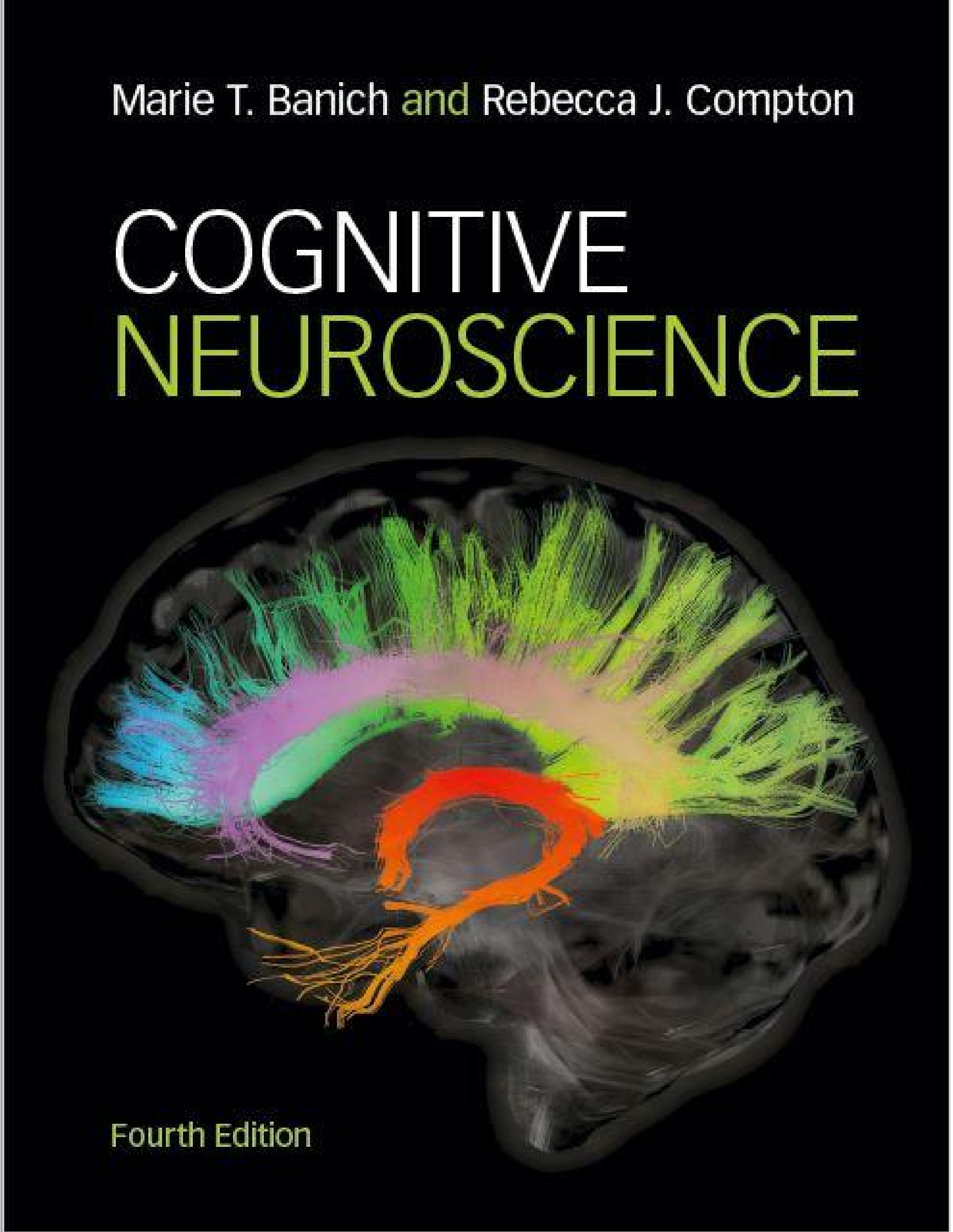
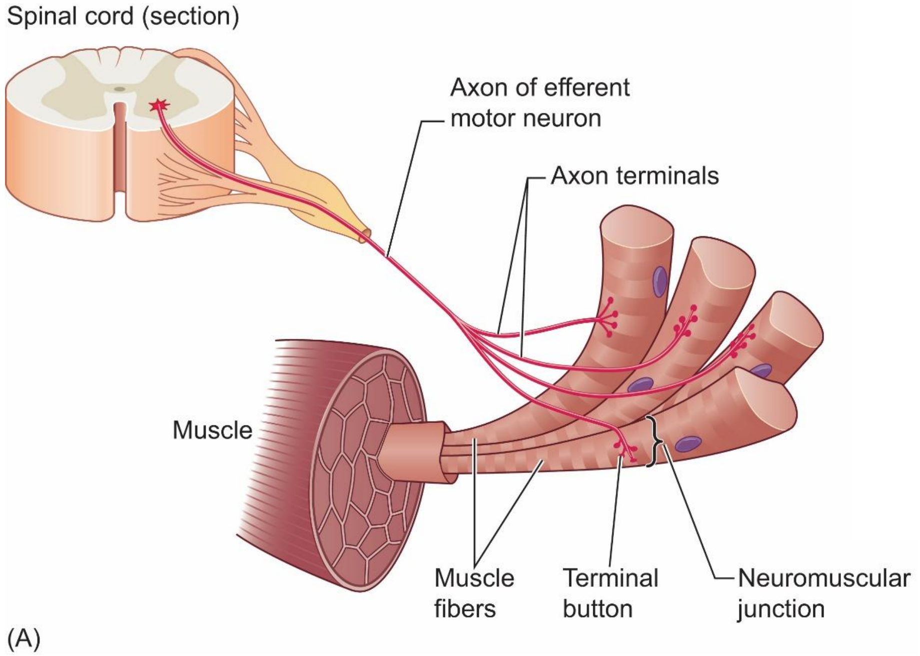


Chapter 4

Motor control

Peripheral control of movement

- Muscles are composed of muscle fibers
  - Muscle fiber contraction is caused by an electrical impulse from a motor neuron
  - The cell body of a motor neuron resides in the ventral portion of the spinal cord.
- Typically, one motor neuron innervates a number of muscle fibers.
  - Innervates only 2-3 fibers for muscles involved in very fine motor control to more than 100 for large muscles.
- A motor neuron and the muscle fibers it innervates are referred to as a **motor unit**.
- The neuromuscular junction is a specialized synapse between the nervous system and muscle fibers



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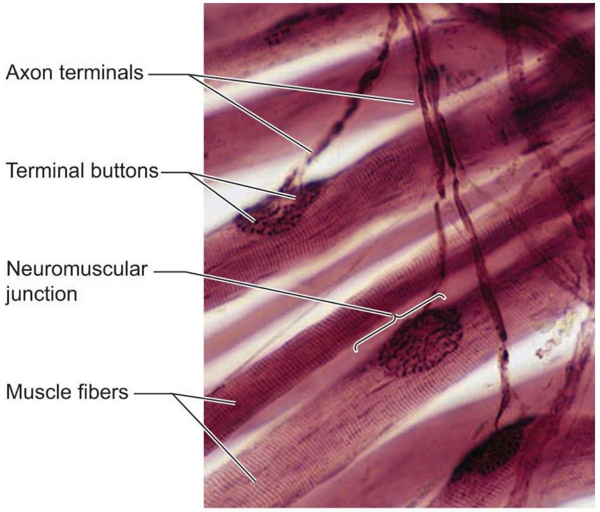
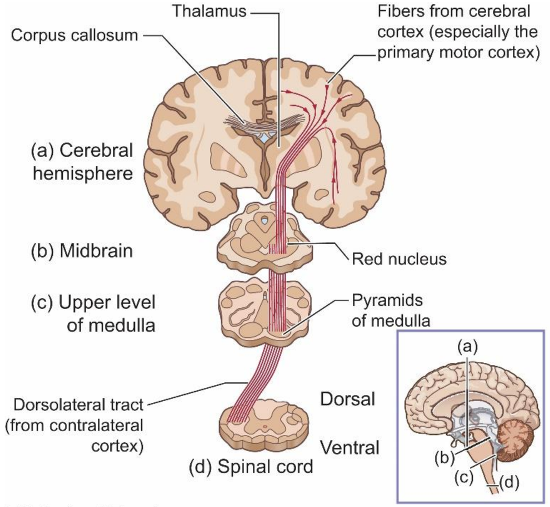


(B)

Peripheral control of movement: Motor Tracts运动神经束

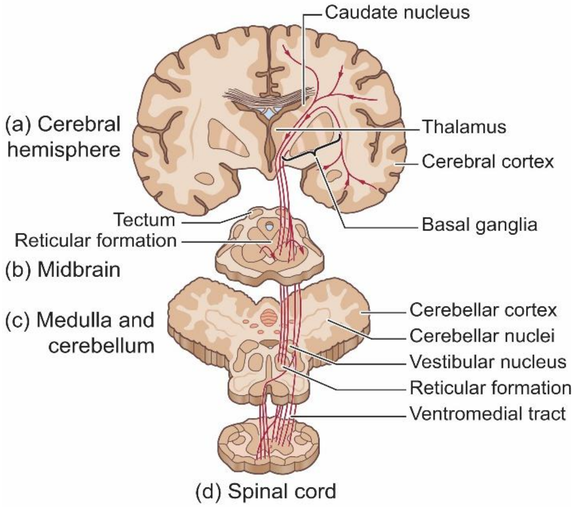
These tracts relay messages from the brain to the target muscles.

