

Voluntary Movement: Control, Learning and Memory

J Houk, Northwestern University Medical School, Chicago, IL, USA

© 2010 Elsevier Ltd. All rights reserved.

Glossary

Attractor networks – Recurrent networks with persistent states toward which the activity state of the network is attracted; persistent states are called fixed points.

Composite action command – Command refers to the output of a motor area, action commands include commands for plans and commands for movements, and a composite command generated by a mesoscopic module refers to a set of elemental commands generated by microscopic modules.

Distributed processing module (DPM) – One motor area together with its subcortical loops through the basal ganglia and through the cerebellum forms a distributed processing module.

Microscopic versus mesoscopic modules – DPMs are mesoscopic modules because they are composed of sets of microscopic modules; the microscopic modules have essentially the same computational architecture as do mesoscopic modules.

Training signal – For supervised learning the training signal specifies how the network can improve its response whereas for reinforcement learning the training signal simply evaluates whether performance is better (reward) or worse (punishment) than previously.

Motor programs involve both the planning and the execution of movements. For voluntary movements of the limbs, these functions are distributed among several cortical motor areas. Generally speaking, planning operations are controlled by premotor areas (PMs in [Figure 1](#)) whereas execution is controlled by the primary motor cortex (M1 in [Figure 1](#)). Although not specifically illustrated in [Figure 1](#), each of these motor areas is regulated by relatively private subcortical loops through the basal ganglia (BG) and the cerebellum (CB). These subcortical loops are specialized for learning from training signals. In contrast, the cortical motor areas are specialized for learning from practice.

Cellular and molecular processes at specific synaptic sites underlie the learning and memory of motor programs. Learning modifies the weights of specific synaptic inputs to specific neurons and the persistence of these weight changes represents one form of memory. Migration is a process that transfers memories from

synapses at one site in the brain to synapses at other sites. For example, during practice of a particular program, planning operations tend to migrate from subcortical sites to cortical sites and then from PM areas of the cortex to M1. These migrations permit more rapid and accurate implementation of automatic movements. Neural signals returning from subcortical loops regulate the process of migration.

The learning rules that mediate synaptic plasticity at different sites in the brain differ (see [Table 1](#) for a summary of the sites highlighted in this article). In the cerebral cortex, plasticity at excitatory synapses onto pyramidal cells utilizes a Hebb-like rule for the detection of coincidence between input and output. In the BG, plasticity at spiny neuron synapses from cortical afferents uses a trace of coincidence detection that is trained by reward signals; this learning rule is called reinforcement learning. In the cerebellum, plasticity at Purkinje cell synapses formed by parallel fiber afferents also uses a trace of coincidence detection, but in this case depressions in synaptic weight are trained (instantiated) by errors in performance; the learning rule is akin to supervised learning. Diffuse synaptic inputs modulate the above learning rules; they function as permissive factors that gate the intensity of learning. Distributed processing modules composed of one area of cerebral cortex, together with its loops through the BG and cerebellum, benefit from all of these mechanisms operating in combination. In this article, motor learning in the cerebral cortex, the BG, and the cerebellum are each treated individually; following this, the benefits of coordinated learning in entire distributed processing modules (DPMs) are discussed.

Hebbian Learning of Motor Programs in Cortical Motor Areas

The learning of motor skills over extended periods of practice results in enlargement of motor and sensory representations in the cerebral cortex. Initial learning relies on long-term potentiation (LTP); this Hebbian learning rule enhances the strength of synapses that participate in practice. Projections from the BG and the cerebellum force their targeted cortical neurons to practice particular firing patterns until more direct inputs from other cortical areas are strengthened enough to generate similar firing patterns without guidance from the BG and/or cerebellum. Cholinergic neuromodulatory

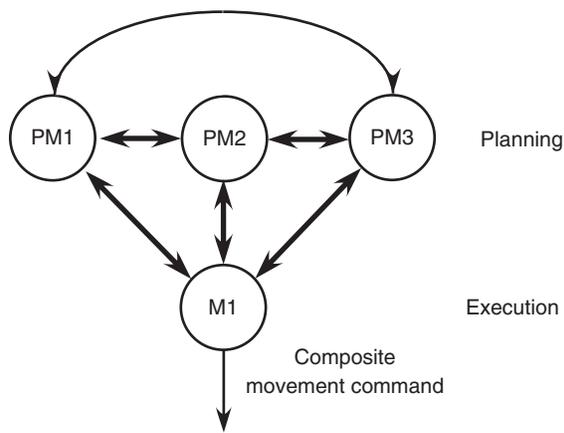


Figure 1 Cortical motor areas. M1 = primary motor cortex; PM1 = premotor area 1; PM2 = premotor area 2; PM3 = premotor area 3.

input from the nucleus basalis is a permissive factor related to attention. It permits the consolidation of cortical memories through synaptogenesis and cyto-genesis. This scenario is especially important for crystallizing automatic movements.

