MODULE 1. The Motor Cortex and Corticospinal Tract

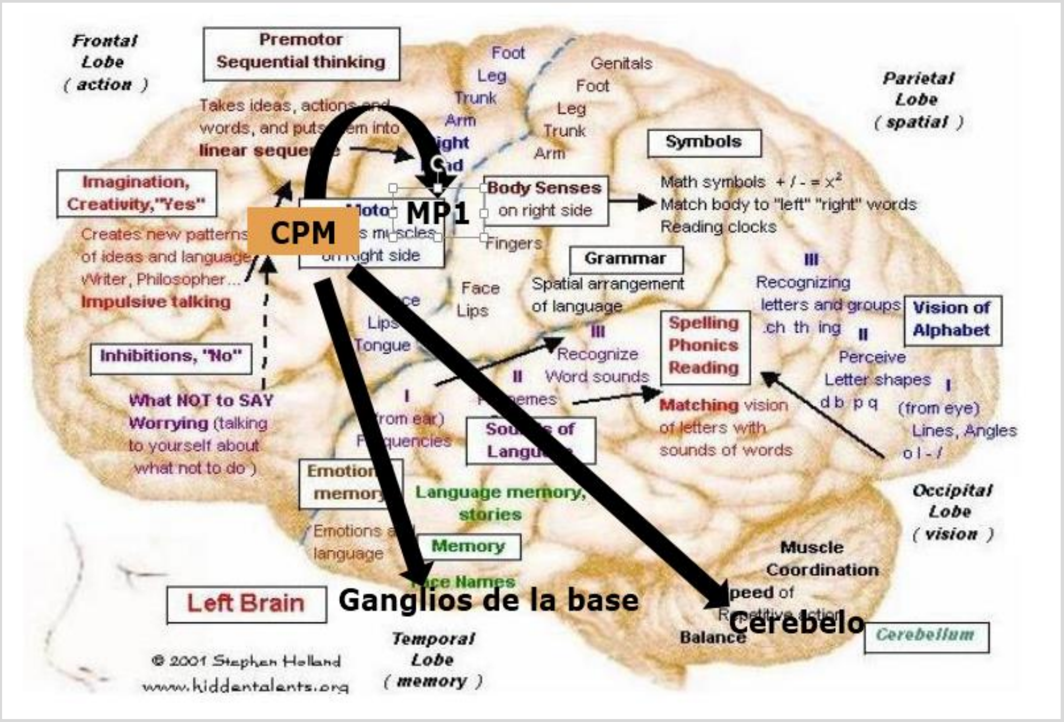
Unit 1.1 Motor Areas

1.1.1 Dimensions of Motor Programs

Following the final decision that bars or initiates the motor program in the supplementary motor pre-area (pre-SMA), it is distributed to the different sectors of the CNS. We include the following primary destinations, without discarding the possibility of others (their functions differ and all are important):

- Primary motor cortex.
- Cerebellum.
- Basal Ganglia.

Figure 1: Dimensions of Motor Programs



Source: Prepared by the author

Overall Description of these Destinations

The apparent immediate destination is the primary motor cortex or **Brodmann area 4**, also called 1MC. However, there are another two destinations that receive the motor program data or **efferent copy** (expected value): the **basal ganglia** and the **cerebellum**. The basal ganglia are responsible for muscle tone, acceleration, and stopping, while the cerebellum focuses on making the necessary corrections and adjustments, or otherwise changes the program if required.

One of the most fascinating aspects refers to the **start of voluntary action** and its immediate development, which assumes communication between the premotor and primary motor cortices. The connection that concerns us at the moment is between the premotor cortex (PMC) and the primary motor cortex (1MC). It is this that triggers actual movement and promotes the action internally, although the other two destinations of the motor program are also crucial, above all to understand motor control, which we will analyze later on.

Primary motor cortex

The **primary motor cortex** is responsible for initiating movements, sending efferent signals to the motor nuclei of the spinal cord. As we will outline in the following topic, the 1MC does not act alone, but instead constitutes the last step before the efferent signal reaches the spinal cord. The primary motor cortex receives signals from the **pre-motor area**, which is responsible for storing motor programs that the individual has been creating throughout their entire motor function history.

The primary motor cortex cannot send the efferent motor signal if the supplementary motor area does not authorize the start of the action. There are other nerve structures that send afferent signals to the 1MC; these will be outlined in other topics of this course.

Basal Ganglia

Physiologically, basal ganglia are considered to be made up of: the **caudate nucleus**, the **putamen**, the **globus pallidus**, the **substantia nigra** and the **sub-thalamus**. However, significant portions of the thalamus, reticular formation and red nucleus work closely with the aforementioned components.

