Brain Mechanisms of Movement

WEEK 7, LECTURE 2

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Okay everyone, this is lecture 2 for this series. In our last lecture we talked about how neurons connect to muscles, and how those neurons induce muscle contractions and reflexive behaviors. Now we're going to get into the more detailed aspects of movement: mainly, the different brain areas that control different types of movement. So let's get started! (writing this out, I realize I say that a lot – sorry!)

Brain Mechanisms of Movement

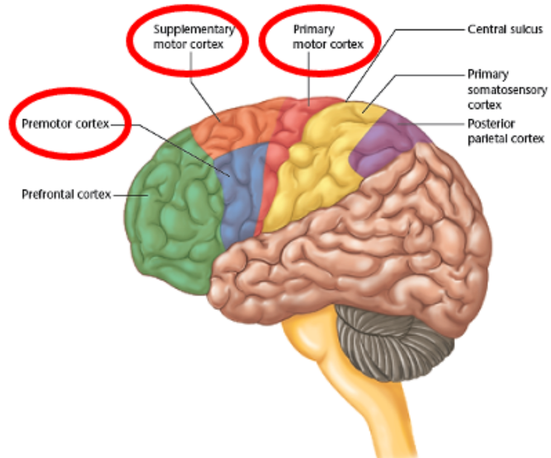
Understanding how the brain controls movement offers hope for spinal cord damage or limb amputations

It's really important to understand how the brain controls movement. First of all, because it's good to know how it's supposed to function under normal circumstances. Second of all, it's important because it can help us develop new technologies to help people with movement disorders, like people with spinal cord damage or limb amputations. Prosthetics that are controlled by brain impulses, like the arm in this image for example, have become more and more refined over the last few years due to this line of research. And it all starts with understanding how the brain initiates and controls movement.

The Cerebral Cortex

The **primary motor cortex** is located in the precentral gyrus in the frontal lobe

Axons from the precentral gyrus connect to the brainstem and the spinal cord, which generate impulses that control the muscles



The first area we'll discuss is the primary motor cortex, which is located in the precentral gyrus of the frontal lobe. This area has a direct connection to the brainstem and spinal cord, and this network together helps generate the impulses that control muscle movement.

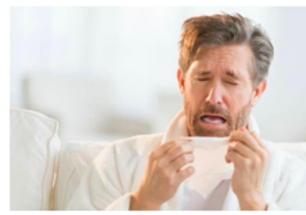
Other areas like the premotor cortex and supplementary motor cortex, are also involved in motion. These areas in particular are activated during the planning of movements. We'll talk more about these areas later – this is just an example.

The Cerebral Cortex

Other areas of the cerebral cortex are also involved in complex movements…

- Also involved in thinking about verbs related to movement, imagining movements, and remembering movements

Complex movements (more voluntary) = talking, writing, etc.



Non-complex movements (more involuntary) = sneezing, coughing, crying, etc.

The primary motor cortex is the main area for motor control, but other areas of the cerebral cortex are also involved in generating more complex movements.

Complex movements are movements that are more voluntary (although again, all movement is a combination of both) – things like writing or talking.

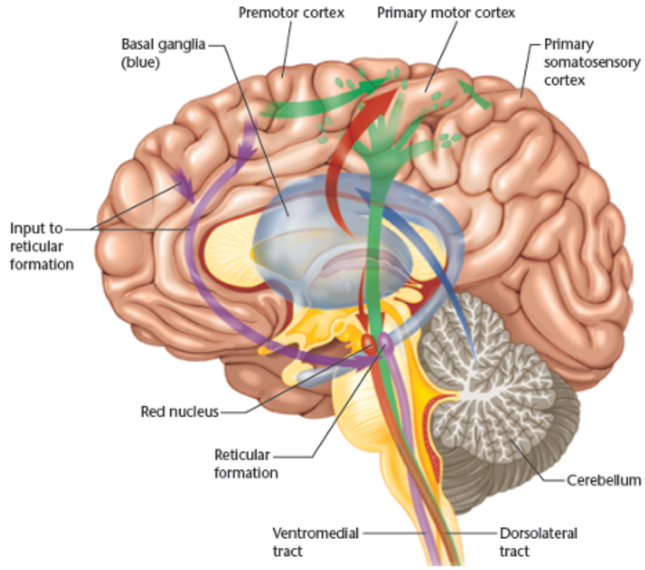
This is in contrast to non-complex movements, which tend to have less involvement of the cerebral cortex. These are things that are more involuntary, like sneezing or coughing.

The cerebral cortex is also involved in movement-related thoughts, like imagining or remembering movements – or even just thinking about verbs related to movement. So the cerebral cortex can simulate movement, even when no overt movement is occurring! This can be especially helpful for planning out sequences of movement.