- Lateral Pathway
- Involved in fine movement of distal (i.e., far) limb muscles,
  - arms, hands, fingers, lower leg, and foot
- Tract crosses entirely from one side of the brain to the opposite side of the body in the medulla, that is project contralaterally



(A) Lateral Tract

- Medial Pathway
  - Involved in control of movements of the trunk and proximal (i.e., near) limb muscles
  - Involved in posture and bilateral movements
  - Projects both contralaterally and ipsilaterally



(B) Medial Tract

Brain structures involved in motor control: Cerebellum

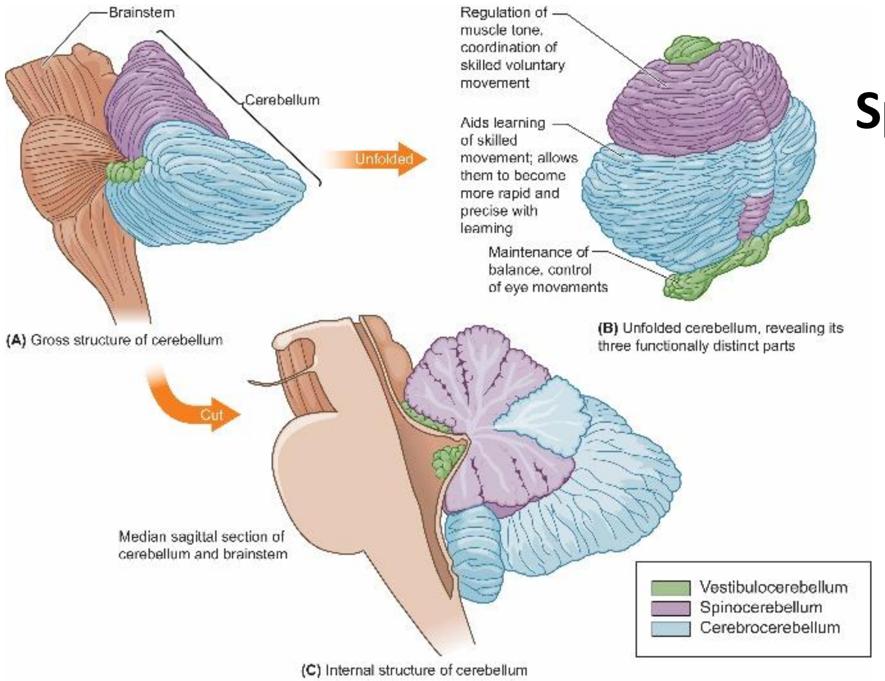
- Plays an important role in
  - the coordination of muscle movement timing
  - the planning of movements
  - the learning of motor skills
- Organized into three main divisions
  - Each receives a distinctive type of information
  - Sends their output to distinct portions of the nervous system
  - Plays a distinct role in motor control
- Information flwoing through these cerebellar loops allows it to *modulate* motor processing.
  - Cerebellar damage does not eradicate movements; rather, they degrade motor capabilities.
- Modulates ipsilateral muscles
  - Unlike the motor cortex that acts on contralateral muscles
- Areas near the midline tend to be responsible for functions associated with the body’s center, including posture.
- In contrast, more lateral areas of the cerebellum control lateralized structures, including the limbs.

Brain structures involved in motor control: Cerebellum

3 main divisions

Vestibulocerebellum *前庭小脑*

- Receives input from the vestibular nuclei in the brainstem
- Projects back to this region
- Damage to this region leads to difficulty with balance and to postural instability.



Spinocerebellum 脊髓小脑

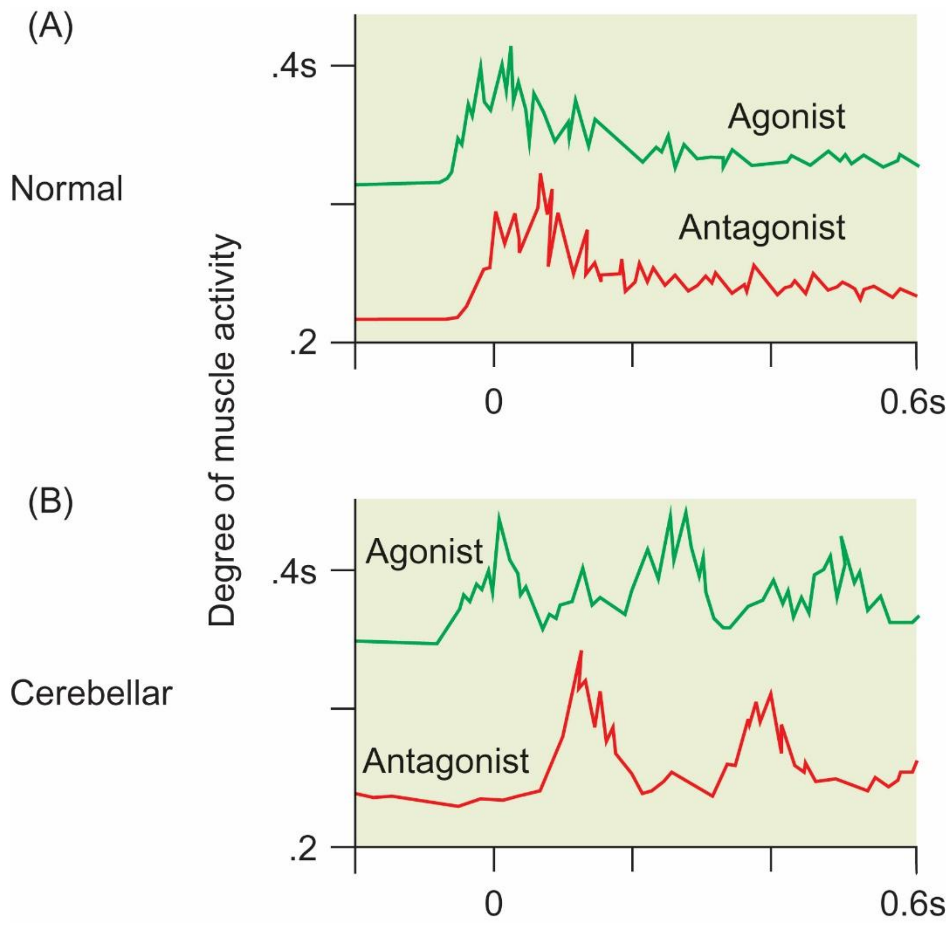
- Receives somatosensory and kinesthetic information (which is information about body movement derived from the muscles, skin, and joints) from the spinal cord
- Projects back to the spinal cord
- Damage to this region results in difficulty with the smooth control of movement, and movement of proximal muscles, such as coordinating the trunk and leg muscles for walking

Cerebrocerebellum *大脑小脑*

- Receives input from many different regions of the cortex, including both motor and association cortices.
- Involved in the regulation of highly skilled movement that requires complex spatial and temporal sequences involving sensorimotor learning.
  - These activities include motor abilities such as throwing a pitch, serving a tennis ball, and juggling, as well as fluent writing and speaking.

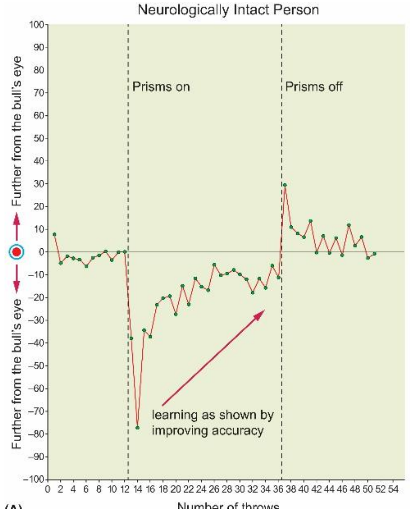
Brain structures involved in motor control: Effects of Cerebellar damage

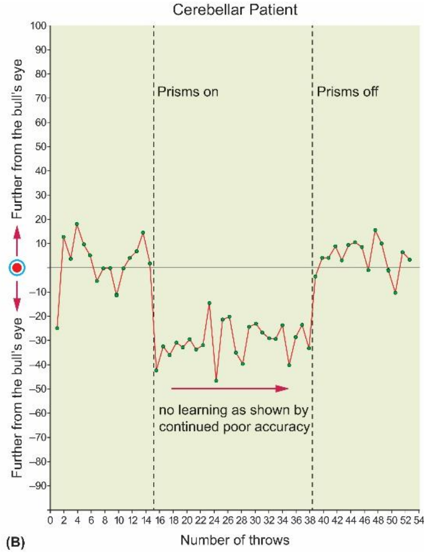
- Difficulties in coordinating movement after cerebellar damage is called **cerebellar ataxia**.
  - When it involves speech output it is called **dysarthria**.
- Traditional test is to have a patient touch his or her nose and then the neurologist's finger.
  - Movement can be performed but the path is often staggered, jerky, and zigzag, and typically involves an overshoot of the target
  - Occurs because activity of agonist and antagonist muscles are not well coordinated
  - This behaviour is sometimes referred to as an **action tremor** or **intention tremor** because it occurs during the performance of an act.
    - Distinct from tremors seen with disorders of the basal ganglia, which typically occur during rest



Brain structures involved in motor control: Effects of Cerebellar damage

- Difficulties also include the coordination of multi-joint movements
  - Patients move one joint at a time in a serial manner, a strategy known as **decomposition of movement**.
    - For example, rather than lifting a glass by moving the entire arm, a person with damage to the lateral cerebellar cortex may place an elbow on a table, lean forward, and bring the glass to his or her mouth.
    - With the elbow stationary, the number of joints that must be moved is decreased, which increases the likelihood of a successful movement
- Difficulties in sensory-motor learning after damage to lateral portions of the cerebellum
  - Difficulties in learning to adjust an action such as throwing a dart at a target after visual input is modified by having to wear prisms over the eyes
  - Difficulties in eye-blink conditioning paradigms



