Motor Adaptation

By Natalie Frederick, Carmen Lin, Jordan Manes, and Kristen Warren
Adapted from previous lesson plan by Jessica Wilson, Nelly Papalambros, Natalia Sanchez, and Laura Shanahan

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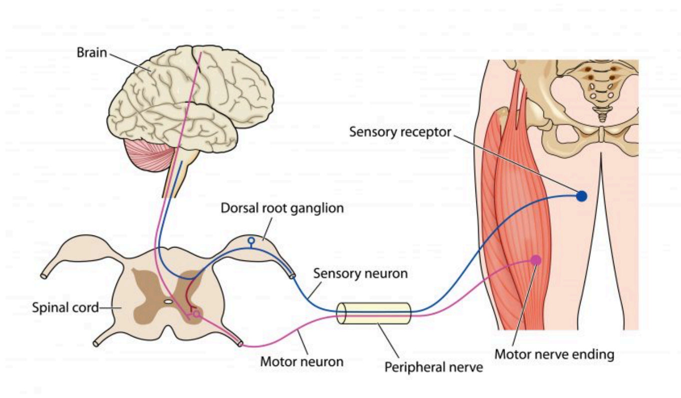
Objectives

1. Understand the basic components of the motor system and how motor information is conveyed from the brain to the body
2. Understand the basic circuitry of the basal ganglia and cerebellum
3. Understand how the brain can adapt its motor responses with feedforward and feedback control

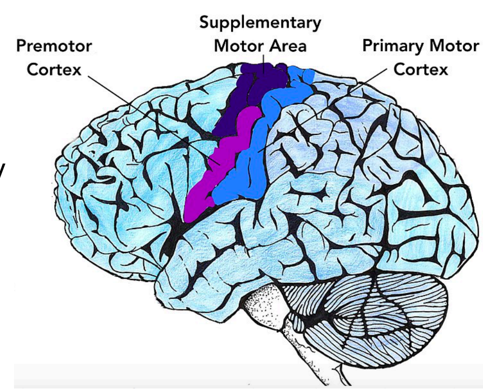
Background Information

Movement is a fundamental aspect of our everyday lives, allowing us to navigate our surroundings, communicate with others, and interact with the world. The motor system is responsible for generating and controlling our movements by enabling coordinated muscle activity through a complex network of neural circuits. It spans multiple levels of the nervous system, from the brain and spinal cord to the peripheral nerves and muscles. By integrating sensory feedback and internal predictions, the motor system ensures smooth, adaptive, and goal-directed actions.

The motor system is made up of three main components: the brain, the spinal cord, and the muscles. The brain acts as the command center to plan and generate voluntary movements. Motor regions in the brain send projections through the spinal cord where those signals can be sent to the muscles. The muscles carry out movement by converting the neural signals into muscle contractions, allowing us to perform everything from simple reflexes to complex, precise actions.

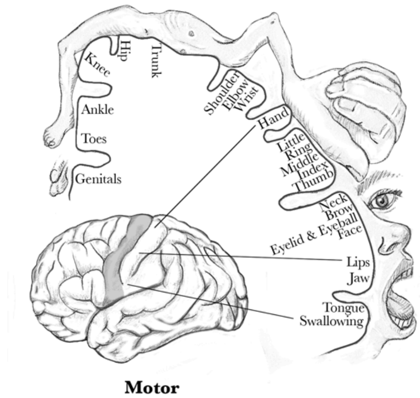


The motor cortex. The brain contains several key regions that work together to control and refine movement. The primary motor cortex is the executive controller of movement, responsible for initiating voluntary movement. It creates the signal to tell the body when to move, what muscles to move, and how exactly to move those muscles. This region contains the largest neurons in the brain, called Betz cells! Anterior to the primary