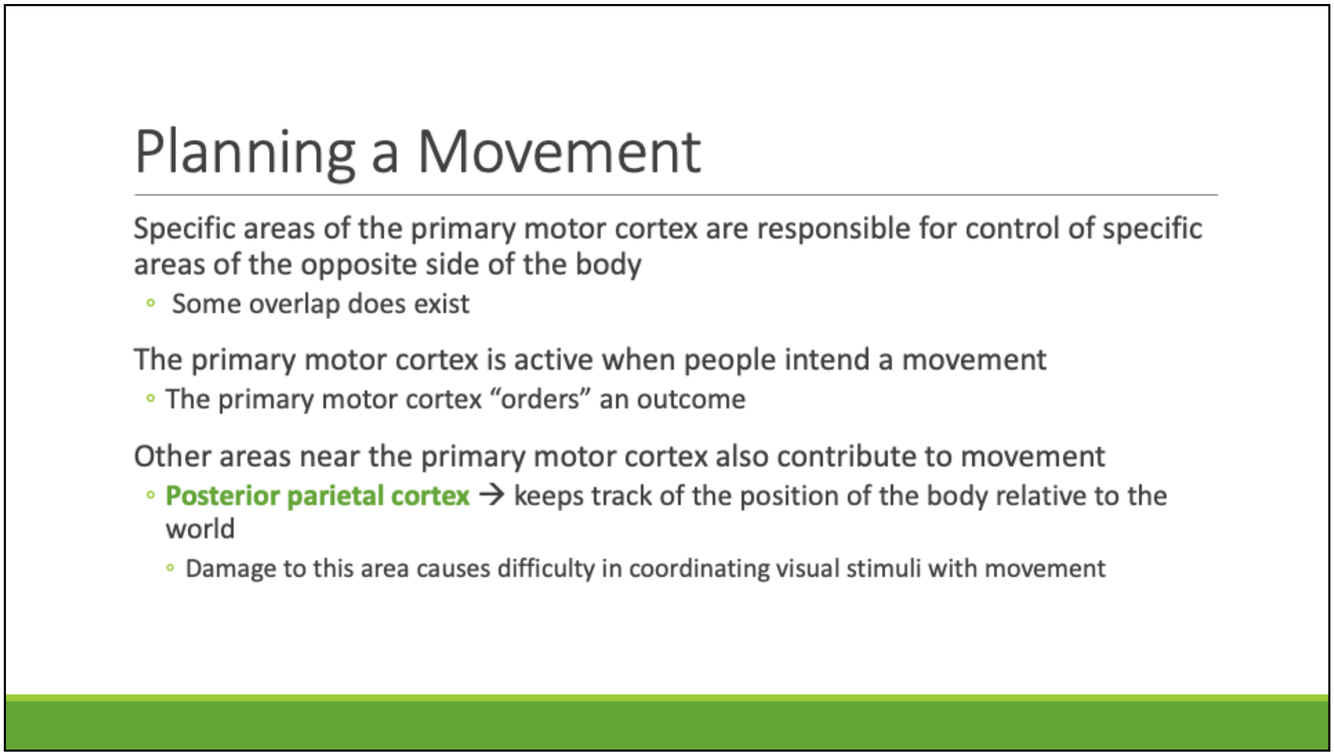
Muscle Control from the Primary Cortex

Different paths from the primary motor cortex, basal ganglia, etc. send signals to the medulla and spinal cord

Signals from the medulla and spinal cord initiate muscle movements in the periphery



This is a diagram of all of the relevant areas and pathways involved in different types of motor movement. Broadly, different paths from areas like the primary motor cortex, basal ganglia, and other cortical areas, send signals to the medulla and spinal cord. Signals from the medulla and spinal cord then initiate muscle movements.

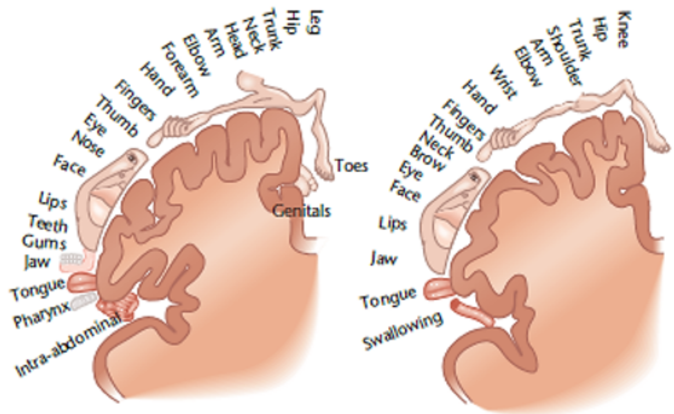


So let’s talk about the planning of movements. While movements themselves can be voluntary or involuntary, the *planning* of movements is largely unconscious. The planning of movements is controlled by specific areas of the primary motor cortex, although some overlap exists. And like many aspects of brain and behavior, this is a contralateral process.

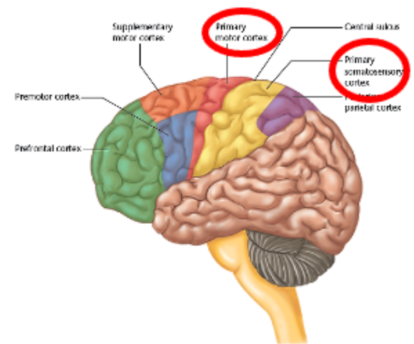
So here’s how it works: the primary motor cortex activates when you intend to initiate a movement, at which point it “orders” an outcome, which will begin to execute no matter which position your body is in. Other areas near the primary motor cortex also help coordinate this movement, which you should read about in the slide above.

People with damage to the posterior parietal area have issues with finding objects in space, even though they can accurately verbally describe them. They also tend to bump into things when walking. So this is an area that provides some of the visual feedback needed to successfully move around in the world. And this makes sense, too, when you think back to the dorsal stream of visual processing and its function, which is also located in the parietal lobe.

The Primary Somatosensory vs. Primary Motor Cortex



(a) Somatosensory cortex (b) Motor cortex



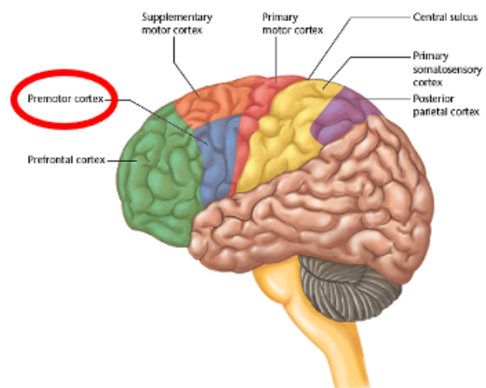
This diagram is very often shown when talking about both movement and sensation, and that's because the somatosensory cortex (on the left) and the primary motor cortex (on the right) are located adjacent to one another!

So the motor area responsible for *moving* a certain body part is actually aligned with the somatosensory area responsible for *feeling* that body part. Communication between sensing and moving is therefore essential for movement.