BG Loops for the Selection of Ballpark Motor Programs

The cortical motor system's loops through the BG learn to regulate the selection of motor plans and movement commands – operations collectively referred to as action selection. The learning rule given in Table 1 includes both coincidence detection, as in the cortex, and also training information transmitted by dopamine neurons. Brief bursts of dopamine-neuron firing signal the likelihood of future reward; these neural signals serve well as training signals for reinforcement learning. Next, we consider just what is being learned and why it is a difficult learning problem. The left side of Figure 2 is a simplified schematic of one mesoscopic loop through the BG; it is comprised of thousands of microscopic loops originating from the same area of the cerebral cortex.

We discuss the coarse selection of a ballpark action since a small set of potential actions is selected rather than

an individual action. This imprecision results from cortex-to-striatum connections: any given spiny neuron (in the input stage of BG, called the striatum) receives a very large array of afferents from neurons in the cerebral cortex. Among several areas sending inputs, one forms a recurrent loop or module. Neighboring spiny neurons representing alternative actions thus receive a very similar, but slightly different, array of potential inputs. Spiny neurons compete with each other via prominent recurrent collaterals of their inhibitory γ -aminobutyric acid (GABA)ergic axons; the winners of this competition transmit their decisions to the next stage of BG processing. This pattern-classification operation by spiny neurons effectively decides on the relative merits of alternative actions based on the synaptic weights of its cortical inputs. These cortical–striatal synapses are trained by the dopamine input that signals the likelihood of future reward. Dopamine signals also function as a permissive factor that enhances the excitability of activated spiny neurons. The result is a powerful pattern classification operation that selects ballpark actions from thousands of alternative actions.

How do the inhibitory GABAergic outputs from selected spiny neurons instantiate their coarse decisions? This question is complicated by multiple stages of inhibition and by the presence of multiple pathways through the BG. Direct pathways learn to select context-dependent desired actions by disinhibiting positive feedback loops between the thalamus and cortex. These operations yield bursts of output from selected cortical neurons. Indirect pathways are tuned to deselect undesired actions by disinhibiting BG output neurons so that they can inhibit activity in inappropriate loops between the thalamus and cortical neurons.

To summarize, a large array of spiny neurons in the striatum receives a diverse convergent input from the area of the cerebral cortex that participates in any given mesoscopic loop. The array of spiny neurons performs a pattern-classification operation that is made competitive by the presence of collateral inhibition. Competition is biophysically mediated by both presynaptic and postsynaptic collaterals of the GABAergic spiny neurons. The superior performance of the presynaptic inhibitory mechanism appears to be augmented in phylogeny, and

Table 1 Different learning rules in the cerebral cortex, basal ganglia, and cerebellum

<i>Brain site</i>	<i>Cerebral cortex</i>	<i>Basal ganglia striatum</i>	<i>Cerebellar cortex</i>
<i>Cellular Site</i>	Excitatory afferents Onto pyramidal cells	Cortical afferents Onto spiny neurons	Parallel fibers Onto Purkinje cells
<i>Learning rule</i>	<i>Hebbian</i>	<i>Reinforcement</i>	<i>'Supervised'</i>
<i>Operation</i>	Coincidence	Coincidence • reward	Coincidence • error
<i>Permissive factors</i>	Cholinergic+	Dopaminergic+	Noradrenergic+

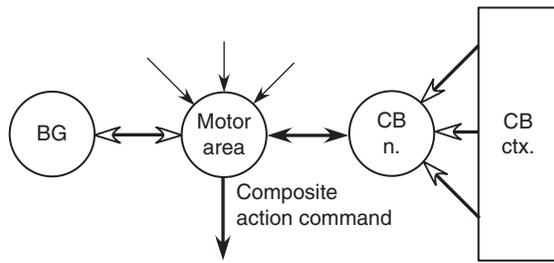


Figure 2 Subcortical loops. BG = basal ganglia; CB n. = cerebellar nucleus; CB ctx. = cerebellar cortex.

its occasional disruption associated with unfavorable epigenetic expression might help to explain schizophrenia. The selection of potential actions (by individual microscopic loops) from thousands of alternative actions is a very difficult pattern-classification task, which probably explains why it typically yields only a coarse selection of ballpark actions. The amplification and refinement of these ballpark actions into a precise action is attributed to the loop through the cerebellum.

