The role of Basal Ganglia and Cerebellum in Motor Learning: A Computational Model

Ing. Rosa Senatore

Dottorato in Ingegneria dell'Informazione X ciclo N.S.

Abstract

Our research activity investigates the computational processes underlying the execution of complex sequences of movements and aims at understanding how different levels of the nervous system interact and contribute to the gradual improvement of motor performance during learning.
Many research areas, from neuroscience to engineering, investigate, from different perspectives and for diverse purposes, the processes that allow humans to efficiently perform skilled movements.
From a biological point of view, the execution of voluntary movements requires the interaction between nervous and musculoskeletal systems, involving several areas, from the higher cortical centers to motor circuits in the spinal cord.
Understanding these interactions could provide important insights for many research fields, from machine learning to medicine, from the design of robotic limbs to the development of new treatments for movement disorders, such as Parkinson's disease.
This goal could be achieved by finding an answer to the following questions:

- How does the central nervous system control and coordinate natural voluntary movements?
- Which brain areas are involved in learning a new motor skill? What are the changes that happen in these neural structures? What are the aspects of the movement memorized?
- Which is the process that allows people to perform a skilled task, such as playing an instrument, being apparently unaware of the movements they are performing?
- What happen when a neurodegenerative disease affects the brain areas involved in executing movements?

These questions have been addressed from different perspectives and levels of analysis, from the exploration of the anatomical structure of the neural systems thought to be involved in motor learning (such as the basal ganglia, cerebellum and hippocampus) to the investigation of their neural interaction; from the analysis of the activation of these systems in executing a motor task to the specific activation of a single or a small group of neurons within them. In seeking to understand all the breadth and facets of motor learning, many researchers have used different approaches and methods, such as genetic analysis, neuroimaging techniques (such as fMRI, PET and EEG), animal models and clinical treatments (e.g. drugs administration and brain stimulation).
These studies have provided a large body of knowledge that has led to several theories related to the role of the central nervous system in controlling and learning simple and complex movements.
These theories envisage the interaction among multiple brain regions, whose cooperation leads to the execution of skilled movements.
How can we test these interactions for the purpose of evaluating a theory?

Our answer to this question is investigating these interactions through computational models, which provide a valuable complement to the experimental brain research, especially in evaluating the interactions within and among multiple neural systems.
Based on these concepts arises our research, which addresses the questions previously pointed out and aims at understanding the computational processes performed by two neural circuits, the Basal Ganglia and Cerebellum, in motor learning.
We propose a new hypothesis about the neural processes occurring during acquisition and retention of novel motor skills.
According to our hypothesis, a sequence of movements is stored in the nervous system in the form of a spatial sequence of points (composing the trajectory plan associated to the motor sequence) and a sequence of motor commands.
We propose that learning novel motor skills requires two phases, in which two different processes take place.
Early in learning, when movements are slower, less accurate, and attention demanding, the motor sequence is performed by converting the sequence of target points into the appropriate sequence of motor commands. During this phase, the trajectory plan is acquired and the movements rely on the information provided by the visuo-proprioceptive feedback, which allows to correct the sequence of movements so that the actual trajectory plan corresponds to the desired one and the lowest energy is spent by the muscular subsystem involved.
During the late learning phase, when the sequence of movements is performed faster and automatically, with little or no cognitive resources needed to complete it, and is characterized by anticipatory movements, the sequence of motor commands is acquired and thus, the sequence of movements comes to be executed as a single behavior.
We suggest that the Basal Ganglia and Cerebellum are involved in learning novel motor sequences, although their role is crucial in different stages of learning.
Accordingly, we propose a neural scheme for procedural motor learning, comprising the basal ganglia, cerebellum and cortex, which envisages that the basal ganglia, interacting with the cortex, select the sequence of target points to reach (composing the trajectory plan), whereas the cerebellum, interacting with the cortex, is responsible for converting the trajectory plan into the appropriate sequence of motor commands.
Consequently, we suggest that early in learning, task performance is more dependent on the procedural knowledge maintained by the cortex-basal ganglia system, while after a long-term practice, when the sequence of motor commands is acquired within the cerebellum, task performance is more dependent on the motor command sequence maintained by the cortex-cerebellar system.
We tested the neural scheme (and the hypothesis behind it) through a computational model that incorporates the key anatomical, physiological and biological features of these brain areas in an integrated functional network.
Analyzing the behavior of the network in learning novel motor tasks and executing well-known motor tasks, both in terms of the neural activations and motor response provided, we found that the results obtained fit those reported by many neuroimaging and experimental studies presented in the literature.
We also carried out further experiments, simulating neurodegenerative disorders (Parkinson's and Huntington disease, which affect the basal ganglia) and cerebellar damages. Results obtained by

these experiments validates the proposed hypothesis, showing that the basal ganglia play a key role during the early stage of learning, whereas the cerebellum is crucial for motor skill retention.

Our model provides some insights about the learning mechanisms occurring within the cerebellum and gains further understanding of the functional dynamics of information processing within the basal ganglia and cerebellum in normal as well as in diseased brains. Therefore the model provides novel predictions about the role of basal ganglia and cerebellum in motor learning, motivating further investigations of their interactions.