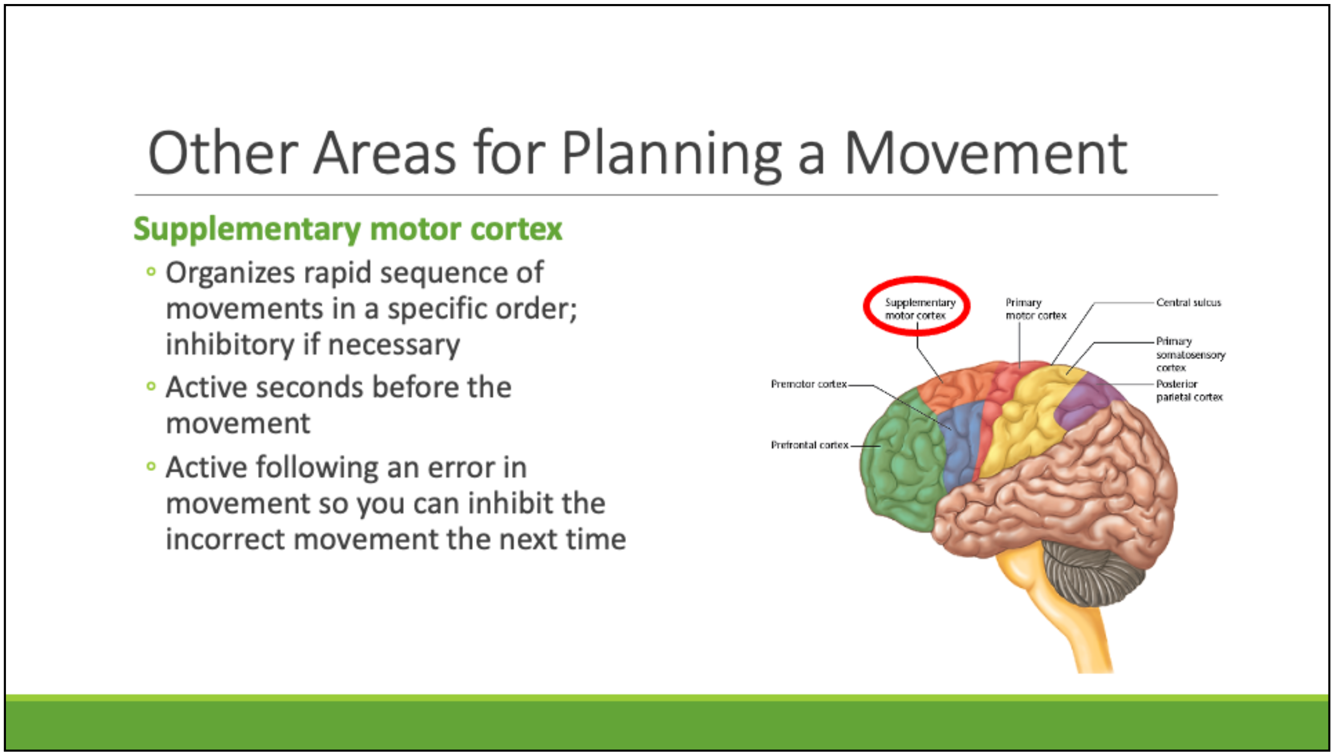
Other Areas for Planning a Movement

Premotor cortex

- Active during preparation for movement
- Receives information about a target
- Integrates information about position and posture of the body → organizes the direction of the movement in space



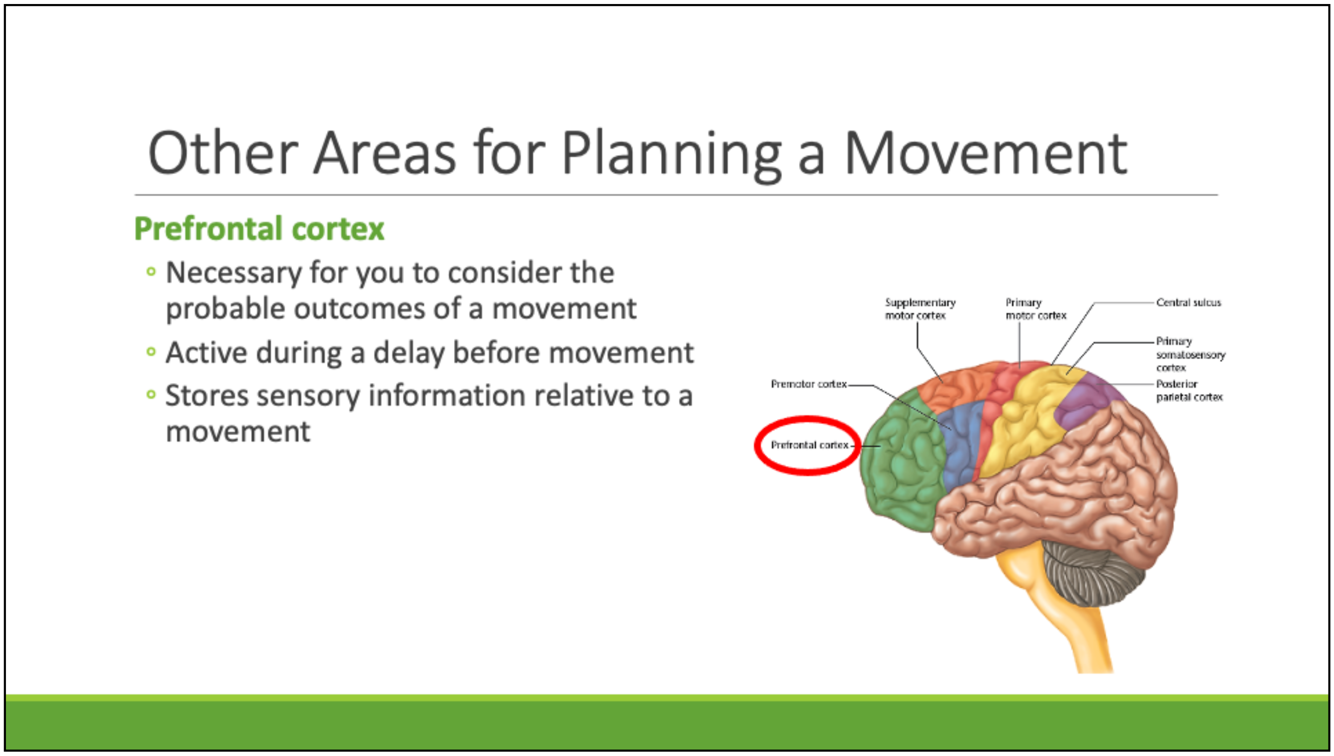
Let’s talk about some other areas involved in movement planning. First we have the premotor cortex, which is active during preparation for movement. You can read more about it in the slide above.



The supplementary motor cortex is also involved… this area helps organize rapid sequences of movement (e.g., throwing a ball, dancing, etc.) into a specific order.

This area can be inhibitory when, say, you need to change up a habitual action, or after you make an error in movement (it'll help correct for that the next time you try it).

You can read more about this area in the slide above.



Finally, the prefrontal cortex is also involved in planning movements. The prefrontal cortex is an area associated with what we often like to call "higher cognitive functions" – things like planning, working memory, and inhibitory control. These functions generally apply to motor movement as well, as, for example, this area helps you simulate the probable outcomes of a movement.

In terms of activation, this area activates during the delay between when movement is intended and when it's initiated. It also stores sensory information relative to a movement, which helps provide feedback as to whether that movement was successful or not.

People with damage to the prefrontal cortex often do really weird things like shower with their clothes on. And actually for most of us, the prefrontal cortex is not active during sleep, and because of that the actions you take in dreams resemble those of people with prefrontal cortex damage.