The basal ganglia have functions that have an impact on muscle actions. These "contain a repertoire of motor automatisms or engrams that, used in this context, would favor the intervention of relevant muscles" (Rigal, 1987, p.86).

Cerebellum

One of the organs that make up the encephalon. It is responsible for regulating muscle tone, balance (tonic), and facilitating movements through tonic pre-activation of the muscles (Rigal, 1987).

The cerebellum participates in **sensory-motor integration** and, by doing so, benefits motor control. The processes performed by this organ are, generally, not a target for consciousness, as they are actually subcortical actions.

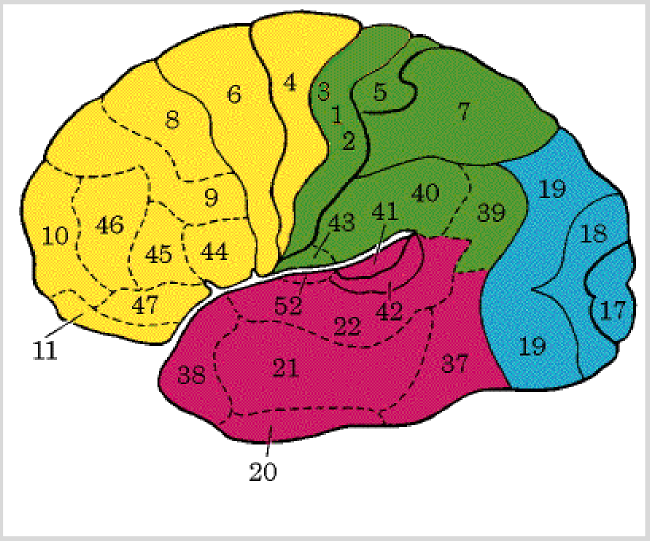
Based on the signals received from the different proprioceptors, the cerebellum can act on movement, and thereby generate small adjustments, or otherwise change the motor action. This is because this organ receives a motor copy of the programmed movement beforehand and constantly compares it with what is being performed (Snell, 1999).

1.1.2 PMC and 1MC, the Pianist and the Kinesthetic Melody

Located on the anterior face of the fissure of Rolando (central sulcus) is the **precentral gyrus (motor strip),** which contains the primary motor cortex (1MC). The precentral area is characterized by "the almost complete absence of granular layers and predominance of pyramidal nerve cells" (Snell, 1999, p. 297).

The **precentral area** can be divided into two regions: the anterior region and the posterior region. The **anterior region** contains the pre-motor area, which comprises Brodmann area 6 and parts of areas 8, 44 and 45; the **posterior region** on the other hand, contains the primary motor cortex or Brodmann area 4. When this sector is stimulated electrically, movements are produced in the opposite side of the body as a result of muscle contractions set off by this stimulus.

Figure 2: Brodmann Areas



Source: [Untitled image of the Brodmann areas]. (undated). Taken from https://goo.gl/Z3QeaP

The movement areas in the precentral region are represented inversely (Snell, 1999). This is explained in the following way: located in the inferior part of the precentral cortex are the structures responsible for swallowing, such as the tongue, jaw, larynx, and other structures, such as the eyelids, eyebrows, and lips. Continuing upward, you find an extensive area that is responsible for the movements of the fingers, wrist, elbow, shoulders, and trunk. The movements of the hip, knees, and ankles are represented in the highest sector of the precentral cortex. The dimension of the area that controls each movement depends on the precision and skill that each movement requires: the finer the movements of a specific segment, the greater the dimension that will represent it in that region (see motor homunculus).

Regarding this we can say that **area 4** is responsible for starting movements in different sectors of the body, although this does not mean in any way that it acts alone. The primary motor cortex (1MC) "is the final station for converting the design into an executed movement" (Snell, 1999, p. 299). The 1MC does not create the movement's pattern, it executes it using the information it receives from structures such as basal ganglia, cerebellum, thalamus and the sensory cortex.

In order to explain the function of the 1MC, it can be compared to the keyboard of a piano. The keys represent the muscles and the movement of these depends on which keys the musician plays. Each muscle would have a specific number of keys: the more motor units it possesses, the more keys the muscle in question will have. The number of motor units that they innervate will depend on the precision of the movements to be performed (this will be seen in greater detail in the “motor homunculus” section).