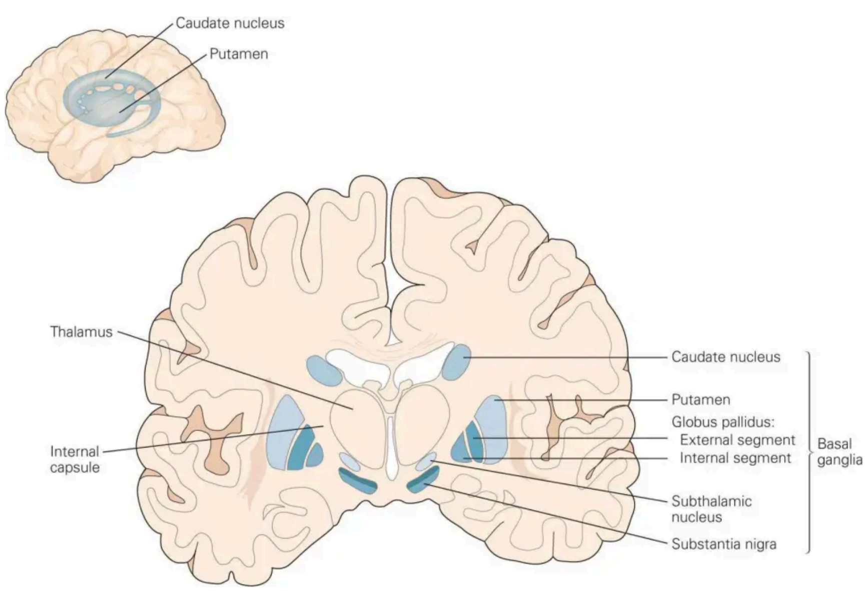


motor cortex is the premotor cortex and the supplementary motor area. The premotor cortex helps to plan and prepare movements, especially in response to external cues, while the supplementary motor area is involved in coordinating complex movements sequences.

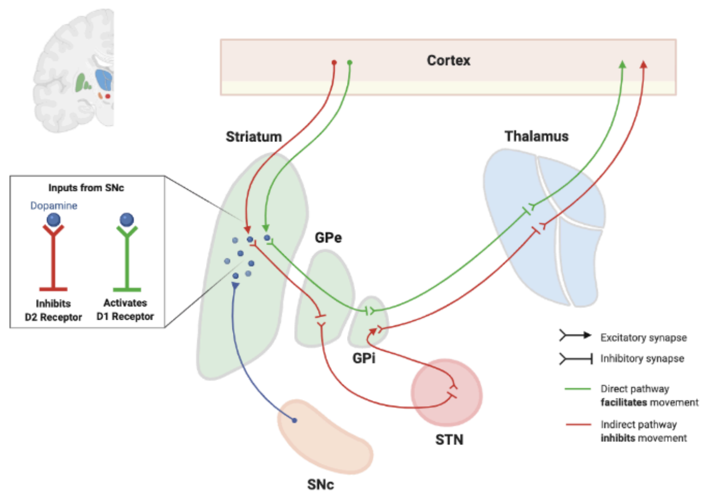
The primary motor cortex has a topographic representation of the body parts. That is, each body part "maps" onto different areas of the primary motor cortex. Scientists have visualized this map as a homunculus (Latin for "little man"), showing how much brain space is dedicated to controlling each body part. You can see that regions requiring fine motor control, like the hands, fingers, and face, have a lot of brain tissue in order to carry out these movements. In contrast, body parts involved in more basic movements, like the torso or legs, occupy smaller amounts of the brain. This organization of the primary motor cortex highlights the brain's prioritization of precise, dexterous movements essential for activities like speaking, writing, and manipulating objects.



<u>The basal ganglia.</u> The basal ganglia are a group of interconnected brain structures that play a critical role in movement control, motor learning, and habit formation. They help refine voluntary movements by filtering out unwanted motions and ensuring smooth, coordinated actions. There are many brain structures that are part of the basal ganglia network. These include the caudate, putamen, substantia nigra pars compacta, substantia nigra pars reticulata, globus pallidus internal segment, globus pallidus external segment, subthalamic nuclei, thalamus, and cortex.



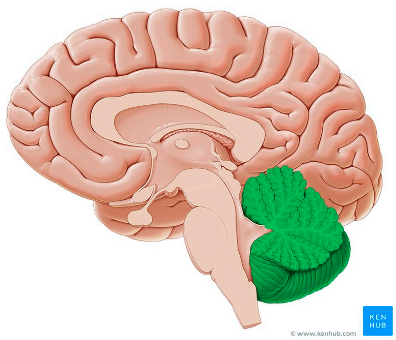
The regions of the basal ganglia are connected in an intricate way to form two main pathways: the direct pathway and the indirect pathway. The direct pathway provides a “Go” signal and promotes movement, while the indirect pathway provides a “Don’t go” signal and inhibits movement. These pathways work together to maintain balance between movement initiation and suppression, ensuring smooth and controlled actions. The diagram highlights these two pathways between the regions, with the direct pathway in green and the indirect pathway in red.