Inhibition of Movements

Antisaccade task → inhibits a voluntary **saccade** (i.e., an eye movement from one target to another)

- In this task, participants are asked to look in the *opposite* direction as a stimulus
  - E.g., if something is presented on the right side, look towards the left side, and vice versa

So those are the areas involved in the *initiation* of movements, but what about when movements need to be *inhibited*? One way to study this is with something called an antisaccade task, which is a task that inhibits saccades. Recall from our lecture on vision that saccades are rapid eye movements that you can make either voluntarily or involuntarily (your book places heavy emphasis on the "voluntary" aspect, but saccades can also be involuntary).

In any case, these tasks are used to measure the parts of the brain that are activated when a movement needs to be inhibited. You can read about how these tasks are generally implemented above.

Inhibition of Movements

Antisaccade task → inhibits a voluntary **saccade** (i.e., an eye movement from one target to another)

Performing this task well requires sustained activity in parts of the prefrontal cortex and basal ganglia before seeing the moving stimulus

Ability to perform this task matures through adolescence

So, performing this task well appears to require sustained activity in parts of the prefrontal cortex and basal ganglia *before* seeing the moving stimulus. Why before? Because the brain needs time to stop the action and replace it with something else.

Performance on this task tends to be very low for children, but it gets better and matures through adolescence, as the prefrontal cortex develops. It also decreases in old age, as the prefrontal cortex tends to lose volume as we age. The ability to inhibit movements is tied closely to the prefrontal cortex, which is an area that controls our ability to inhibit initial responses.

Mirror Neurons

Neurons that are active during both preparation of a movement and while watching someone else perform the same or similar movement

- May be important for understanding, identifying, and imitating other people
- May be involved in social behaviors (e.g., imitating facial expressions)
- Unknown whether they cause or result from social behavior

This is kind of a side bar, but humans (and other animals) appear to have this really interesting ability to coordinate our movements with the movements of others – and this seems to be somewhat involuntary. And researchers have found that a special type of neuron – called a mirror neuron – is activated when mimicking the movements of others. These neurons appear to be active both while watching someone perform a movement, and while performing that movement ourselves, which suggests that we have a built-in propensity to imitate other people. This ability has been heavily implicated in social behaviors and social learning, but we don't really know if they are the cause or result of social behavior.

Speaking to the last point, the question is whether we're born with these neurons, which can help facilitate social learning, or whether we develop and strengthen these neurons and their connections as we gain more experience with imitation, in which case they're a result of social learning, not the cause. The jury is still out, and this is a fairly new area of study, but it's really interesting as it suggests neurological underpinnings for our ability to learn from others.

Connections from the Brain to the Spinal Cord

Messages from the brain must reach the medulla and spinal cord to control the muscles

Corticospinal tracts are paths from the cerebral cortex to the spinal cord

Two such tracts:
- Lateral corticospinal tract
- Medial corticospinal tract

Okay, let's talk a little more about the pathway of motor information. So far we've talked about how the brain begins to initiate movement and how it can inhibit movement – let's talk about what happens once the brain definitively "decides" to execute a movement. So, very generally, once a "decision" is made, these messages are sent to the medulla and the spinal cord, and from the spinal cord they'll be sent to their requisite areas in the periphery.

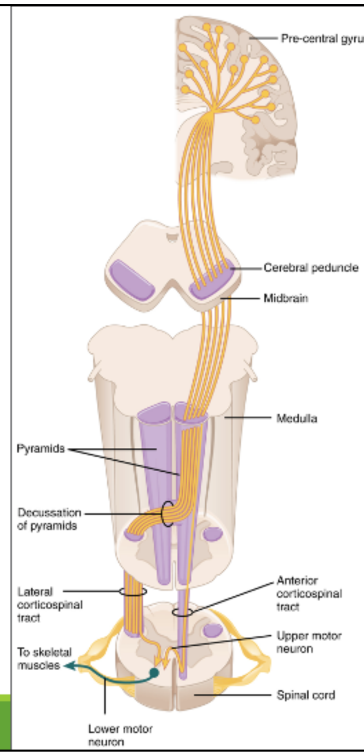
These signals move along special tracts called corticospinal tracts… and there are two of these tracts, which are labeled above.

Lateral Corticospinal Tract

A set of axons from the primary motor cortex and surrounding areas → red nucleus → the spinal cord

- **Red nucleus**: a midbrain area with output mainly to the arm muscles
- Controls movement in peripheral areas (hands and feet)

Axons extend from one side of the brain to the opposite side of the spinal cord, and control opposite side of the body



[read through slide first]

This area is also known as the pyramidal tract, because the tract crosses to the contralateral side of the body in these bulges in the medulla called pyramids. This is the area labelled decussation of pyramids. Decussation essentially indicates an area of crossover.

This is actually a pretty detailed drawing, and while it's hard to read here, you can zoom in and get a closer look at the different components involved (or loosely related to) this tract. Hopefully it'll give you a better idea of how these areas all work together.

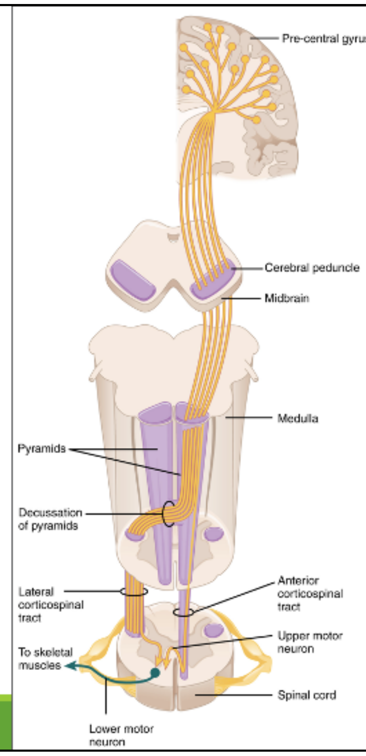
Medial/Anterior Corticospinal Tract

A set of axons from many parts of the cortex

- Reticular formation, midbrain tectum, vestibular nucleus, etc.
  - **Vestibular nucleus** is a brain area that receives information from the vestibular system