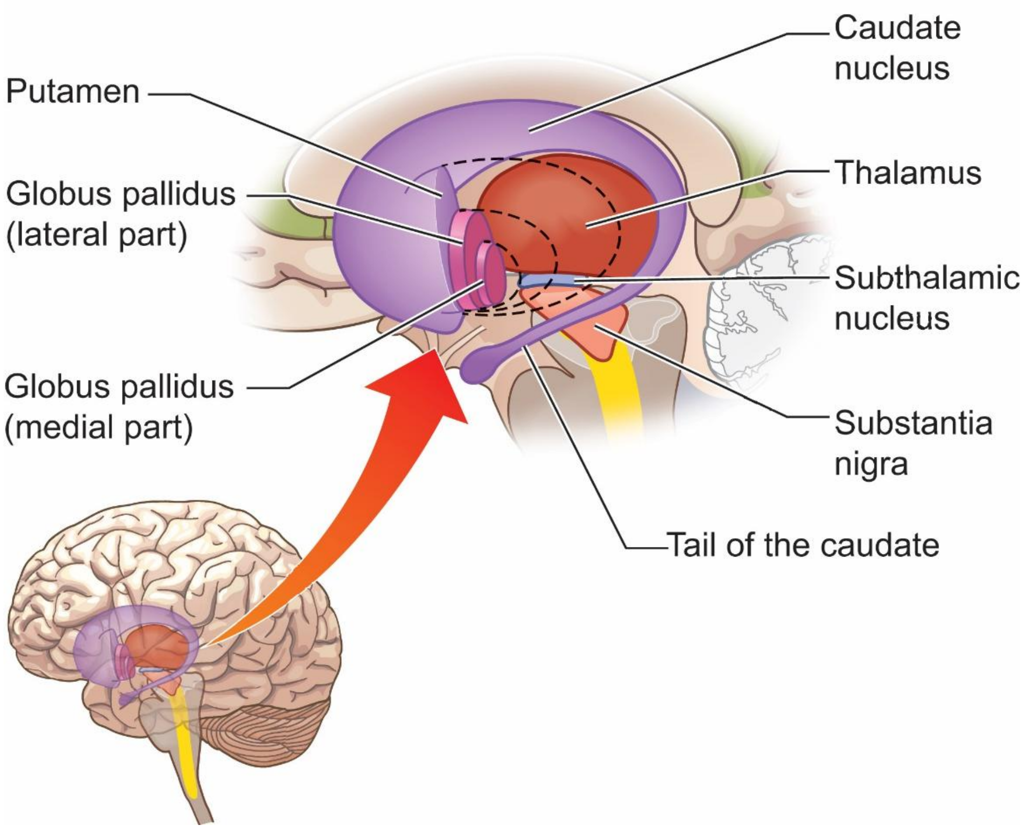


Brain structures involved in motor control: Theories of Cerebellar Function

- One prominent theory argues that the cerebellum helps to predict the sensory consequences of motor plans, often referred to as a **forward model.**
  - Such forward models are not influenced by feedback from the periphery, such as sensory and kinesthetic information.
  - This makes the cerebellum particularly important for *ballastic movements,* which occur rapidly over a short period of time with maximal velocity and acceleration, leaving little or no opportunity for on-line modification.
- Another theory is that the cerebellum acts as a timing device that provides a clock for events.
  - Cerebellar lesions impair the ability to make judgments about the temporal duration of events
    - E.g., whether the time gap between two tones is longer or shorter than a reference interval (e.g., 400 ms)
    - which of two successive displays of dots is moving more quickly across the screen.
  - This role may be limited to timing of discrete intervals that are not continuous or dynamic in nature.
    - For example, patients with cerebellar damage are not impaired in drawing a circle, which requires continuous movement
- Both theories are consistent with a role of the cerebellum in
  - Coordination, learning, and timing of movement
  - Aspects of higher-level cognition

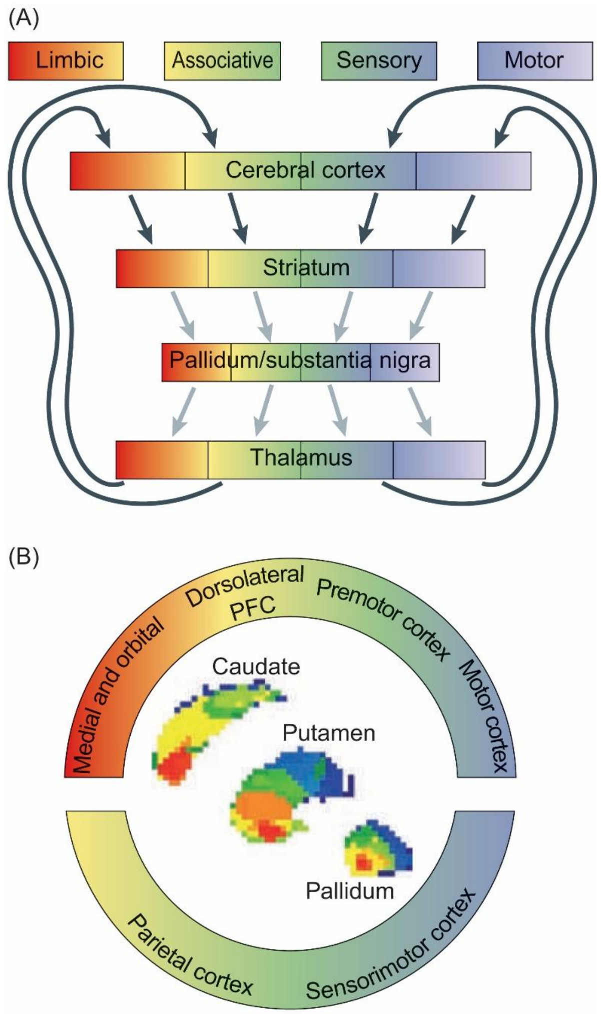
Brain structures involved in motor control: The basla ganglia

- The **basal ganglia** are a complex collection of subcortical nuclei,
- It consists of
  - the **caudate nucleus**,
  - **putamen**,
  - and **nucleus accumbens** (known collectively as the *striatum*),
  - the **globus pallidus** (or *pallidum*),
  - the **substantia nigra**,
  - and the **subthalamic nucleus**.

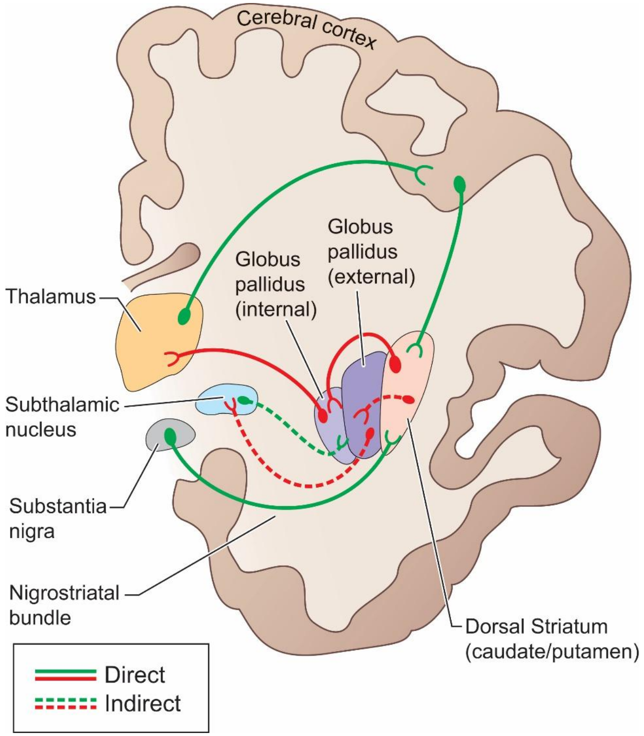


Brain structures involved in motor control: The basal ganglia

- Like the cerebellum, the basal ganglia modify movement
- They do via a series of somewhat separable loops with cortical regions.
    - Each loop consists of input from a cortical region to which information then returns.
    - Distinct cortical regions projecting to provide input to distinct regions of the caudate and putamen.
    - Then output from the basal ganglia occurs via the globus pallidus to the thalamus, which then projects back to the cortex.
- Four such loops have been identified:
    - a limbic (emotional) circuit
    - an associative (cognitive) circuit,
    - a sensory circuit, and
    - a motor circuit



Brain structures involved in motor control: The basal ganglia



- There are two routes via which information passes through the basal ganglia.
  - One route, the *direct* route, contributes to sustaining or facilitating ongoing action.
    - Input to the basal ganglia occurs via inputs that synapse on D_1 receptors of medium spiny neurons of the caudate and putamen.
  - The other route, the *indirect* route, is thought to be important for suppressing unwanted movement.
    - Input to the basal ganglia occurs via inputs that synapse on D_2(rather than D_1) receptors of medium spiny neurons of the caudate and putamen.
- Classically these two pathways have been considered to work in opposition to one another.
- However, newer research suggests there is more ongoing interaction between them in the selection and patterning of motor behaviors than previously thought

Brain structures involved in motor control: The basal ganglia

- The basal ganglia are important for the accomplishment of movements that may take some time to initiate or stop,
  - Distinct from the cerebellum, which plays a role in movements that are not modified once they have been initiated.