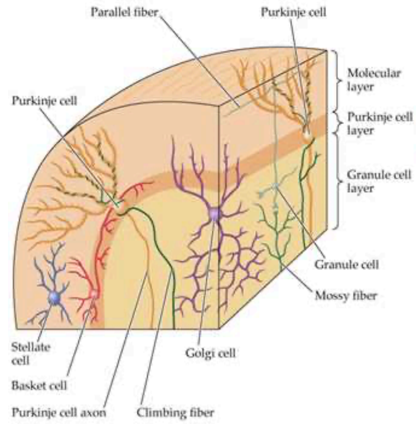


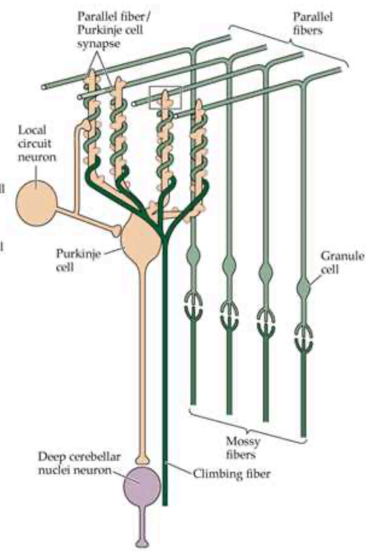
Also shown in the diagram are dopamine inputs from the substantia nigra pars compacta (SNc). Dopamine, one of the brain’s neurotransmitters, plays a key role in the basal ganglia circuitry and can change its neural activity. Dopamine acts on its receptors in the striatum to excite the direct pathway and inhibit the indirect pathway. Together, this further facilitates movement!

Disruptions in the basal ganglia system can lead to movement disorders like Parkinson’s disease (PD) and Huntinton’s disease (HD). PD is the second most common movement disorder in the United States. It is characterized by a decrease in spontaneous movements, gait difficulty, problems initiating movement, postural instability, rigidity, and tremor. In PD, the dopamine-producing neurons in the SNc die. Without dopamine, activity in the direct pathway is reduced and activity in the indirect pathway is increased, making movement initiation difficult. On the other hand, HD is a genetic disorder. As opposed to patients with PD, HD patients begin with impairments in their indirect pathway function, leading to excessive, involuntary movements. As the disease progresses, the direct pathway eventually loses function, and patients can no longer move.

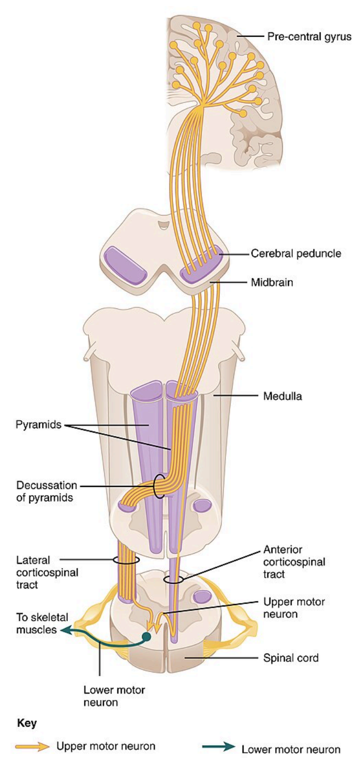
The cerebellum. The cerebellum (Latin for “little brain”), plays a crucial role in coordinating movement, maintaining balance, and refining motor control. Located in the back of the brain, this region contains over 50% of all the brain’s neurons. The neural circuitry of the cerebellum is complex, but its ability to fine tune movements relies on its highly organized circuitry. The cells in the cerebellum receive sensory input from the body and compare intended movements with actual performance, making real-time adjustments to ensure smooth and precise actions. This process helps with motor learning, allowing movements to become more accurate with practice, like when learning to ride a bike or play a new instrument.







Damage to the cerebellum results in the loss of the automatic, unconscious nature of movement. Without the movement correction from the cerebellum, patients may have difficulty in controlling the accuracy of their movements, an impaired ability to perform rapid, alternative movements (i.e. flipping the palms up and down quickly), or struggle to adapt their movements based on experience. They will have difficulties walking or standing upright and will compensate by spreading their feet to stabilize their balance.



The spinal cord and muscles. The spinal cord is the primary pathway for transmitting motor commands from the brain to the muscles in the body. The most prominent motor control pathway in humans is the corticospinal tract, where upper motor neurons in the primary motor cortex send information to lower motor neurons in the brainstem and spinal cord. These lower motor neurons can then directly innervate skeletal muscles at specialized synapses called neuromuscular junctions.

There are many other motor pathways in addition to the corticospinal tract. For example, the corticobulbar tract carries information from the motor cortex to the brainstem to control the muscles of the face, head, and neck. The cortico-cerebello-cortical pathway transmits information from the motor cortex to the cerebellum and back.

