for different types of learning[23,24], as summarized in Figure 1. 1) The cerebellum is specialized in supervised learning based on the error signal encoded in the climbing fibers[2,25-27]. 2) The basal ganglia is specialized in reinforcement learning based on the reward signal encoded in the dopaminergic fibers from the substantia nigra[28-30]. 3) The cerebral cortex is specialized in unsupervised learning based on Hebbian plasticity and reciprocal connections within and between cortical areas[31-34].

Reward-based learning in the basal ganglia

A breakthrough in elucidating the function of the basal ganglia was given by a series of experiments by Schultz and colleagues on the activity of midbrain dopamine neurons in primates [35,36]. In a conditional reaching task, dopamine neurons initially respond to the liquid reward after successful trials. However, as the animal learns the task, dopamine neurons start to respond to the conditional visual stimulus and cease to respond to actual reward delivery. This means that the activity of dopamine neurons does not just encode immediate reward, but prediction of future reward. Prediction of future reward is one of the key element in the theory of reinforcement learning[37,38]. Especially, the sum of the actual reward and the increase in the predicted future reward, which is called the `temporal difference (TD) signal,' is the main teaching signal for selection of actions as well as prediction of future reward. The change of response of the dopamine neurons in the course of learning turned out to be very similar to that of the TD signal in reinforcement learning.

This finding prompted proposals of reinforcement learning models of the basal ganglia[28-30,39-41], as summarized in Figure 2. Among the two compartments of the striatum, the striosome, which projects to nigral dopamine neurons, evaluates the state in a form of cumulative future reward. In the other compartment, the matrix, different groups of neurons evaluates the merits of possible actions. An action output is selected within the output pathways from the globus pallidus and the substantial nigra through the thalamus to the cerebral cortex. The TD error is represented by the nigral dopamine neurons based on limbic inputs about the actual reward and the striatal input about the predicted reward. It is fed back to cortico-striatal synapses for the learning of evaluation of states and actions. Such models have successfully replicated the learning of conditioning tasks as well as sequence learning tasks [39-41].

However, there still remain several issues to be clarified in the reinforcement learning hypothesis of the basal ganglia. First, it is not clear how the `temporal difference' of expected future reward is calculated in the circuit leading to the substantia nigra, although a few possible mechanisms have been suggested [28,36,40]. Recently, Brown and colleagues[42] proposed an alternative model in which two different pathways to dopamine neurons are responsible for acquisition of reward predictive response and inhibition of predicted reward response. They argued that their model better explains experimental data than the TD based models do.

Another open issue in TD based models is the plasticity of cortico-striatal synapses. The above reinforcement learning model predicts that there should be different plastic mechanisms for the striosome and the matrix, which are respectively involved in evaluation of current state and possible actions. Although it has been shown that cortico-striatal synaptic plasticity is strongly modulated by dopamine[43,44], it remains to be clarified whether there are different plastic mechanisms in different compartments.

Reward related activities have also been found in frontal cortices, including dorsolateral prefrontal cortex [45], orbitofrontal cortex [46], and cingulate cortex[47]. Dopaminergic neurons in the ventral tegmental area project to those cortical areas. What is the difference of reward processing in the cerebral cortex and the basal ganglia? A systematic comparison of the reward related activities in the orbitofrontal cortex, the striatum, and the dopamine neurons revealed the following characteristics [48]: the cortical neurons retain more information about sensory input; the striatal neurons show richer variety of activation in relation to task progress; the dopamine neurons respond mainly to unpredicted reward or sensory stimuli. This suggests that the cortex is responsible for analyzing sensory input, the striatum is involved in production of actions, and the dopamine neurons are most responsible for learning new behaviors.

Error-based learning in the cerebellum

The idea that the cerebellum is a supervised learning system dates back to the hypothesis by Marr[25] and Albus[26]. It was shown by Ito in vestibulo-ocular reflex (VOR) adaptation experiments [2,49] that the long-term depression of the Purkinje cell synapses depending on the climbing fiber input is the neural substrate of such error driven learning (Figure 3). Although it is still controversial whether the LTD in Purkinje cells is the only locus of plasticity and memory storage in VOR [50], recent results are in accordance with the cerebellar error-based learning hypothesis.