The medial tract controls the muscles of the neck, shoulders, and trunk

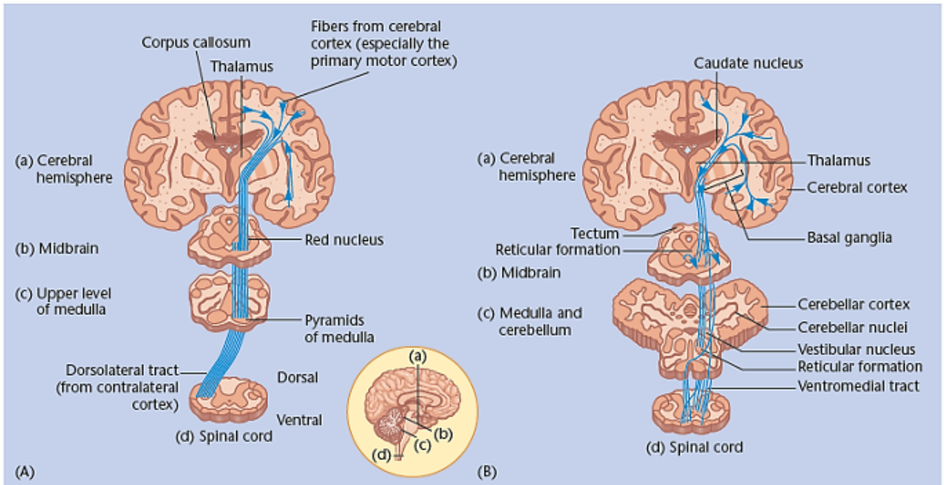
- Responsible for bilateral movements like walking, turning, bending, standing up, and sitting down



The other tract is the medial or anterior corticospinal tract, and you should read through the slide to learn more about it.

The medial/anterior tract is responsible for bilateral movements, which are movements that require coordination of both sides of the body – things like walking or standing up. Because this tract controls movements that require coordination of both sides of the body, axons in this tract go to both sides of the spinal cord, rather than just to the contralateral side. You can’t really make it out on this diagram (unless you zoom in, which I recommend!), but I’ll give you a clearer image on the next slide…

The Lateral and Medial Corticospinal Tracts



Lateral Tract | Medial/Anterior Tract

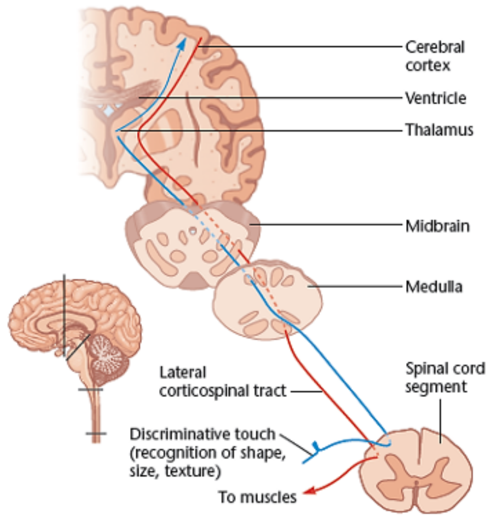
For a summary, see: https://www.youtube.com/watch?v=Ma4i6nH3qMQ

Here’s a comparison of the two tracts. The lateral tract is on the left, and you can see how it’s much more tightly concentrated and contralaterally organized, right? It goes directly from the right side of the cortex, down through the pyramids of the medulla, and then to the opposite side of the spinal cord.

In contrast, the medial/anterior tract on the image on the right is more spread out, and once it leaves the reticular formation it innervates (i.e., connects) to both sides of the spinal cord.

If you’d like a summary of these two tracts, I’ve included a 2-minute neuroscience video for you at the bottom of the slide here. It goes into a little more detail than I did, and so just to remind you – you’re only responsible for the information in my lectures, not in these videos, unless I say otherwise.

The Touch Path and the Lateral Corticospinal Tract



Just to provide one more example before we move on… This is a comparison of the touch tract, which is indicated in blue, to the lateral corticospinal tract, which is indicated in red. Both paths cross in the medulla, meaning both are contralateralized. Notice also that touch information arrives at brain areas that are also responsible for motor control. This again highlights the close relationship between sensation and movement – we need to be able to get sensory feedback from the environment in order to successfully navigate through the world around us.

Disorders of the Spinal Cord

Disorder	Description	Cause
Paralysis	Inability for voluntary movement in part of the body	Damage to motor neurons or their axons in the spinal cord
Paraplegia	Loss of sensation and voluntary muscle control in the legs (Despite the lack of sensations from the genitals, stimulation of the genitals can produce orgasm.)	A cut through the spinal cord in the thoracic region or Lower
Quadriplegia (or tetraplegia)	Loss of sensation and voluntary muscle control in both arms and legs	Cut through the spinal cord in the cervical (neck) region (or cortical damage)
Hemiplegia	Loss of sensation and voluntary muscle control in the arm and leg of either the right or left side	Cut halfway through the spinal cord or damage to one hemisphere of the cerebral cortex
Tabes dorsalis	Impaired sensations and muscle control in the legs and pelvic region, including bowel and bladder control	Damage to the dorsal roots of the spinal cord from the late stage of syphilis
Poliomyelitis	Paralysis.	A virus that damages motor neurons in the spinal cord
Amyotrophic lateral sclerosis	Gradual weakness and paralysis, starting with the arms and spreading to the legs	Unknown. Traced to genetic mutations in some cases, and to exposure to toxins in other cases

As you might have seen in the video (and even if you haven't seen it yet), there are lots of things that can go wrong due to damage to the spinal cord. This is another one of those tables that I do not need you to memorize, but it's here if you're interested in some of the different types of injuries that can occur that we don't have time to touch on in this class.

The Cerebellum

A structure in the brain often associated with balance and coordination

- More neurons in the cerebellum than in all other brain areas combined

Important for the establishment of new motor programs that allow the execution of a sequence of actions as a whole (e.g., tasks that require timing)

Damage to the cerebellum causes trouble with rapid movements requiring aim/timing

- Examples: clapping hands, speaking, writing, etc.

Okay, so let's move on and talk about some of the other major areas involved in the actual execution of movement. We'll start with the cerebellum, which is the brain structure most commonly associated with balance and coordination. And, fun fact – this area is jam-packed with neurons. It has more neurons than in all other brain areas combined! So there's a lot going on here.

This area is hugely important in executing sequences of movement – especially those that require precise timing, like catching a ball. And so it follows that damaging this area will cause trouble with movements that require coordination – things like clapping, speaking, or writing (or catching a ball) will be impaired.