Feedforward and feedback control. One amazing feature of the human brain is its plasticity. This refers to the ability of the brain to change and adapt in response to sensory stimuli or with experience. This adaptation is accompanied by physical changes in the connections between neurons; new connections are made or strengthened, and others are lost. The motor system is a highly plastic system, allowing us to constantly adapt and fine-tune our movements.

Have you ever tried to develop a new motor skill, like learning an instrument, drawing, or playing a sport? You're always told that practice makes perfect, but why? The brain allows this by correcting previous motor errors and anticipating potential obstacles that might affect your ability to move correctly. These strategies are called feedback and feedforward control systems respectively.

Feedback control is when the brain receives sensory information from the body, telling the brain what exactly the limbs are doing. The brain then compares this information to what it actually wants the body to do. The brain uses this comparison to change what it's telling the limbs and the movement should improve with continued practice. For example, if you're reaching for a glass of water and your hand slightly overshoots the target, your sensory system tells the brain that the movement was inaccurate. The brain then updates and sends the proper signals to the body to adjust your hand's position.

Feedforward control anticipates the necessary motor actions based on prior experience, knowledge, and environmental cues. Instead of waiting for sensory feedback to correct mistakes, the brain predicts what the body needs to do to achieve a movement goal and prepares the motor system in advance. For example, when you throw a ball, you don't wait for feedback about the angle or velocity after each throw. Instead, you rely on prior knowledge to predict how hard to throw the ball, where your arm should be positioned, and how to adjust for distance. This prediction-based control helps you to execute movements quickly and efficiently.

The activities in this lesson are designed to demonstrate how the motor system can adapt, relying on both feedback and feedforward mechanisms.

Activity 1: Prism Goggles

Materials

Item	**Quantity**	**Notes**
Prism goggles	At least 1	Shifts the wearer's vision to the left or right. Can also build your own https://www.exploratorium.edu/snacks/distortion-goggles
Bean bags	~10	Used for throwing. Can get a set of 12 for $17 on Amazon
Large bucket	At least 1	Used to throw the bean bags into. Can get on Amazon for $7

In the Class

1. Have a student begin by throwing 10 bean bags aiming for a bucket at a reasonably challenging distance.
    a. Keep track of how many bean bags make it in.

2. Have the student then put on the prism goggles. These will shift their vision to the left or to the right.
3. Throw the 10 bean bags again, aiming for the bucket at the same distance.
    a. Keep track of whether the bean bag makes it for every trial. This allows you to see how long it takes the students to adapt their throw
    b. If needed, allow the student to continue throwing more than 10 bean bags. Have them throw until their movement is corrected and they make the bucket.
4. Remove the prism goggles, and repeat step 3.

Try out different kinds of movements with your goggles!

- Catching or throwing a ball
- Throwing darts at a target
- Giving somebody a handshake
- Giving somebody a high-five
- Reaching out at a target

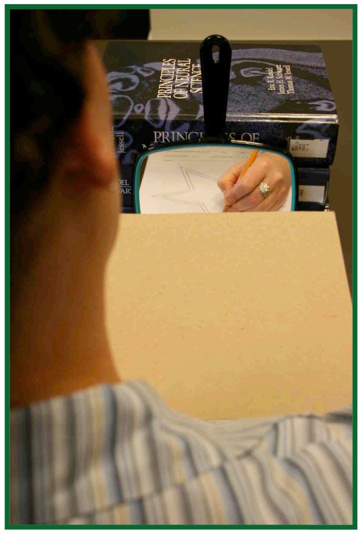
Activity 2: Mirror tracing activity

Materials

Item	**Quantity**	**Notes**
Star pattern-tracing sheets	1 per student	Attached in lesson plan
Mirror	At least 1	Can be any kind of or reflective surface
Pencils, pens, or markers	1 per student	
Cardboard	At least 1	Used to block direct viewing of hand when tracing
Timekeeper	At least 1	Clock, watch, or stopwatch to keep time

In the Class

1. Lay out the star pattern-tracing sheet of paper on the table. Have the student sit in front of the paper.
2. Arrange the mirror and the cardboard. The mirror must be arranged so that you can view your hand on the star pattern in the mirror while using the cardboard to block the direct view of your hand. It should look something like below.



3. With a writing utensil, trace the star, trying to stay between the double lines. Don't lift the pencil at all, and keep the line continuous.
4. Record the time it takes to trace the outline.
5. Repeat step 3 multiple times (and possibly across multiple days!). With practice, students should become faster at tracing.

Alternatively, you can do an online version of this task at https://projectneuron.illinois.edu/games/mirror-tracing-game-intro.html

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