In ocular following response movement, Kobayashi and colleagues[51] showed that the response tuning of complex spikes is the mirror image of that of simple spikes[52]. This is in agreement with the hypothesis that the simple spike response of Purkinje cells are shaped by LTD of parallel fiber synapses with the error signal provided by the climbing fibers. They also showed that the modulation of simple spikes by complex spikes is too weak to be useful for real-time motor control.

Kitazawa et al. analyzed the information content of complex spikes in arm reaching movement in monkeys. The result showed that complex spike firing carries information about the target direction in early phase of the movement while it carries information about the end-point error near the end of the movement [53]. The coding of end-point error is consistent with LTD hypothesis. What is the role of the target related activity at the beginning of movement? The low probability of firing (less than one spike per trial) suggests that the signal may not be useful for on-line movement control. One possibility is that they are potential error signals that could be used for further improvement of the performance should there be any preceding sensory cues that enable movement preparation.

Collaboration of Learning Modules

In the above framework of `specialization by learning,' each organization is not specialized in *what* to do, but in *how* to learn it. Specific behaviors or functions can be realized by combination of multiple learning modules distributed among the basal ganglia, the cerebellum, and the cerebral cortex[23,24].

The use of internal models of the body and the environment can improve the performance of motor control[54,55]. Such internal models could be acquired by supervised learning with the motor command as the input and the sensory outcome as the teacher signal. Furthermore, for supervised or reinforcement leaning, it is often helpful to use unsupervised learning algorithms to extract the essential information in the raw sensory input. Such ways of combination of different learning modules could be helpful in exploring possible collaborations of the cerebellum, the basal ganglia, and the cerebral cortex[24]. Table 1 summarizes possible roles of the learning modules in the cerebellum, the basal ganglia, and the cerebral cortex.

In many brain imaging experiments, different parts of the cerebellum, the basal ganglia, and the cerebral cortex are activated simultaneously. The above hypotheses on the specialization by the frameworks of learning can provide us with a helpful hint as to the different roles of simultaneously activated brain areas. Below we review recent studies from the viewpoint of this learning-oriented specialization.

Eye movement

Recent experiments on saccadic eye movement have shown separate gain adaptation for different types of saccades, such as visually guided and memory guided [56]. A recent model by Gancarz and Grossberg[57] explained the mechanism for separate adaptation based on error-based learning of synaptic weights for multiple input pathways to the cerebellum.

Neurons in the caudate nucleus have been known to be activated in memory-guided saccades [58]. Recently, Kawagoe and colleagues performed delayed saccade experiments in which reward is given only in one of four possible saccade directions. Surprisingly, the direction tuning of caudate neurons were strongly modulated by the reward condition. In some neurons, direction tuning was sharper when the preferred direction coincided with the rewarded direction. In others, the preferred direction changed with the reward direction [59]. In a recent review article[60], Hikosaka et al. proposed a model on how different types of neuronal tuning could be realized due to modulation of striatal plasticity by dopaminergic input. Their study suggests that the basal ganglia associate spatial information from the cortex and the reward-related information from the midbrain dopaminergic neurons and thus take a key role in selecting goal-directed actions.

Arm reaching

It has been shown in arm reaching studies in monkeys that the cerebellum is involved in externally driven (e.g., visually guided) movement while the basal ganglia are involved in internally generated (e.g., memory guided) movement [61]. Recent recording and inactivation studies of motor thalamus [62,63] further confirmed this contrasting involvement. In the area X of thalamus, which receives input from the cerebellum and projects to the ventral premotor cortex [21], majority of neurons were selectively activated in visually triggered movements. On the other hand, in the nucleus VApc, which receives input from the basal ganglia and projects to the prefrontal cortex, majority of neurons were selective for internally generated movements.

What is the reason for such differential involvement? In visually guided movements, the most critical computation is coordinate transformation of visual input to corresponding motor output. Such mapping could be learned in a form of supervised learning in the cerebellum. In memory guided or internally generated movements, what is most critical is selection of an appropriate action and suppression of unnecessary actions, both of which require prediction of reward value.