The **pre-motor area** does not have large Betz pyramidal cells, since it is not specifically responsible for executing movements. Instead, the pre-motor area stores motor programs that are produced from past motor experiences. The primary motor cortex (PMC) receives multiple sensory afferent signals from different nerve structures, such as the thalamus and basal ganglia.

In addition to the specific areas responsible for motor efferent signals, the **way the information enters the cerebral cortex** is also of great importance. One question that should be considered is that when the information reaches the primary projection area, it does not do so haphazardly, but rather follows a very specific path of conduction in the granular layers. Another interesting detail of primary projection areas is the existence of a topography that reflects the distribution of receptors on the periphery. For example: in the visual primary projection area or Brodmann area 17, a specific set of neurons corresponds to each sector of the retina (the rods of the retina correspond to a more external sector of the primary projection area (PPA) and the cones correspond to a deeper or more central sector). In these primary projection areas, access to information is organized and stimulation of the neurons that constitute it also follows a specific order. The combination of this information between the granular layers also follows a precise order. There is a structural and functional order to capture information with greater quality (Snell, 1999).

Finally, with regards to the topic of **neuromotor programming**, because of its complexity, we suggest comparing it to a theater play. A **theater play** remains unchanged throughout the years. Its script, its scenes, the characters may change slightly. but if the main actors were essential, the play would not be able to continue when they grew old and died. It is exactly for this reason that the actors are changeable, they are temporary and it could be one or another. By contrast, the play itself, meaning the engram, is essential. In reality, the protagonists or actors are muscles and the act of programming decides which muscle performs in the play. If the muscle was essential and experiences some problem, such as an illness or limitation, we could no longer deploy the engram, which would be a huge disadvantage in evolutionary history. On the contrary, it is an advantage for the muscle to be contingent and the engram not to be contingent. **Program** *is to make decisions in respect to the involvement of the invariant or engram*; in short, it is the assembly of a sequence with very specific actors which are the different muscles that perform the movement. When the supplementary motor area provides the "approval" to start the action; that is, unblock or allow it to start, the motor program communicates or transmits to the primary motor cortex to start development sequentially. Accordingly, the stimulatory information travels along the spinal cord to the different muscle groups so that the movement can ultimately be deployed.

Some suggest comparing the motor program to a **kinesthetic melody**, as proposed by Alexander Luria (1973), who understood the motor program as a musical score produced in the brain. The implementation of this score would be the melody responsible for the muscle activations, which would fulfill the roles of musicians that are conducted by the cerebellum.

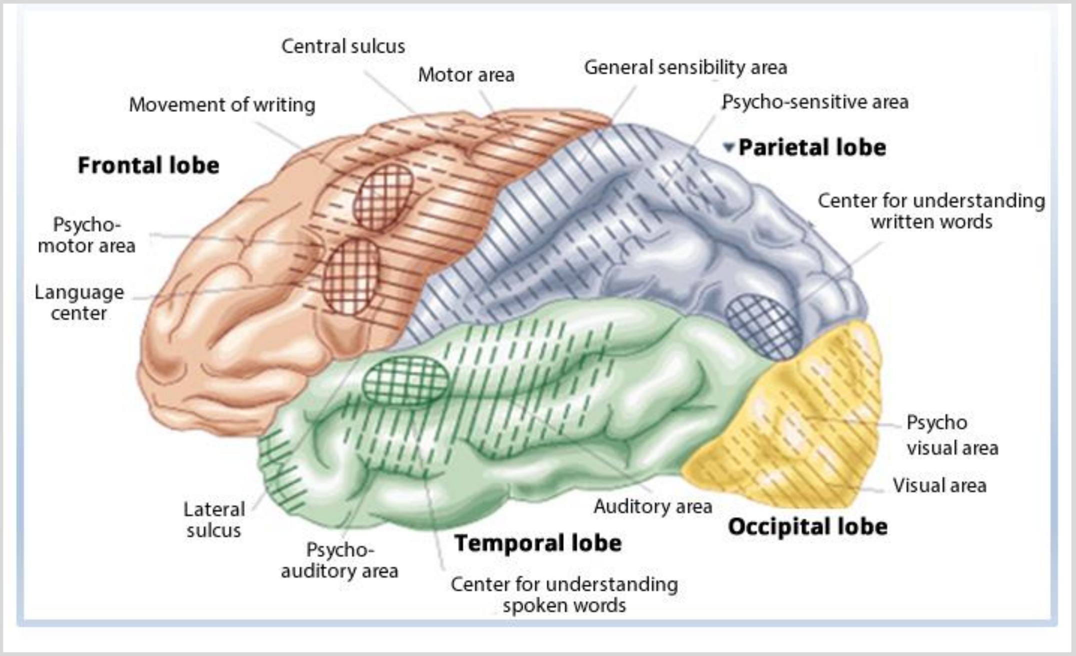
In the last stage of the motor act, when the motor program is ready, several copies are emitted to different sectors of the nervous system. This occurs even before the supplementary motor area stops prohibiting the movement and begins to unfold from the action of the primary motor cortex. The basal ganglia receive the information about the motor program before they start to execute the movement and our muscle tone starts to accumulate so that the quality of the movement can be sustained for an effective background (including the red nucleus that the gamma activity controls). In addition, the cerebellum receives a copy in order to regulate the motor act and compare the action in practice with the "ideal" model.