The Cerebellum and Functions Other than Movements

Responds to sensory information even in the absence of movement

Responds strongly to violations of sensory information

- Example: reaching to touch something and not feeling it or feeling something when you don't expect to feel it

Also critical for certain aspects of attention, such as the ability to shift attention and attend to visual stimuli

The cerebellum is often primarily attributed to movement, but it also responds to sensory information in the absence of movement. You can read some examples in the slide above.

Cellular Organization of the Cerebellum

The cerebellum receives input from the spinal cord, from each of the sensory systems and the cerebral cortex, and sends it to the cerebellar cortex

The **cerebellar cortex** is the surface of the cerebellum

Cerebellar cortex neurons are arranged in precise geometrical patterns that provides outputs of well-controlled duration

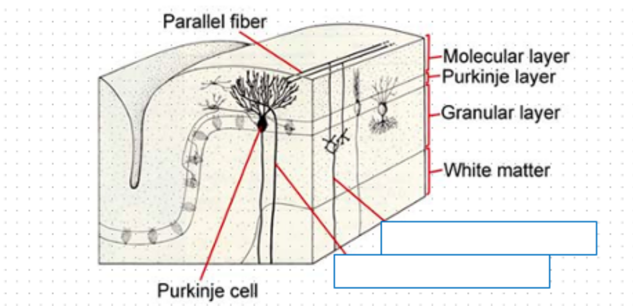
- **Purkinje cells**: flat parallel cells in sequential planes
- **Parallel fibers**: axons parallel to one another; perpendicular to planes of Purkinje cells

The greater the number of excited Purkinje cells, the greater their collective duration of response

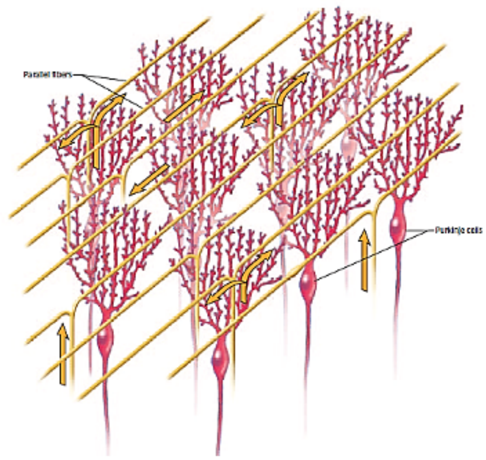
[read through slide first]

Basically, parallel fibers send messages out one after the other. If only a few signals from these fibers reach the purkinje cells, they won't fire for very long. On the other hand, if these parallel fibers are continually firing, they'll essentially lengthen the amount of time the purkinje cells will fire.

Parallel Fibers and Purkinje Cells



From erraticwisdom



Here’s a couple of diagrams just to show you how these cells are organized in the cerebellum.

The pinkish-red cells are purkinje cells, and you can see how they’re organized in this really nice pattern. The yellow lines here are parallel fibers, which run across the length of the purkinje cells.

Cellular Organization of the Cerebellum

Parallel fibers excite Purkinje cells

Purkinje cells transmit inhibitory messages to the cells in the **nuclei of the cerebellum** (clusters of cell bodies in the interior of the cerebellum) and the vestibular nuclei in the brain stem

Messages then sent to the midbrain and the thalamus

For more information, see: https://www.youtube.com/watch?v=Fir-v6EoZNE

So how does this all come together? Well, you have these parallel fibers that lie across the top of purkinje cells. And they synapse onto and excite purkinje cells. Purkinje cells are primarily inhibitory, meaning that when they're excited they send out an inhibitory signal (typically in the form of GABA). This inhibitory signal travels to two areas: the nuclei of the cerebellum, and the vestibular nuclei in the brain stem.

Their job is to basically regulate the signals received from different areas of the body. If you think about it, many of the signals that come from the rest of the body are excitatory. Purkinje cells inhibit these different excitatory responses strategically, which controls when and how all of this excitatory information reaches the rest of the brain. So they essentially regulate movement by telling the brain and body when to inhibit certain actions.

I've included another 2-minute neuroscience video if you're interested in learning more. Again, this goes into WAY more detail than our class, but it's here if you're interested!

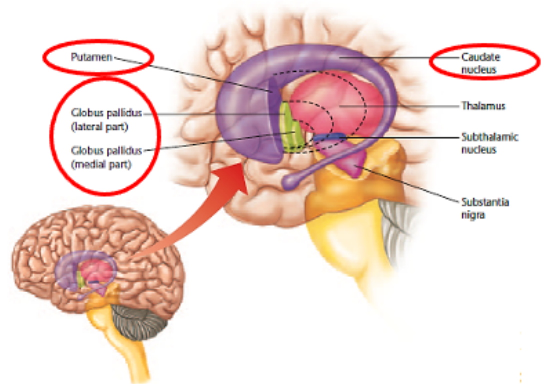
The Basal Ganglia

The basal ganglia is a group of large subcortical structures in the forebrain

- Primarily responsible for initiating more voluntary (and less reflexive) behaviors

Comprised of the following structures*:

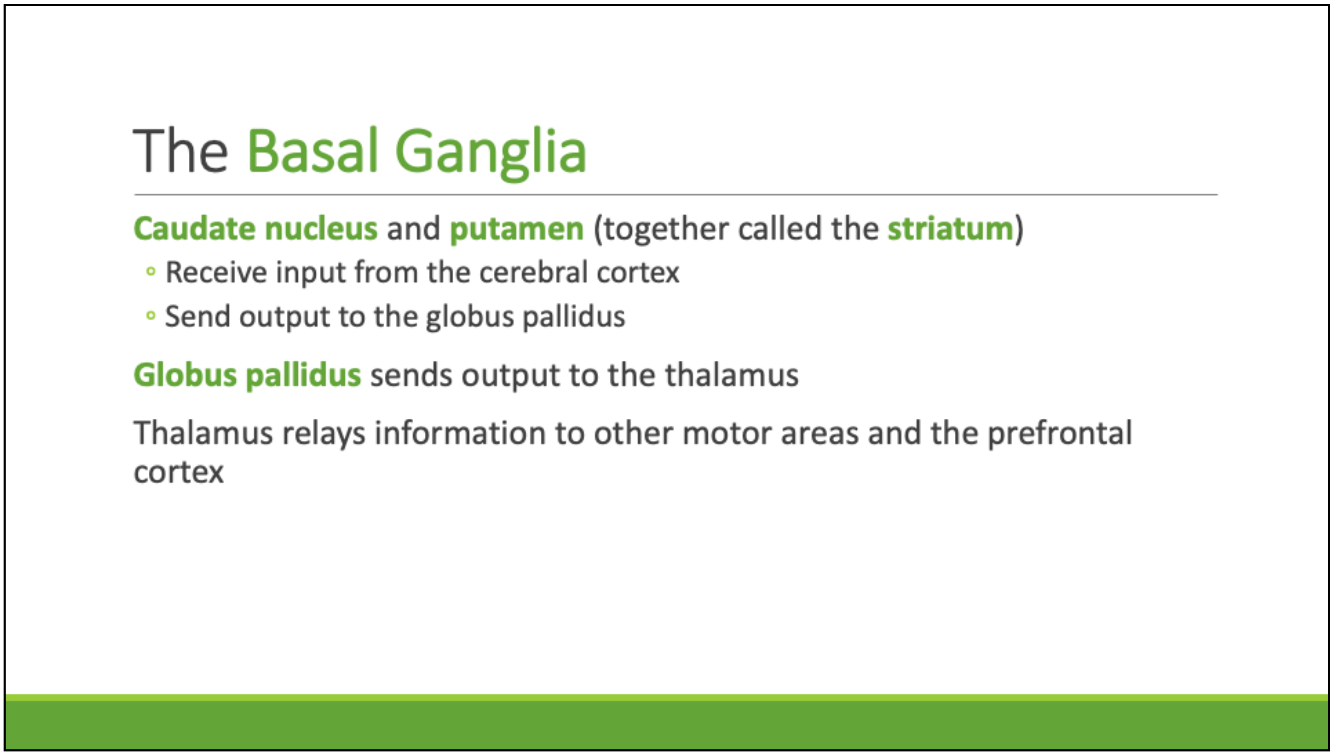
- Caudate nucleus
- Putamen
- Globus pallidus



* There are other structures, but these are the main ones

Okay, let's move on and talk about another major structure involved in movement: the basal ganglia. We talked a little about the basal ganglia in our lecture on neuroanatomy, but now we're going to look at it a much more closely.

So, the basal ganglia isn't just a single structure, it's actually a group of subcortical structures in the forebrain, which are listed in the slide above.



So let’s talk about what each of these substructures is responsible for. To give you a general idea, you should read through the slide above.

The Basal Ganglia

Two pathways:

- **Direct** (excitatory) → enhances a selected movement
  - Inhibits the globus pallidus, which inhibits part of the thalamus
  - Net result is excitation!
- **Indirect** (inhibitory) → inhibits competing movements
  - This one's complicated…*
    - Inhibits the globus pallidus, which inhibits the subthalamic nucleus
    - The subthalamic nucleus loops back and excites part of the globus pallidus
    - Causes inhibition of the thalamic nuclei
    - Net result is inhibition!

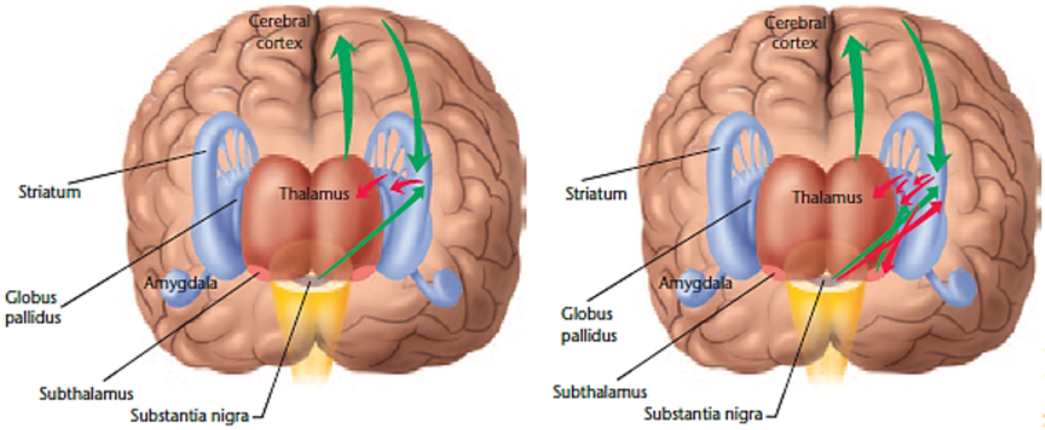
* You do not need to know these processes for the exam, this info is for those who want to know how it works!

There are actually two pathways involved here: the direct and indirect pathway.

[read through the direct pathway first] Basically, the thalamus tends to send out inhibitory signals with regards to movement. When it receives an inhibitory signal from the globus pallidus, the net result is an excitation, which can initiate movement.

[Now read through the indirect pathway. Take a deep breath, and read the little footnote at the bottom. All I want you to know is the function of each pathway, not how they work in detail. But I hate hand-wavy explanations, so I made you read through this just so you would have an idea of what's involved ☺]