Cerebellar Loops for the Amplification and Refinement of Motor Programs

The motor system's loops through the cerebellum (right side of **Figure 2**) are needed to amplify and refine potential action – ones that are promoted by synaptic input from other areas of the cerebral cortex and selected by loops through the BG. Amplification is mediated by positive feedback in an array of microscopic loops between a given area of the cerebral cortex and the corresponding division of a cerebellar nucleus. These loops form attractor networks that facilitate the planning and execution of motor programs. Purkinje cells in the cerebellar cortex control the fixed points of these attractor networks and, in doing so, create spatiotemporal patterns of cortical output that represent refined motor plans and motor commands. Sets of microscopic loops between primary motor cortex and cerebellum are forced by Purkinje cell inhibition to coordinate their activities in order to command movement at a selected velocity to a desired endpoint in space and time. The complete array of microscopic loops forms the composite action command for any given mesoscopic loop. The loops with the cortex thus generate composite motor plans and movement commands that control accurate movements.

Motor learning in Purkinje cells is guided by error-driven feedback from climbing fibers. These training signals signify punishment when an error is made. They instantiate long-term depression (LTD) – the 'supervised' form of learning in the cerebellum (**Table 1**). If, for example, a movement stops short of the target, a

corrective movement toward the target fires climbing fibers. LTD is then instantiated, and this delays the time at which Purkinje cells fire to terminate the next movement in the same direction. As a permissive factor, noradrenergic fiber discharge has two modes of action. Phasic discharge signals good outcomes and helps to consolidate LTD. Tonic discharge signals poor outcome and facilitates alternative actions. Another permissive factor, serotonergic discharge, signals the opposite of urgency; thus, pauses in discharge facilitate faster actions.

To summarize, composite action commands are initiated in loops through the cerebellar nucleus (CB n. in **Figure 2**), and they are then shaped and ultimately are terminated by prominent inhibitory input from the cerebellar cortex (CB ctx.). Arrays of Purkinje cells learn to detect input patterns signifying that the time has come to terminate elements of action plans and/or movement commands. Microscopic loops generate elemental commands and mesoscopic loops generate the several composite action commands in different motor areas. The overall result is a well-coordinated and precise composite movement command.

Coordination of Eyeblink Conditioning

Eyeblink conditioning is given special treatment here, since so much is known about how the cerebellum participates in the generation of eyeblink motor commands. The core of **Figure 3** is the same as **Figure 2**, except that the 'red' nucleus replaces the general label 'motor area' because it constitutes the main output for conditioned reflex (CR) motor commands. Conditioned stimulus (CS) signifies all of the variety of sensory inputs that can be used by the other four structures. The brainstem circuitry that mediates an unconditioned response (UR)

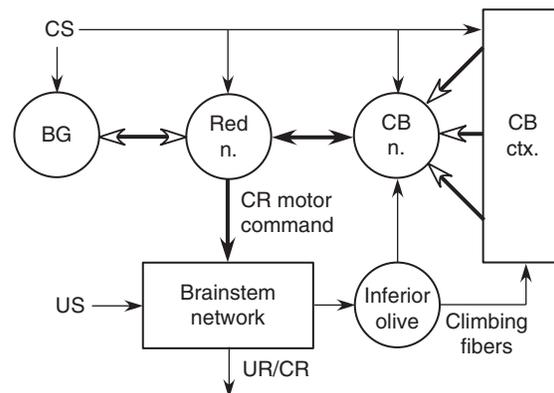


Figure 3 Eyeblink conditioning. BG = basal ganglia; CB n. = cerebellar nucleus; CB ctx. = cerebellar cortex; CR = conditioned reflex; CS = conditioned stimulus; Red n. = red nucleus; UR = unconditioned reflex; US = unconditioned stimulus.

to an unconditioned stimulus (US) and sends climbing-fiber input to CB cortex is shown at the bottom. This network also generates a CR in response to a CR motor command.

Much of the research in this field has focused on the association between a CS and the initiation of the eyeblink CR. While the BG is likely to be crucial in the discovery of potential stimuli that might fulfill a CS role, until recently the emphasis has been on where the associative link is actually made with the cerebellar circuitry that is required for CR responding. The most prominent link appears to be formed at CS synapses onto neurons in a CB nucleus – the interpositus nucleus. Once formed, this associative link is responsible for initiating positive feedback in the reciprocal loop between the red nucleus and the cerebellar nucleus. This loop forms CB modules that are analogous to the CB modules formed with motor cortex. The CB cortex then refines the amplitude and timing of the CR motor command so that it closes the eyelid in time to protect the cornea from the US.

Note that synapses at any site along the reciprocal pathway between the red nucleus and CB nucleus can fulfill the associative role ascribed to the interpositus nucleus for CRs. Viewed in this manner, eyeblink conditioning provides an excellent model system for studying learning mechanisms for motor control. The learning rule in the loop between CB nucleus and red nucleus is Hebbian as in the cerebral cortex, whereas the learning rule in CB cortex is supervised.