Sequence learning

It has been shown in trial and error learning of sequential movement that cortico-basal ganglia loops are differentially involved in early and late stages of learning. Brain areas in the prefrontal loop (prefrontal cortex, preSMA, caudate head) are involved in learning new sequences, while those in the motor loop (SMA, putamen body) are involved in execution of well learned movements [64,65]. Why should the information about the sequence learned initially in the prefrontal loop be copied to the motor loop? We hypothesized that the two cortico-basal ganglia loops learn a sequence using different representations: visuospatial coordinate in the prefrontal loop and motor coordinate in the motor loop[66]. A reinforcement learning model of sequence learning based on this hypothesis could replicate many experimental findings, for example, time course of learning, performance for modified sequences, and the results of lesion experiments[41]. In a recent psychophysical experiment motivated by this hypothesis, it was confirmed in a sequential key-press task that human subjects depend gradually more on body-specific representation than on visual representation with the progress of learning [67].

While the use of different learning algorithms is associated with differential involvement of the cerebellum, the basal ganglia, and the cerebral cortex, the use of different representations is associated with differential involvement of different channels in cortico-basal ganglia loops and cortico-cerebellar loops.

Timing and rhythm

In a series of imaging studies by Sakai and colleagues [68][69], it was shown that the memory of simple rhythms involves anterior cerebellum, while memory of complex rhythms and adjustment of movement timing to irregular external triggers involve the posterior cerebellum. A possible reason for such differential involvement is the use of different representations [66]. The anterior cerebellum can provide internal models of body dynamics, which can be helpful in prediction of regular timing as well as in controlling detailed movement parameters. The posterior cerebellum may provide internal models for prediction of sensory events, which may be useful in timing perception and adjustment.

Cognitive processing

Involvement of the basal ganglia and the cerebellum in cognitive functions once was a controversial issue[14,70]. However, now there are abundant brain imaging data showing their involvement in mental imagery[5,6], sensory discrimination[7-9], planning[10-12], attention[13], and language[14-17]. Careful studies of cerebellar and basal ganglia patients have also revealed that their impairments are not limited to motor control but also extend to cognitive functions [21,71,72]. Lesion studies in rodents also suggest the involvement of the basal ganglia in rule based learning [73] and spatial navigation [74].

In a recent PET study, Dagher and colleagues used the Tower of London task and found that the activity of the caudate nucleus as well as the premotor and prefrontal cortices are correlated with the task complexity [11]. This suggests that the cortico-basal ganglia loops may be involved in multi-step planning of actions.

Conclusion

A new hypothesis on the specialization of brain structures based on learning paradigms provides helpful clues as to the differential roles of the basal ganglia and the cerebellum. The frontal cortex has been regarded as the site of high-level information processing because of their activity related to working memory, action planning, and decision making. However, what has been found in the cerebral cortex could be just the tip of an iceberg. The activities of the cortical neurons could be the results of recurrent dynamics of the cortico-basal ganglia and cortico-cerebellar loops. An important role of the cerebral cortex is to provide common representations on which both the basal ganglia and the cerebellum can work together. Unsupervised learning of the cerebral cortex may also be the foundation of building modular organization in which learning modules in the basal ganglia and the cerebellum are flexibly combined.