The Basal Ganglia



(a) The direct pathway

(b) The indirect pathway

Want a brief summary? See: https://www.youtube.com/watch?v=OD2KPSGZ1No

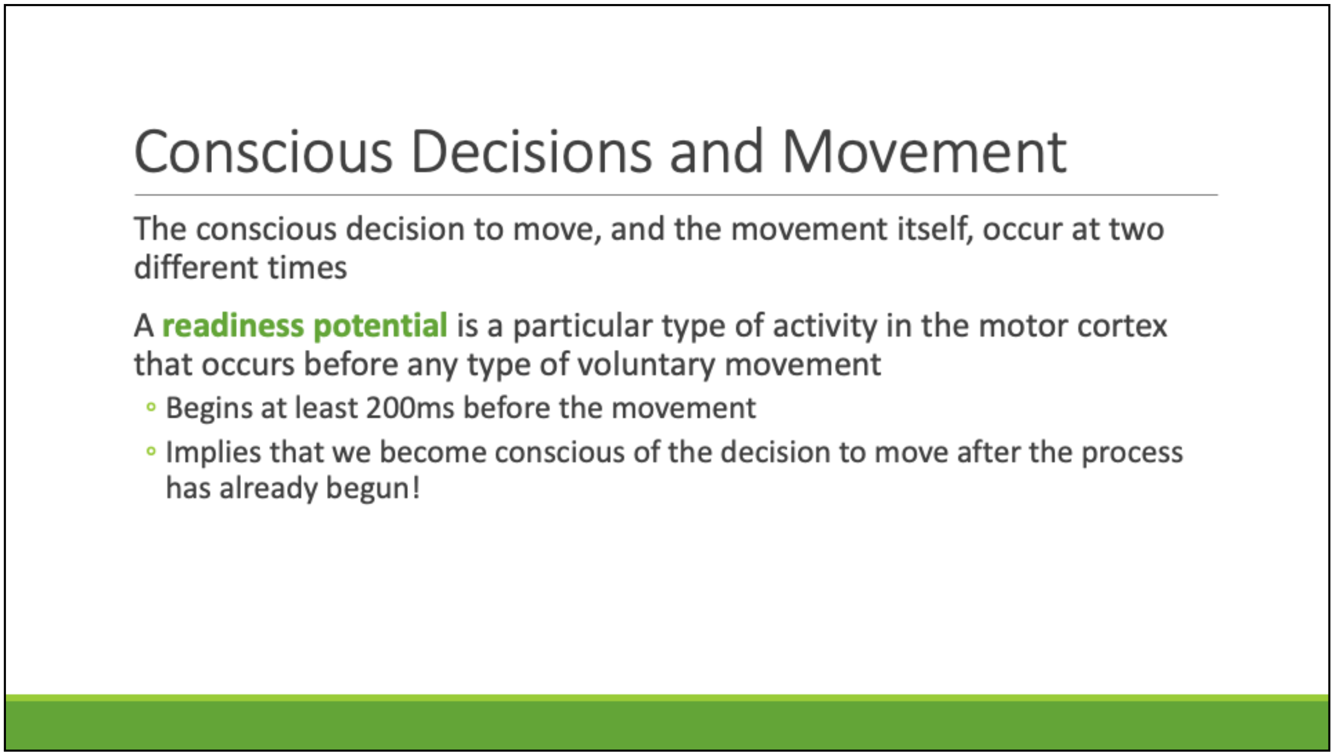
This is a diagram of the two pathways – the direct on the left and the indirect on the right. I've also included yet another two-minute neuroscience video, in case you'd like a quick summary of what I just described.

Brain Areas and Motor Learning

The learning of new skills requires multiple brain areas involved in the control of movement

- Basal ganglia is critical for learning motor skills, organizing sequences of movement, “automatic” behaviors, and new habits
  - Example: driving a car
- The pattern of activity of the neurons in the motor cortex becomes more consistent as a new skill is learned

The basal ganglia is especially relevant for the learning of new skills, which you can read about in the slide above.



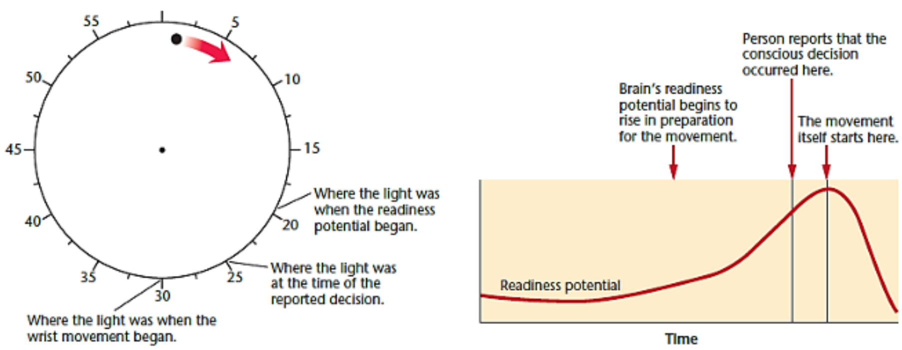
Okay, that does it for the basal ganglia. There's a section in your book that goes into more detail about the specific movements it controls, and I highly recommend you read up on that section while you're studying, as this is information I would like you to know for this class.

But let's move on now and talk about conscious decisions and movement.

So, this might seem a little unintuitive, but the conscious decision to move and the movement itself actually occur at two different times.

Our brains have something called a readiness potential, which involves activation in the motor cortex that can be observed before any type of voluntary movement is actually made. Research has shown that this potential starts at least 200ms before the movement itself occurs, which is really crazy, because it implies that we move first and become conscious of that movement later!

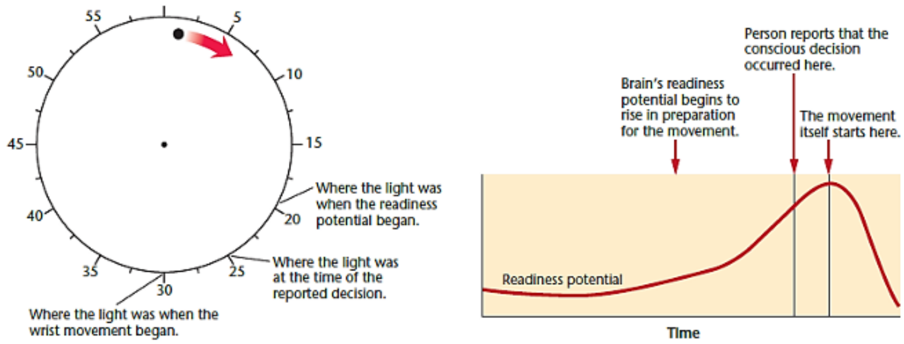
Libet's Study of Conscious Decisions and Movement



This was one of my favorite studies to learn about when I was an undergraduate… although I have to say, its results have been called into question in recent years. But! I think it's still worth learning about, because it'll get you thinking about the potential disconnect between how our bodies behave and our conscious perception of how our bodies behave. So here's how the study went...

A participant was hooked up to an EEG and a sensor was placed on their wrist. They were asked to watch a display in which a light moved around a clock. They were told that they could move their wrist whenever they wanted, but to note where the light was on the clock when they decided to move.

Libet’s Study of Conscious Decisions and Movement



This diagram on the right here is their brain activity as they made the decision to move and then moved. On average, people reported that their decision to move occurred *about 200ms before they actually moved*, and the brain’s readiness potential reflected that. Looking at the diagram, the readiness potential began at least 300ms before the reported decision, which itself occurred about 200ms before the movement.

So I think this is really cool. It suggests that your brain starts preparing to make a movement BEFORE you consciously decide to move. You become conscious of the decision to move after the process to initiate movement has already begun. I can’t say this enough - that’s really cool! But like I said, this is a controversial finding. Your book actually does a good job addressing some of these concerns. I unfortunately don’t have time to go over them here, but the information is there if you’re interested.

Questions for your discussion groups…

1. Describe the lateral and medial corticospinal tracts, both in terms of physiology and function
2. How does the basal ganglia initiate movement?

Okay, that does it for the second lecture in our series for this week. Our last and final lecture will cover movement disorders. See you all there! ☺