Once the motor program is chosen by the PMC and the 1MC is ready to recruit motor units, the **supplementary motor area (SMA)**, which is responsible for giving permission to the 1MC to act, enters into action, delaying the start of a movement or otherwise directly canceling the motor action. We could say that it is the SMA which authorizes the pianist to start the concert.

In processes for learning new movements, their execution will involve significant activity from one's consciousness, and although conscious processes will not be present during programming, they will be at the time this new motor pattern, movement, or action is implemented. In these instances, the **prefrontal cortex (PFC)** (together with other nerve structures) is responsible for assembling all components and parameters that form the motor program.

As an activity is practiced regularly, the responsibility of the PFC in its regulation will be reduced and, in so doing, leave it free to perform other actions. This is because the tasks that the PFC performed previously, at the time of automating a movement, will now be carried out by the subcortical nerve centers. When this happens, structures such as the basal ganglia take over control of the movement releasing the motor cortex to perform other functions, for example: decision-making.

Figure 3: The Pianist and Motor Programming



Source: Prepared by the author based on [Untitled image on motor programming]. (s. f.). Taken from https://goo.gl/vH2Agr

1.1.3 The Motor Homunculus

The information that was collected by the receptors and modified the status of the sensory neuron continues its journey to the control centers, is switched and enters the cerebral cortex. This information finally arrives at the cerebral cortex, which we call **primary projection area** or areas that have become specialized to receive this information after it has been processed by different lateral geniculate nuclei of the thalamus.

Among the areas of primary projection that we are interested in for processing the neuromotor information, we can cite: in the occipital lobe, Brodmann **area 17;** in the temporal lobe, **area 41;** in the parietal lobe (ascending temporal gyrus), **areas 3, 1 and 2** for processing mechanical, thermal and pain information; **area 5** for proprioceptive information, and lastly **area 7** for vestibular information (Guyton, 2006).

What particular features are present in these areas of primary projection?

To start with, we can say that the size "assigned" to each part of the body in each of the primary projection areas depends on the density of the receptors that this sector of the body has, which is why the idea of a small **sensory human or sensory "homunculus"** has been built.

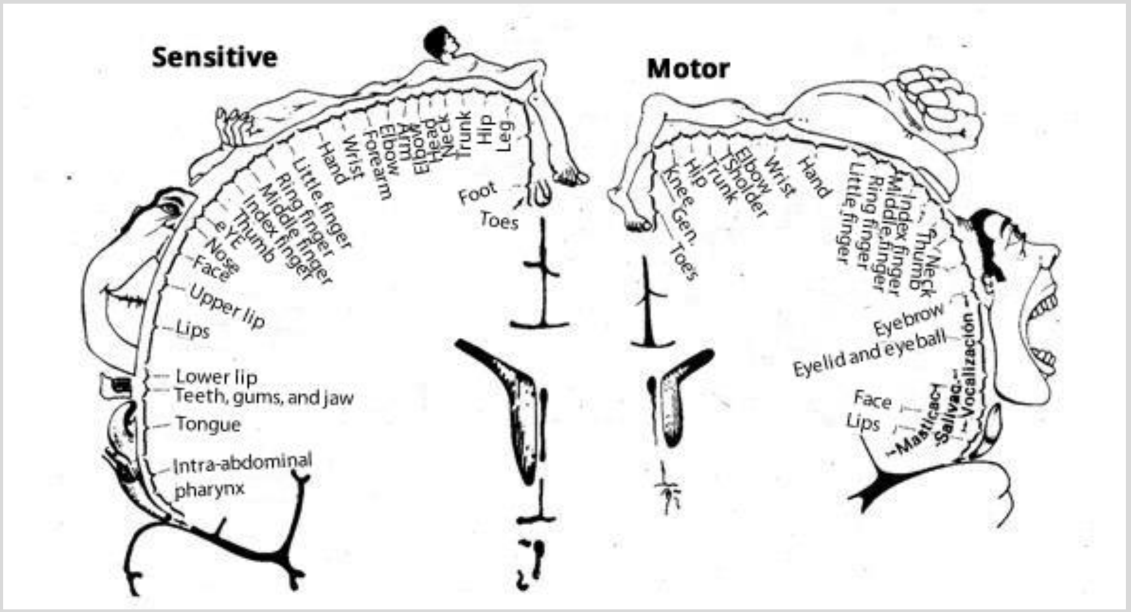
The second point that must be considered is that these areas map the distribution of the receptors in the rest of our body; that is, to be aware of the internal and external world.