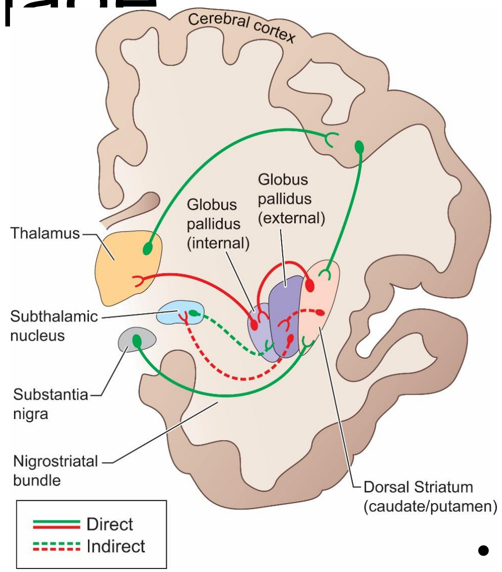
- The basal ganglia are thought to have multiple roles in motor action themselves:
  - "setting" the motor system with regard to posture
  - preparing the nervous system to accomplish a voluntary motor act
  - acting as an autopilot for well-learned sequential movements
  - controlling the timing of and switching between motor acts

- Because they receive both motor and nonmotor information, the basal ganglia are also thought to assist in motor planning and learning,
  - especially when motor acts have motivational significance or have a large cognitive contribution

Brain structures involved in motor control: Theories of basal ganglia function

- One overarching theory of basal ganglia function suggests that the basal ganglia facilitate the synchronization of cortical activity underlying the selection of appropriate series of movements while inhibiting inappropriate ones.
- Another theory states that the basal ganglia "chunk" individual actions into coordinated, stereotyped, and habitual units of action
- Another theory suggests that they aid the ability to execute movements with varying vigor, that is, over a range of speeds, amplitudes, and frequencies
    - Relatedly, the degree of vigor may be linked to motivational factors, such as whether a motor action led to a reward or not, and how much effort you wish to put into your actions.
- Regardless of which of these theories proves to be the best description, the anatomy of the basal ganglia provides them with the ability to both facilitate action and also to inhibit it.

Brain structures involved in motor control: Effects of basal ganglia damage



Parkinson’s disease

- Parkinson’s disease is characterized by:
  - **akinesia** (the inability to initiate spontaneous movement)
  - **bradykinesia** (slowness of movement)
  - **tremors** (rhythmic, oscillating movements).

- Affects the direct pathway and reduces its function
  - Due to death of cell bodies in the substantia nigra, there is inadequate input to the basal ganglia via the nigrostriatal bundle
  - This results in the indirect pathway becoming overactive
  - This causes much activity in the internal portion of the globus pallidus, which in turn
  - Inhibits the thalamus and
  - Results in decreased motor activity

Huntington’s disease

- Huntington’s disease is characterized by:
  - **Hyperkinesias,** which are involuntary, undesired movements
    - **Chorea:** uncontrollable, jerky movements such as twitching and abrupt jerking of the body.
    - **Athetosis**: involuntary writhing contractions and twisting of the body into abnormal postures.

- Affects the indirect pathway and reduces its function
  - Selective loss of striatal neurons that bind gamma-aminobutyric acid (GABA).
  - These neurons give rise to the indirect pathway from the striatum to the globus pallidus
  - Loss of inhibitory input to the external globus pallidus causes it to become more active.
  - Resulting in increased inhibition of the subthalamic nucleus.
  - Hence, the subthalamic nucleus does not excite the internal section of the globus pallidus
  - Reducing output from the globus pallidus,
  - Which lessens inhibition of the thalamus,
  - Which in turn leads to more motor activity in the cortex

Cortical Regions

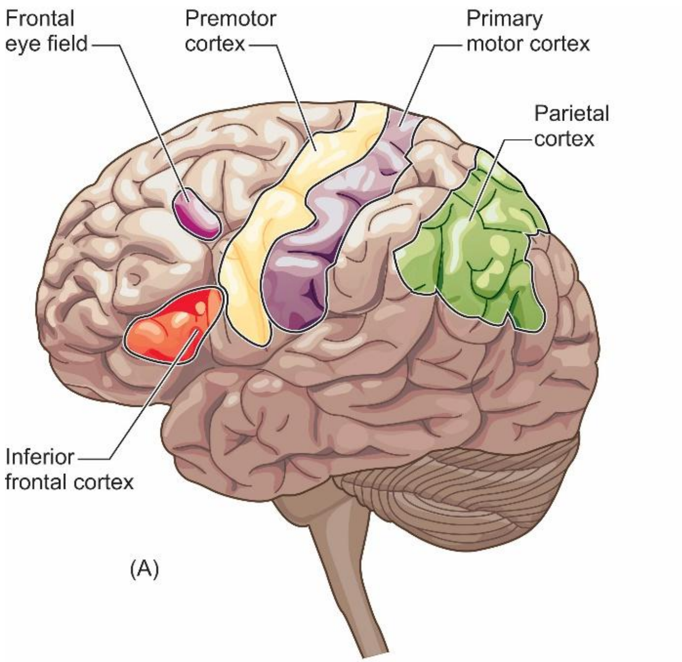
- The major role of cortical regions in motor control is in
  - Planning and guiding skilled movements and
  - Movements that require linking sensory inputs with motor outputs.
- Cortical regions support a range of motor abilities including:
  - picking up an object
  - producing a gesture in response to a verbal command
  - moving the eyes to explore the image of a face
- Regions involved in motor control are distributed across both lateral and medial portions of the brain

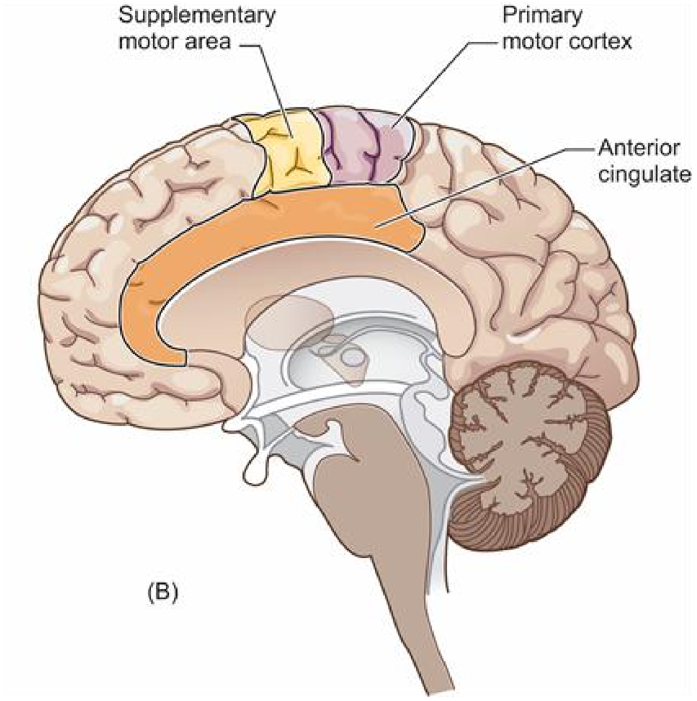
Cortical Regions

Lateral Regions

- the **primary motor cortex**
- the **premotor cortex**
- the **frontal eye fields** (FEFs)
- Parietal cortex

- **Medial Regions**
  - **anterior cingulate cortex**
  - the **supplementary motor complex** (SMC)





Cortical Regions: Contributions

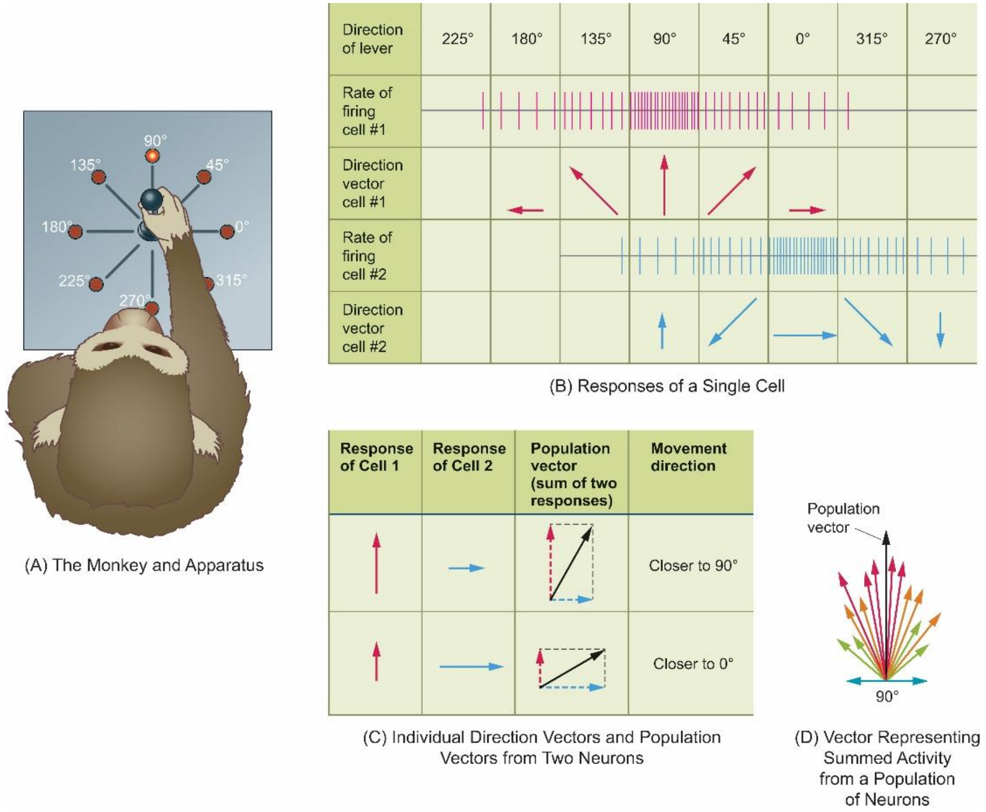
- Primary motor cortex:
  - Thought to control the force and/or direction with which the motor plans are executed
- The premotor region, supplementary motor complex, and frontal eye fields:
  - Involved in the specifying, preparing, and initiating of movement
- The anterior cingulate:
  - Important for selecting among particular responses and monitoring whether the execution of those actions occurred appropriately
- Parietal regions:
  - Involved in linking movements to extrapersonal space and sensory information, as well as linking movements to meaning, as occurs in gesture.
- Through the multiplicity of roles of these regions and their coordination, the richness of our ability to act on the world is expressed.