Figures

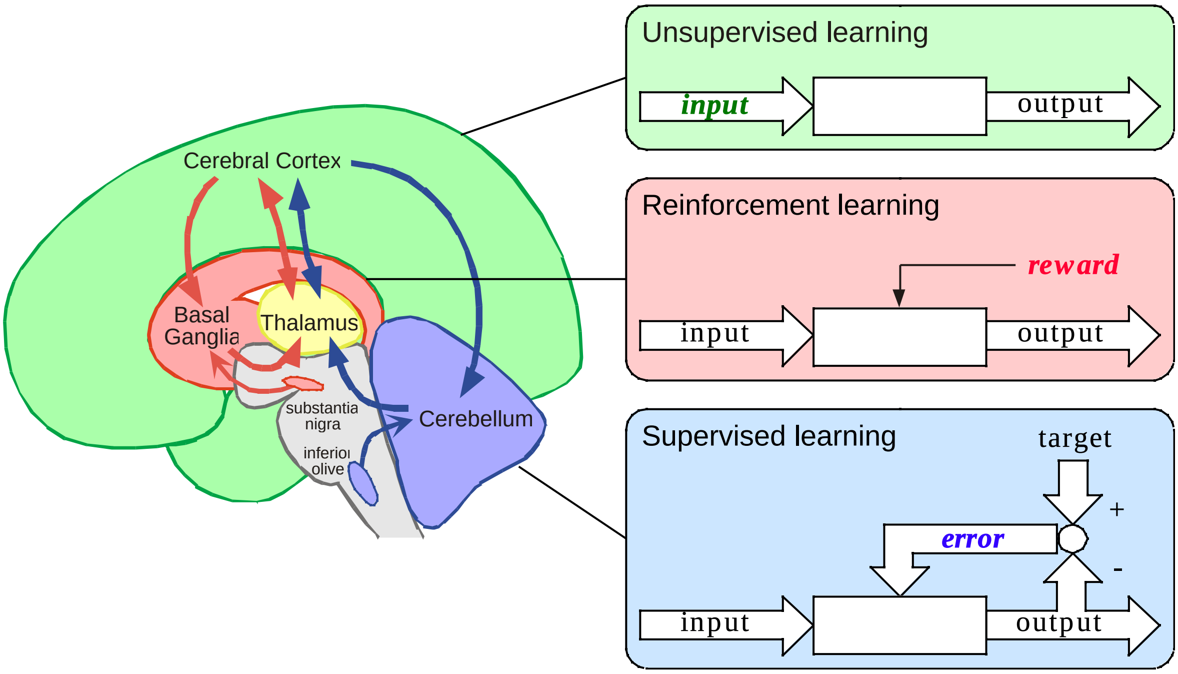

Figure 1:

In *supervised learning*, a detailed target output is given for each input and the goal of learning is to minimize the error signal. In *reinforcement learning*, no explicit target output is given, but a scalar reward signal is given that notifies how good or bad the output (or a sequence of outputs) was. In *unsupervised learning*, no target or reward signal is given and the output is determined to best represent the statistical features in the input.

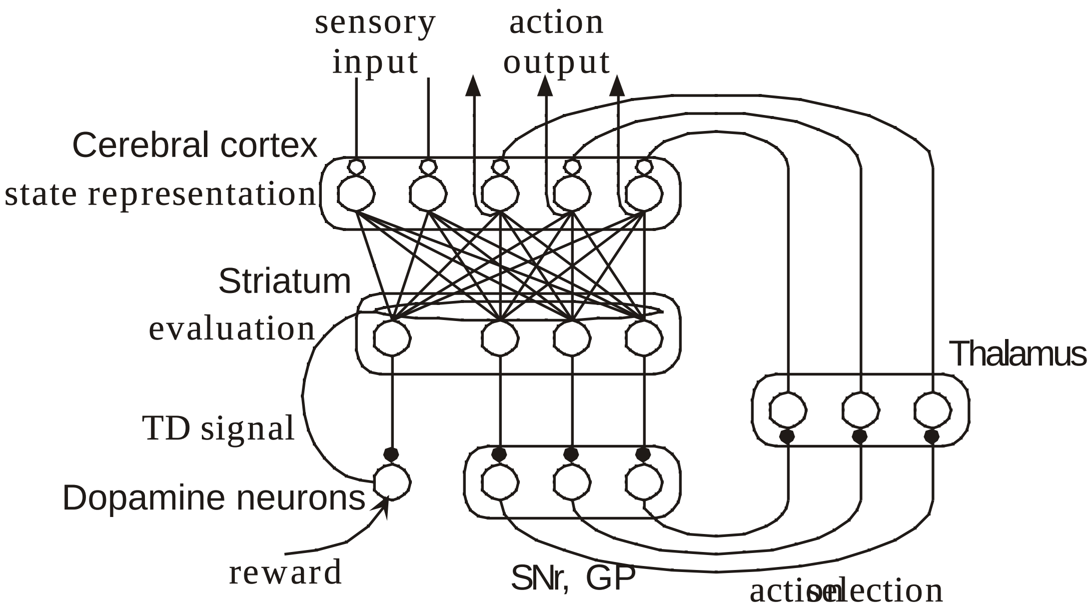

Figure 2:

A schematic diagram of the cortico-basal ganglia loop and the possible roles of its components in a reinforcement learning model. The neurons in the striatum predict the future reward for the current state and the possible actions. The error in the prediction of future reward, the TD error, is encoded in the activity of dopamine neurons and is used for the learning of cortico-striatal synapses. One of the candidate actions is selected in the pathway through SNr and GP to the thalamus and the cerebral cortex as a result of competition of predicted future rewards. SNr: substantia nigra, pars reticulata, GP: globus pallidus. The direct and indirect pathways within the globus pallidus are omitted for simplicity.