Coordinated Operation of DPMs

All of the operations outlined above occur in parallel in our brain, resulting in a high level of performance. Sensory and other inputs to the cerebral cortex begin the process of initiating actions. Inputs from BG regulate this process through the selection of ballpark actions and reinforcement learning that homes in on promising actions. Once competitive interactions within BG produce a 'winner,' that tentative action is selected and loops through cerebellum amplify and refine it into a precise composite action. Training signals from climbing fibers allow the cerebellum to optimize the action, permitting us to hit a desired endpoint with precision in both space and time. As the motor areas of the cerebral cortex practice controlling these actions, their signal-processing activities become consolidated into long-term memories, and eventually even the most elegant of actions becomes almost automatic.

Note that many factors influence motor learning. One can think of these diverse factors as different constraints on the evolutionary process that fine-tunes the

mechanisms used by the motor system. Since we live in an uncertain world, any given action may have many possible outcomes. Decision theory provides an approach to motor learning and control that can yield compact assessments of outcomes. Combining the various types of knowledge outlined in this article should help us to fathom the complexity of motor control and learning.

See also: Behavioral Planning: Neurophysiological Approach of the Frontal Lobe Function in Primates; Motor Function and Motivation; Motor Learning in the Vestibulo-Ocular Reflex.

Further Reading

- Aston-Jones G and Cohen JD (2005) Adaptive gain and the role of the locus coeruleus–norepinephrine system in optimal performance. *Journal of Comparative Neurology* 493(1): 99–110.
- Blake DT, Byl NN, and Merzenich MM (2002) Representation of the hand in the cerebral cortex. *Behavioural Brain Research* 135(1–2): 179–184.
- Christian KM and Thompson RF (2003) Neural substrates of eyeblink conditioning: Acquisition and retention. *Learning and Memory* 10(6): 427–455.
- Doya K (1999) What are the computations of the cerebellum, the basal ganglia and the cerebral cortex? *Neural Networks* 12(7–8): 961–974.
- Flores LC and Disterhoft JF (2009) Caudate nucleus is critically involved in trace eyeblink conditioning. *J. Neuroscience* 29(46): 14511–14520.
- Houk J and Mugnaini E (2003) Cerebellum. In: Squire LR, Bloom FE, Roberts JL, and McConnell SK (eds.) *Fundamental Neuroscience*, 2nd edn., ch. 32, pp. 841–872. New York: Academic Press.
- Houk JC (2005) Agents of the mind. *Biological Cybernetics* 92: 427–437.
- Houk JC (2007) Models of basal ganglia. *Scholarpedia* 2(10): 1633.
- Houk JC (2010) Action Selection and Refinement in Subcortical Loops Through Basal Ganglia and Cerebellum. In: Seth AK, Bryson J, and Prescott TJ (eds.) *Modelling Natural Action Selection*. Cambridge: Cambridge University Press.
- Houk JC, Bastianen C, Fansler D, et al. (2007) Action selection and refinement in subcortical loops through basal ganglia and cerebellum. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences* 362(1485): 1573–1583.
- Houk JC and Wise SP (1995) Distributed modular architectures linking basal ganglia, cerebellum, and cerebral cortex: Their role in planning and controlling action. *Cerebral Cortex* 5(2): 95–110.
- Kording K (2007) Decision theory: What "should" the nervous system do? *Science* 318(5850): 606–610.
- Lavond DG (2002) Role of the nuclei in eyeblink conditioning. *Annals of the New York Academy of Sciences* 978: 93–105.
- Matsuzaka Y, Picard N, and Strick PL (2007) Skill representation in the primary motor cortex after long-term practice. *Journal of Neurophysiology* 97(2): 1819–1832.
- Merzenich M, Wright B, Jenkins W, Xerri C, Byl N, Miller S, and Tallal P (1996) Cortical plasticity underlying perceptual, motor, and cognitive skill development: Implications for neurorehabilitation. *Cold Spring Harbor Symposia on Quantitative Biology* 61: 1–8.
- Middleton FA and Strick PL (2000) Basal ganglia and cerebellar loops: Motor and cognitive circuits. *Brain Research. Brain Research Reviews* 31(2–3): 236–250.
- Redgrave P (2007) Basal ganglia. *Scholarpedia* 2(6): 1825.
- Wang J, Dam G, Yildirim S, Rand W, Wilensky U, and Houk JC (2008) Reciprocity between the cerebellum and the cerebral cortex: Nonlinear dynamics in microscopic modules. *Complexity* 14(2): 29–45.