Cortical regions: Primary Motor Cortex (M1)

- Provides the command signal to drive motor neurons to make muscles move.

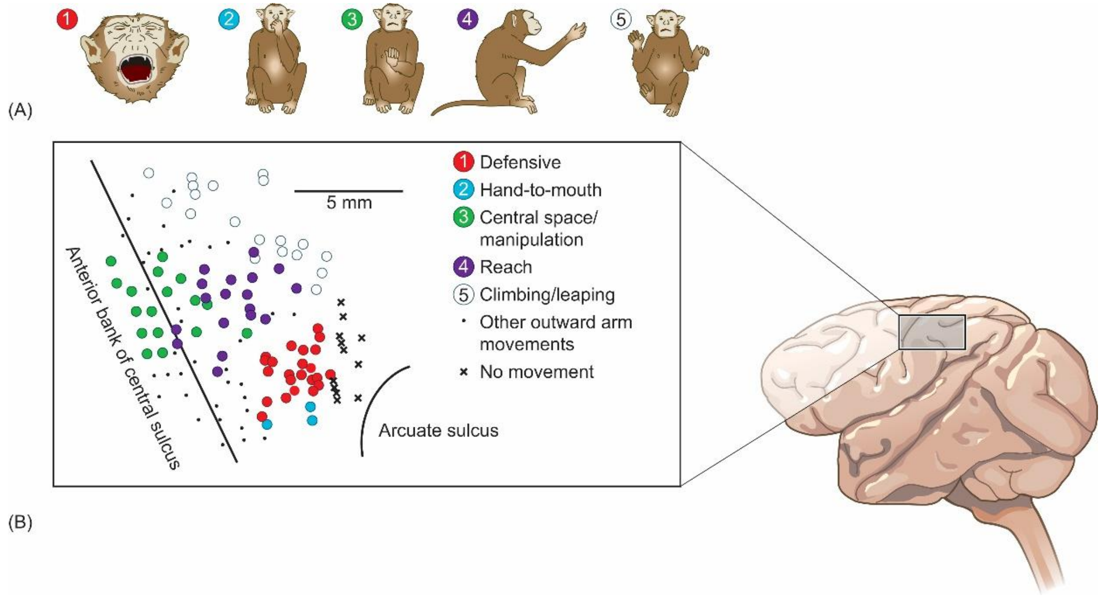
- When damaged, the person cannot control the force with which muscles are exerted.
    - In the most severe cases the result is hemiparesis, the inability to make motor movements on one side of the body.

- Summed activity across the population of neurons determines the direction of the movement.



Cortical regions: Primary Motor Cortex, Organization

- Classic models argue that the motor cortex is organized so that different subregions of motor cortex control action of specific portions of the body, such as the fingers, arms, or legs.
- Alternative models suggest that motor cortex may be organized with regards to actions relevant for survival, such as reaching and defensive action

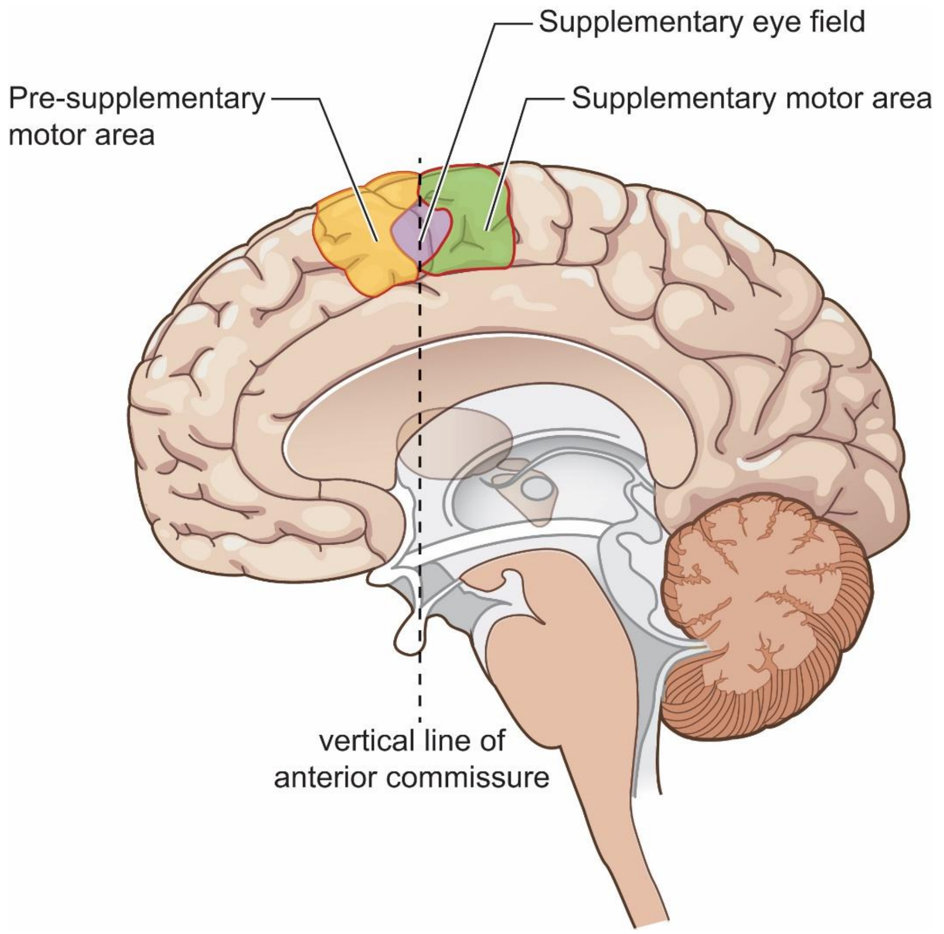


Cortical regions: Supplementary motor complex and Premotor areas

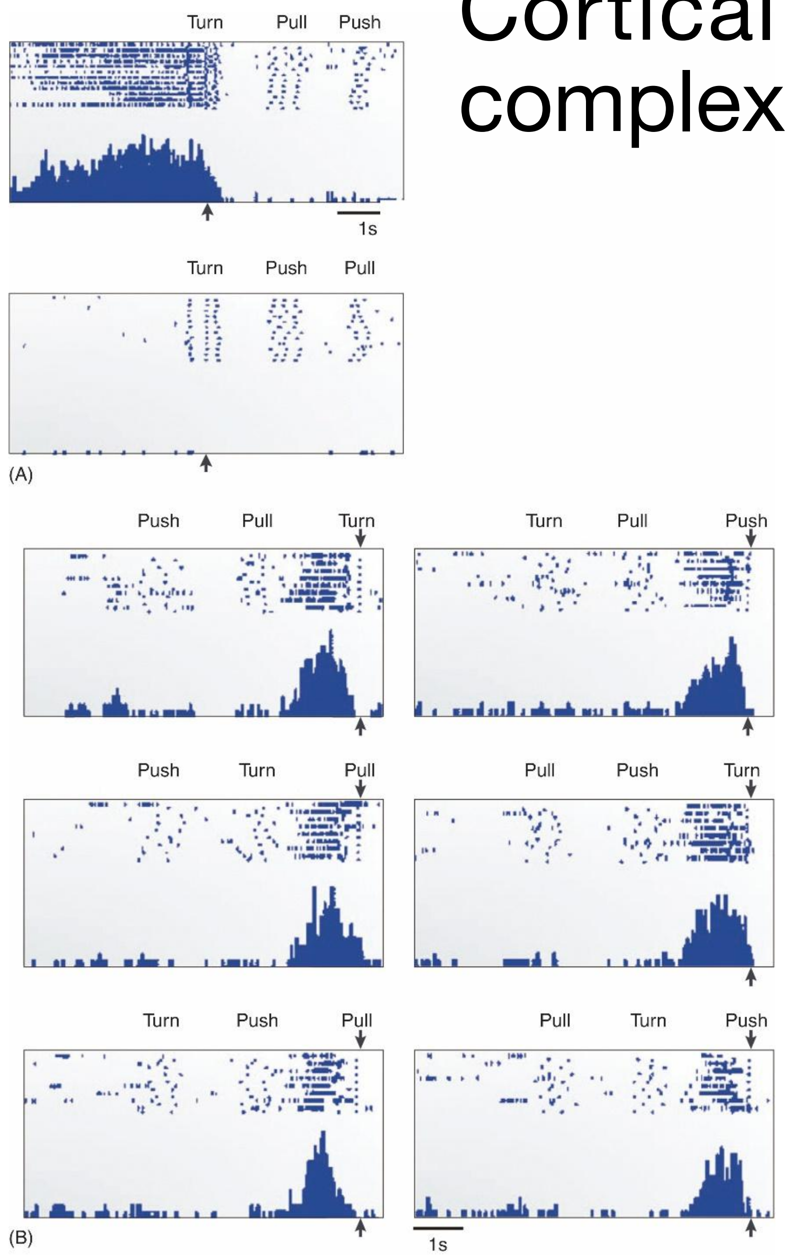
- Involved in creating a **motor plan**, which is an abstract representation of intended movement.
- The brain generates this entire plan of action before movement commences rather than creating the plan in a step-by-step manner as actions are being performed.
  - One manifestation is **coarticulation**, which refers to differences in how the vocal muscles produce sounds (most notably vowels) depending on what precedes or follows them.
- The supplementary motor complex (SMC) comes up with the motor plan at the most abstract level, that is, sequencing the critical pieces
- The premotor areas then code for the types of actions that must occur to meet that motor plan, and then
- Primary motor regions execute the commands to move the muscles.