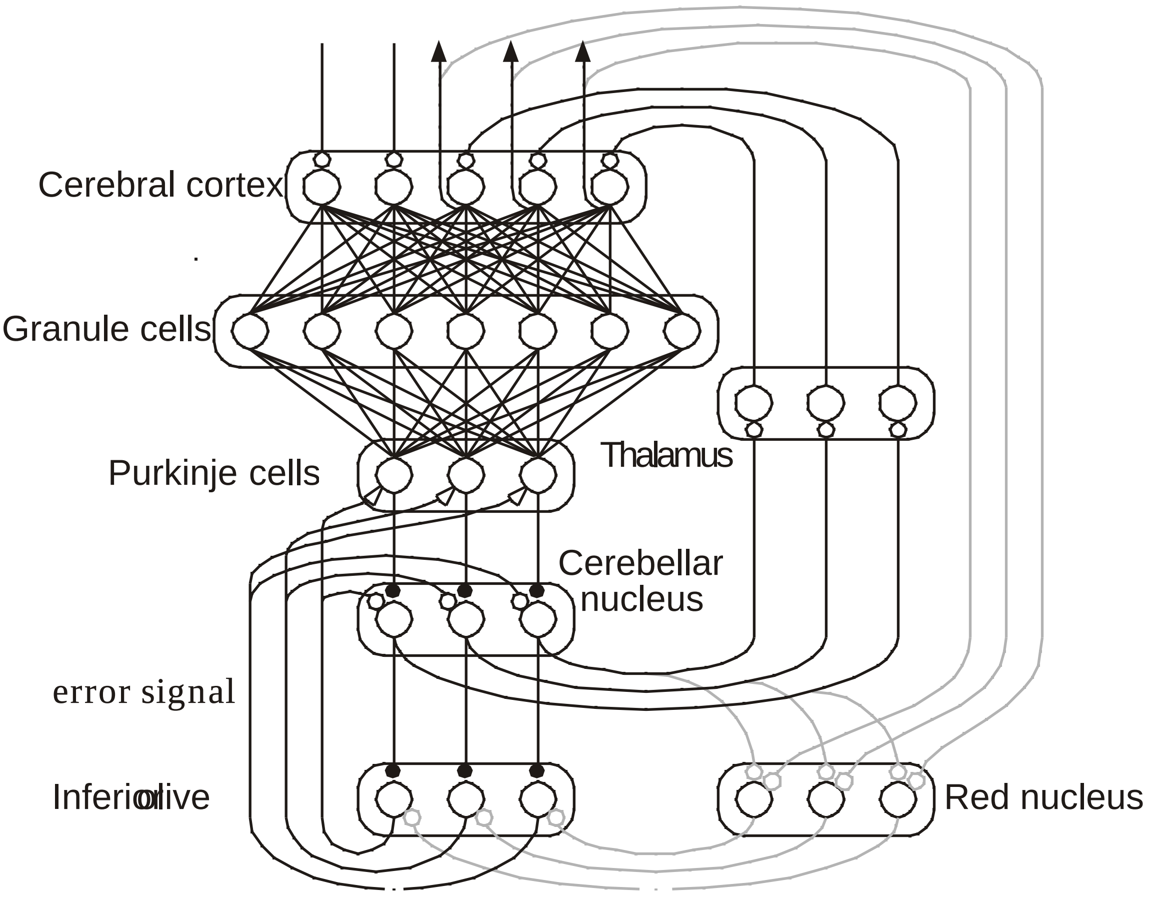

Figure 3:

A schematic diagram of the cortico-cerebellar loop. In a supervised learning model of the cerebellum, the climbing fibers from the inferior olive provides the error signal for the Purkinje cells. Coincident inputs from the inferior olive and the granule cells result in a long-term depression (LTD) of the granule-to-Purkinje synapses.

Table 1:

Possible roles of different learning modules.

1) Cerebellum: Supervised learning
    a) internal models of the body and the environment.
    b) replication of arbitrary input-output mapping that was learned elsewhere in the brain.
2) Basal ganglia: Reinforcement learning
    a) evaluation of current situation by prediction of reward.
    b) selection of appropriate action by evaluation of candidate actions.
3) Cerebral cortex: Unsupervised learning
    a) concise representation of sensory state, context, and action.
    b) finding appropriate modular architecture for a given task.

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