Cortical regions: Supplementary motor complex

- Plays a role in planning, preparing, and initiating movements
- Composed of three subregions:
  - the more anteriorly located pre-SMA
    - Involved in selecting what actions should be implemented
  - the supplementary eye field (SEF)
    - Involved in the planning of eye movement.
  - the more posteriorly located supplementary motor area (SMA)
    - Involved in planning movement of body parts (other than the eyes)



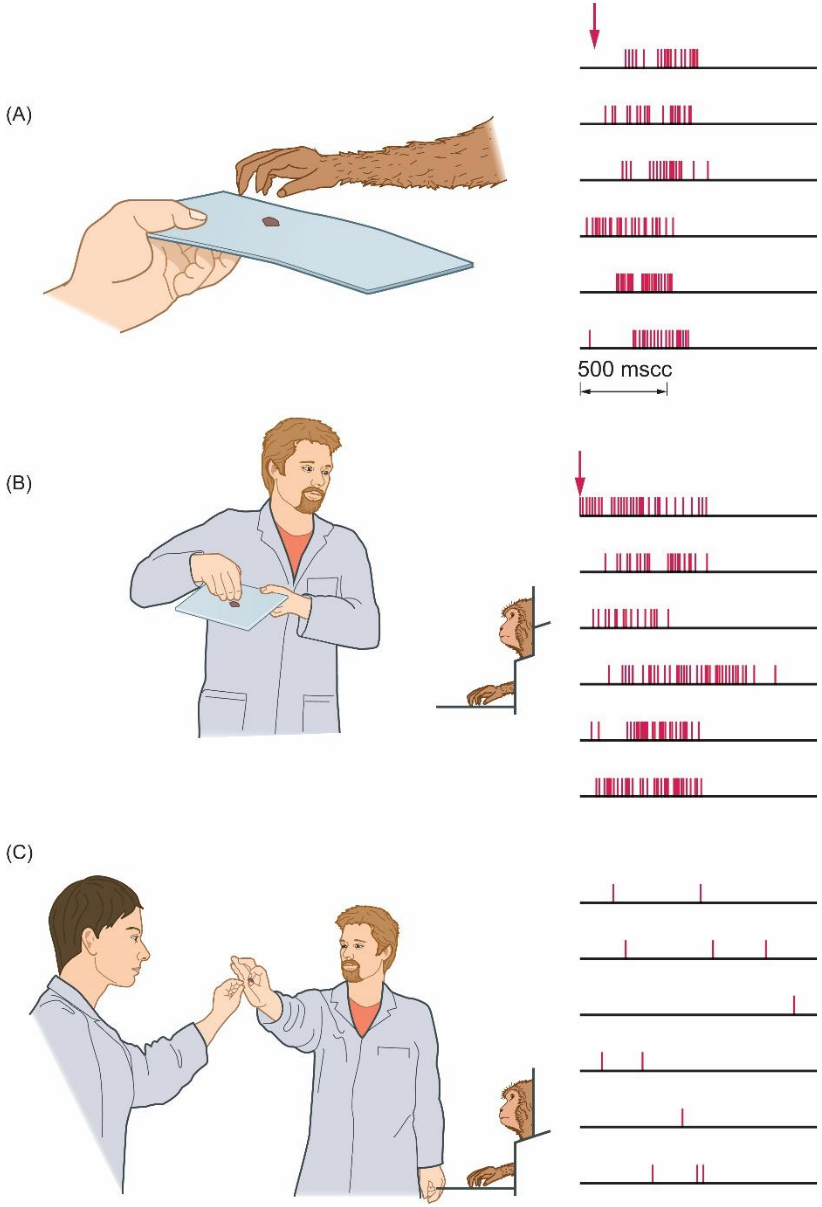
Cortical regions: Supplementary motor complex



- Its role in motor planning is indicated by findings that activity in this region precedes motor action.
- It plays an important role in planning the sequence and order in which actions occur.
  - E.g., SMC neurons will fire before a given sequence that starts with a particular action (say, a turn), but only when that action is followed by a specific sequence (say turn, pull, and then push a lever, but not turn–push–pull)
- SMC projects to both the ipsilateral and the contralateral motor cortex, as well as to the contralateral SMC.
  - Distinct from primary motor cortex in which activation is predominantly observed contralateral to the hand that is moving.

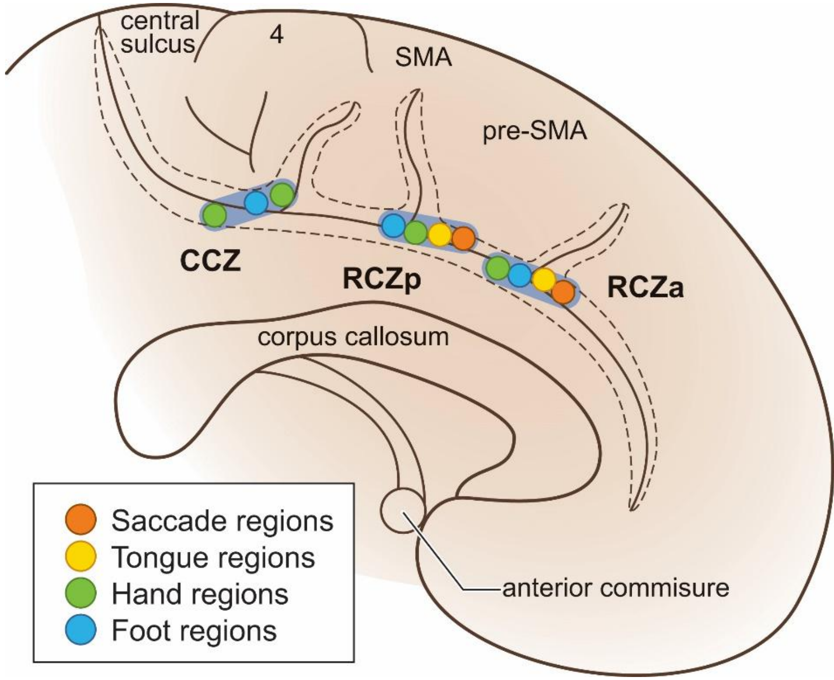
Cortical regions: Premotor regions

- Two distinct areas subregions
  - Dorsal premotor area (PMd)
    - Processes the motor significance of sensory cues, coding what type of motor action should be chosen or selected based on sensory information
  - Central premotor area (PMv)
    - More involved in implementing these motor programs and adjusting them so that objects can be manipulated
    - Contains *mirror neurons* that fire both when an action is performed and when another organism is observed performing the same action
      - Hypothesized that these cells may serve as a basic building block that allows for a shared communication system
- The **frontal eye field (FEF)** is a area specifically involved in planning and controlling the voluntary execution of eye movements.
  - Distinct from reflexive eye movements which are controlled by the superior colliculus.



Cortical regions: Anterior cingulate cortex

- Aids in the planning and execution of movement
- Most involved when an action is novel or requires cognitive control, such as when a well-engrained response must be overwritten
- Three divisions:
  - Caudal region
    - connects mainly to primary motor cortex and the parietal lobe
    - may modulate or override activity during simple motor tasks
  - Middle region
    - connects primarily to premotor cortex
    - may modulate the selection of movements
  - Anterior region
    - connects primarily to dorsolateral prefrontal cortex
    - may modulate more complex motor actions or become active when a high degree of conflict exists.
- Within each region there is a specific topography that is linked to the body part that will be performing an action



Cortical regions: Right inferior frontal cortex

- Suggested to play a role in interrupting or inhibiting motor actions.
- This ability is often assessed via the stop-signal paradigm
  - Participants press a button whenever a stimulus appears
  - However, on some trials, a cue occurs after the stimulus, signalling that individuals should abort their motor action.
- Greater damage to the right inferior frontal cortex is associated with more difficulty on the stop signal task
- However, this region is also activated when people have to push a button twice rather than aborting a response
- Hence some researchers argue that the right inferior frontal lobe plays a role in in altering actions based on the current environmental context rather than in inhibiting actions.

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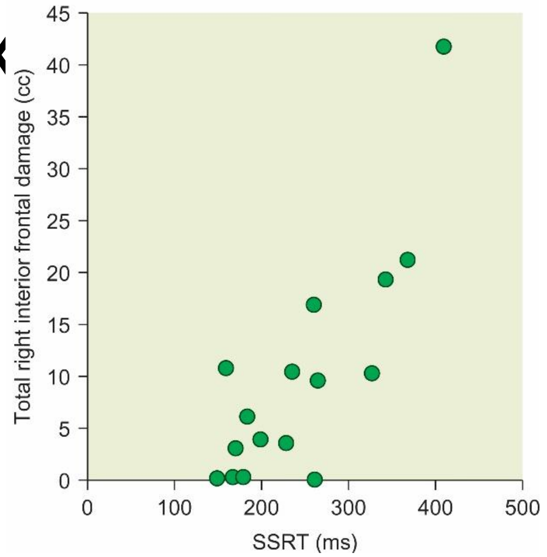

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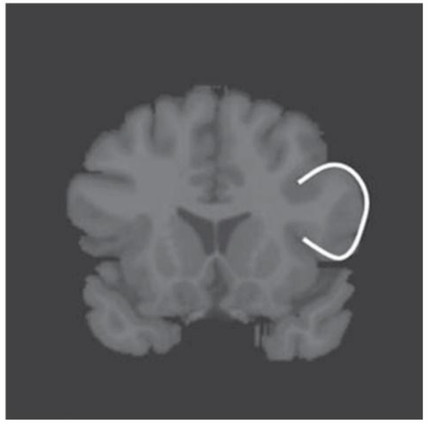
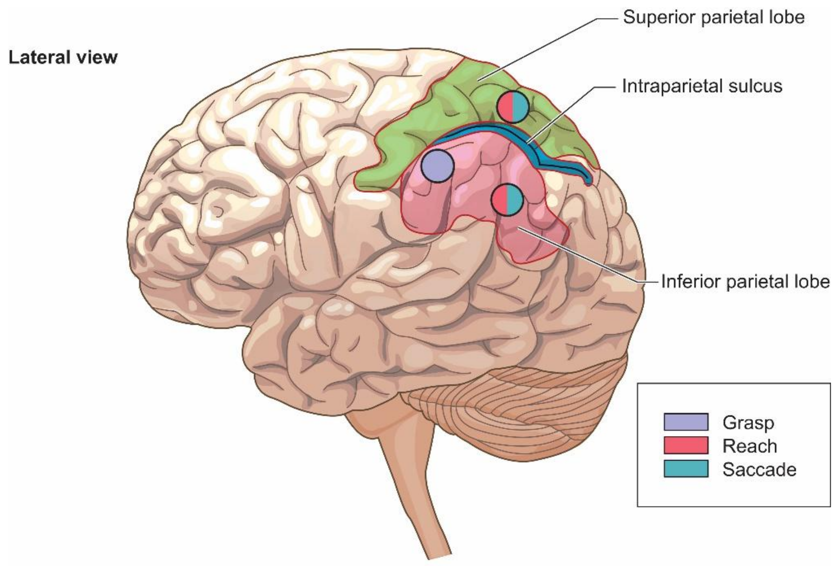
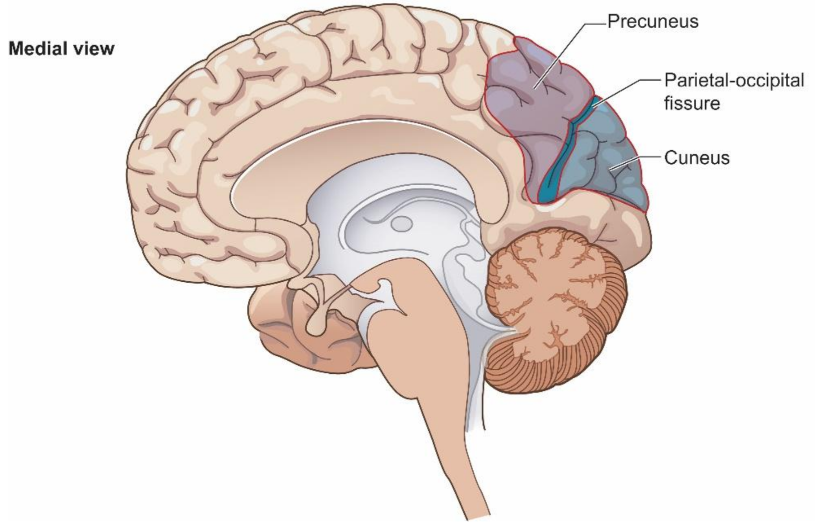


Cortical regions: Parietal lobe

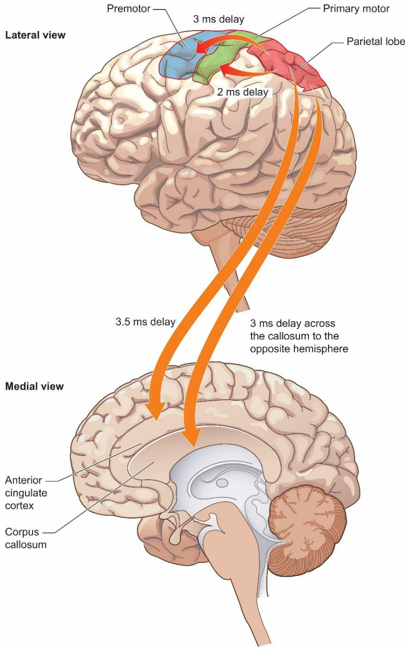
- Parietal regions are sensitive to:
    - *proprioceptive information*, a type of sensory information received from internal sensors in the body, such as that about the position of body parts relative to one another
    - *kinesthetic* information about actual movement of body parts.
- Proprioceptive information can be sent forward to premotor and primary motor regions to enable the selection of appropriate motor programs, which in turn provide feedback to parietal regions.
- Superior regions act as an interface between movement and sensory information, so that the limbs or eyes can be guided correctly during motor acts.
    - Damage leads to an inability to guide limbs in a well-controlled manner, and is often accompanied by a tendency to misreach.
- Inferior regions contribute to the ability to produce complex, well-learned motor acts.
    - Damage to these regions leads to a disorder known as apraxia.





Integrated models of motor system

- Regions can be conceptualized as involved in
  - Movement Planning
  - Movement Specification and Initiation
  - Movement Monitoring



- Information transfer between regions must take into account differential neural conduction delays between regions

Table 4.1 Functions of Major Brain Regions Involved in Movement

Brain Region	Computation
Movement Planning	
Inferior parietal regions	Generating an estimate the state of limbs and effectors required for a movement
Supplementary motor complex	Selecting and initiating the order of movements
Premotor area	Selecting the types of movements required (e.g., a grasp)
Frontal eye fields	Voluntarily controlling saccades
Posterior regions of the anterior cingulate cortex	Selecting among competing responses, initiating novel responses, and overriding prepotent responses
Movement Specification and Initiation	
Cerebellum	Creating a forward model
Basal ganglia	Switching between different patterns of movement initiation and cessation; chunking motor patterns; modulating movement parameters, such as their vigor
Motor cortex	Executing the force and/or direction of movement; driving muscle activity
Movement Monitoring	
Anterior cingulate cortex	Evaluating the outcome of a response (e.g., detecting when an action is erroneous or its consequences are unexpected)
Parietal cortex	Using sensory feedback to adjust movement on-line

Motor disorders: subcortical motor disord

Parkinson's disease

- Four major symptoms (generally observed on both sides of the body):
  - **tremors**,
  - **cogwheel rigidity**,
  - **akinesia/bradykinesia**, and
  - **disturbances of posture**
  - Not all of these symptoms are always observed in any one person.
- Due to loss of dopaminergic neurons in the substantial nigra
  - Reduces activity of direct pathway and leads to overactive indirect pathway
  - Behavioral effects of the disease typically are not evident until 60% of nerve cells and 80% of dopamine is lost.
  - Delay in symptom onset occurs because the brain tries to compensate for the loss of dopamine in a number of ways.

Motor disorders: subcortical motor disorders

Parkinson's disease

- The severity of rigidity and bradykinesia can be directly predicted by the degree of dopamine depletion as measured by PET.
- Parkinson's also may involve alterations in neural synchrony
- The mechanism that produces tremors is not clear
  - May be an attempt at compensation by regions downstream from the cerebellum to compensate for low levels of movement.
  - Another possibility is that tremor is caused by the disruption of circuits between the cerebellum and the thalamus.
  - Other evidence suggests that a different neurotransmitter system, serotonin, is associated with tremor
    - the depletion of serotonin (rather than dopamine) may predict the severity of tremor

Motor disorders: subcortical motor disorders

Parkinson's disease

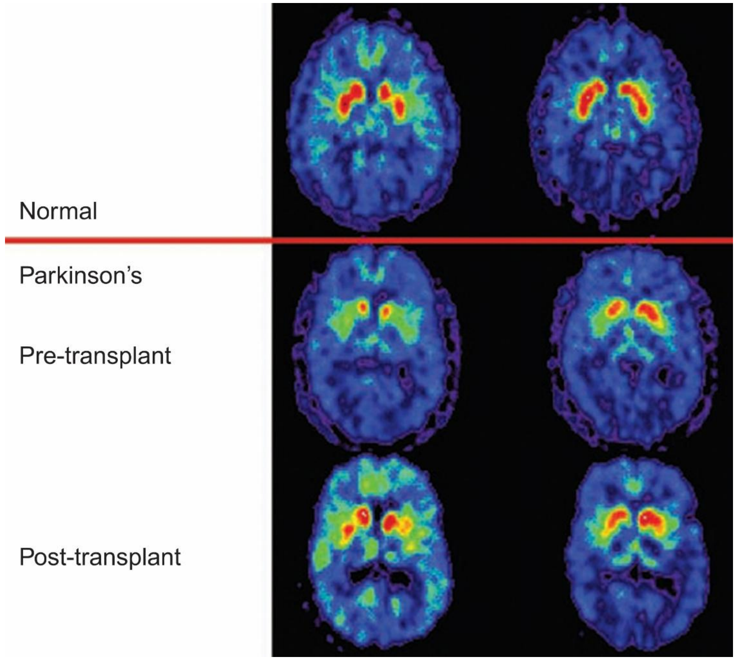
- Etiology of the disease is not clear
  - general agreement that it results from a complex interaction of genetic and environmental factors
- Standard treatment typically is drug therapy designed to increase the level of dopamine such as L-dopa which ameliorates the symptoms but is not a cure
- These drugs have numerous side effects:
  - May alter a person's mood, leading to euphoria or depression.
  - Sometimes they interfere with memory and the ability to pay attention.
  - Can lead to disorders in impulse control (such as binge eating, pathological gambling, hypersexuality, and compulsive shopping).
  - In extreme cases, an individual may even experience hallucinations and delusions.
- These side effects tend to go away when the person stops taking the drug or when the dosage is reduced.
- Medicine tends to lose effectiveness after a number of years.

Motor disorders: subcortical motor disorders

Parkinson's disease

Experimental therapies

- Grafting into the striatum of fetal tissue rich in dopamine-producing cells
  - Initial results seemed promising, but does not always work and sometimes had unintended side effects.
- **Deep brain stimulation (DBS)**, in which electrodes are implanted into the brain to stimulate tissue.
  - Appears to be quite effective but
  - Potential side effects include stimulation spreading to surrounding structures, negative neurocognitive changes, and the invasiveness of the procedures.
- Intensive behavior training for certain compromised behaviors exhibited by Parkinson's patients can have wide-reaching effects.



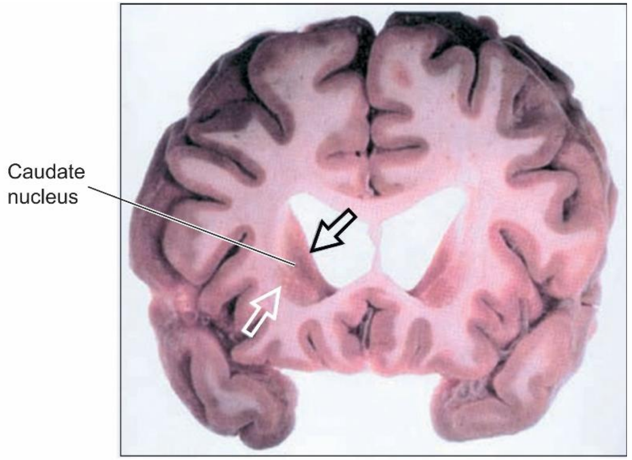
Motor disorders: subcortical motor disorders

Huntingdon’s disease

- Produces abnormal movements, cognitive deficits (eventually dementia), and psychiatric symptoms.
  - Main motor symptom of Huntington’s disease is **chorea**, a variety of rapid, jerky movements that appear to be well coordinated but are performed involuntarily and ceaselessly in an irregular manner.
    - They never involve just one muscle, but instead affect whole limbs or parts of a limb.
  - Also present is **dystonia**, slower movements caused by increased muscle tone and contractions that lead to abnormal posture, such as tilting of the head or arching of the back.
  - Eventually, all movement becomes uncontrollable as the disease affects most of the body, including the head, face, trunk, and limbs.
- Caused by an autosomal dominant gene. Although rare (1.6 cases per million), when the Huntington’s gene is inherited, it always expresses itself.

Motor disorders: subcortical motor disorders

- **Huntingdon's disease**
- Leads to atrophy of the striatum, with the disease usually manifesting in earnest between the ages of 30 and 45 years.
- The reduction in the size of the caudate has been linked to the severity of both motor and cognitive deficits
- The size of the striatum in individuals who are carriers of the Huntington's gene but not yet exhibiting motor symptoms is a predictor of disease onset, up to 15 years prior to diagnosis.
- Although atrophy is most pronounced in the striatum, atrophy is observed in other brain regions as well, including the cingulate cortex, and premotor cortex, among other regions thalamus.



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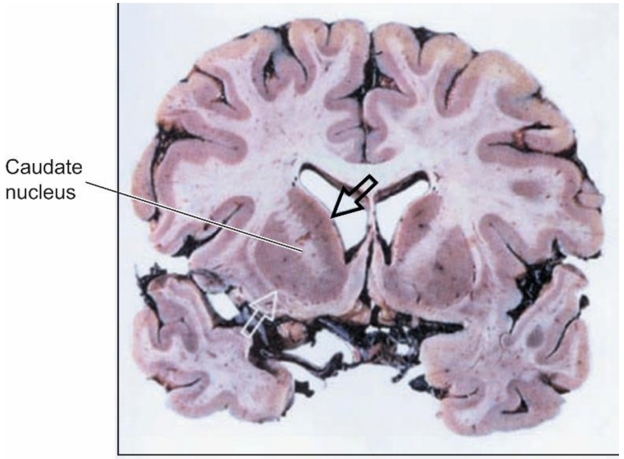


(A)

Motor disorders: subcortical motor disorders

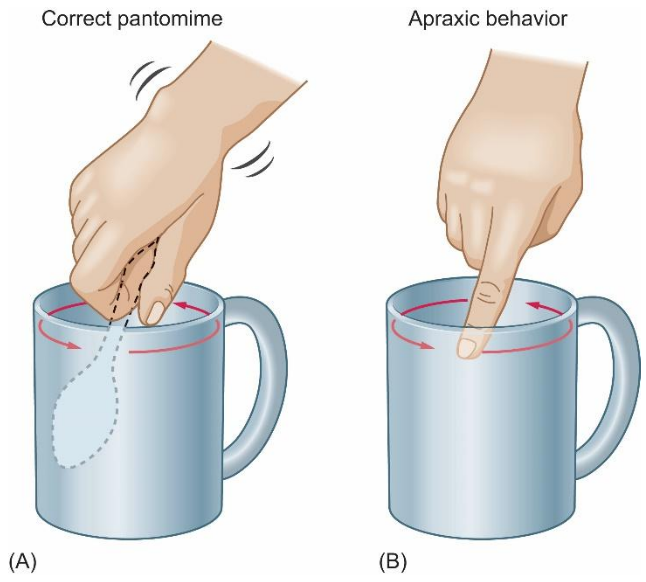
Tourette's syndrome

- Relatively rare disorder that manifests as a variety of vocal and motor **tics**, which are repetitive involuntary movements of a compulsive nature.
- Can vary in severity from a few tics that occur only when the person is tired or tense to between 30 and 100 tics per minute.
- Manifests in childhood, usually before the age of 11 years.
- Because these motor tics occur involuntarily, repetitively, and in a stereotyped manner, Tourette's syndrome has long been thought to involve dysfunction of subcortical motor regions
- Evidence points to dysfunction of the basal ganglia and the associated cortical–striatal–thalamic–cortical brain circuitry, with alterations of both dopaminergic and GABAergic function.

Motor disorders: cortical motor disorders

Apraxia

- An inability to perform *skilled*, sequential, purposeful movement that cannot be accounted for by disruptions in more basic motor processes (e.g., muscle weakness).
- Tends to disrupt the ability to pursue specific plans of motor action
  - E.g., Striking a match against a matchbox cover
- or to relate motor action to meaning
  - E.g., Pantomime, gesture
- Commonly observed after stroke, traumatic brain injury, and in people with neurodegenerative disorders.



Motor disorders: cortical motor disorders

Apraxia

- Classically (Liepmann, 1905) differentiated two types of apraxia
  - **ideational apraxia:** impaired ability to form an idea of intended movement
  - **ideomotor apraxia:** disconnection between the idea of the movement and its execution
- Decades of debate around the definition of these disorders, and whether they indeed represent two separate syndromes.
- Some researchers instead categorize apraxia on descriptive grounds
  - e.g., “apraxias of symbolic actions” or “apraxias of object utilization”.
- Others classify apraxia by reference to the part of the body that is affected
  - If facial movements are disordered, the condition is known as **oral (buccofacial) apraxia.**

Motor disorders: cortical motor disorders

Lesions that lead to apraxia

- No agreement on the lesion location that leads to apraxic behavior.
- But most typically observed after parietal or frontal lesions of the left hemisphere
- Conception, planning, and production of skilled movement, often referred to as **praxis**, probably requires a set of brain structures
  - including the parietal, prefrontal, motor, and subcortical regions,
  - each contributes in a different manner to the planning, retrieval, and/or implementation of motor action plans.

Motor disorders: cortical motor disorders

- Related syndromes, while referred to as apraxia appear to arise primarily from difficulty in spatial processing.
  - In **constructional apraxia**, items cannot be correctly manipulated with regard to their spatial relations.
  - In **dressing apraxia**, the affected individual has difficulty manipulating and orienting both clothes and his or her limbs so that clothes can be put on correctly.
- s
  - **Callosal apraxia**, is a disconnection syndrome, which is characterized by an inability to perform a skilled motor act with the left hand in response to a verbal command
    - Verbal information interpreted by the left hemisphere cannot be transferred to the opposite hemisphere to control the left hand due to a lesion of the callosum