In order to be able to build an object of perception, our brain must map the distribution of the information collection systems that are on the periphery of our body.

In a certain way, our brain is also a small map that accounts for the distribution of receptors on the periphery and this re-circulation of the information captured from the periphery by the structures of the CNS is precisely what allows us not only to be aware of the outside world, but also to generate the phenomenon of **self-awareness**; in short, the ability to detect not only what we perceive, but also what we do not perceive; that is, the inner world.

Returning to the sensory homunculus, this has been represented in different graphical forms.

Figure 4: Motor Homunculus and Sensory Homunculus



Source: [Untitled image of the motor homunculus and sensory homunculus]. (u.d.). Taken from https://goo.gl/aIxiYU

We can observe the large size of the hands, mouth, lips and tongue; that is, all those sectors of our body where we have a high density of receptors, which have tremendously small sensory fields. This happens in sectors of the body from where we have to collect vast amounts of information, and in turn, with great discriminative capacity, which clearly gives us evolutionary advantages.

There are differences and similarities between the sensory homunculus and the motor homunculus: increased fine motor control and, therefore, more space to represent the motor homunculus, coincides with more space to represent the sensory cortical homunculus. In other words, wherever increased calibration and fine motor adjustment is needed, we also need a higher density of receptors, which is why we find a large similarity between the homunculi. The exception is the genital region, an area where we need a very high level of sensitivity. However, for reproduction functions, we don't need fine motor function (in this case there is no similarity between the sensory and motor homunculus). If we consider the functions of our hands, lips, tongue and even our eyes, the similarities between the homunculi are very significant.

If we take a closer look at the primary projection areas, it is rather surprising that we can find **discriminative correlates** between each of the features we capture through each specific sensory system. For example: in the visual area, there are neurons that are arranged in different layers that activate in response to extremely specific features of an object, such as the different wavelengths. There are also neurons that react to vertical lines, obliques, or different angles to subsequently build the object through the act of perception.

In short, we can say that we find very specific neural analytical correlates that justify the sensory phenomenon. Perception is however, much more complex because it justifies the final construction of the object. It implies an **act of creation** where other areas, other subsystems of our brain end up building the object of perception or object of awareness.

1.1.4 Assemblage as an Object of Consciousness

After the action begins, the kinesthetic melody unfolds sequentially and its final manifestation is precisely the neuromuscular activation and the movement itself. In other words, the melody starts to play.

The deployment should include:

- Fluidity.
- Ensemble.
- Rhythm.
- Continuity.

This is where we find that the prefrontal cortex (PFC) and other areas must deal with assembling the different components of the motor program. The deployment of the kinesthetic melody is supervised by the frontal cortex, which cannot be occupied with anything else. The more automatic we make the movement, the more the prefrontal cortex is free to make decisions regarding other programs (Di Santo, 2015).

Motor automatisms are what allow us to perform motor skills or actions effectively without having to think about them. This enables us to execute several motor skills simultaneously. A clear example is driving a car: when we know how to drive a vehicle well, we do many of the motor actions, such as changing gear, stepping on the clutch, looking in the mirror, etcetera, automatically and, therefore, subcortically.

There are voluntary movements that are innate to each individual over which we do not have absolute control, but which can influence others, such as respiration and heartbeat. There is also a broad repertoire of movements called automatic or automated that are a consequence of the repetition of voluntary movements, which no longer need the intervention of the conscious mind or attention.

Automatic motility (paleokinethic) neuroanatomically corresponds to a first level suprasegmental paleoencephalon which comprises the striate body, subthalamic nucleus, substantia nigra, red nucleus, quadrigeminal tubercles, vestibular nucleus, bulbar olive, reticular formation and cerebellum. In mammals some areas of the cerebral cortex that control these subcortical paleoencephalic centers are added. During phylogenetic development, the paleoencephalic centers modify the discontinued reflex activity, which gives rise to automatic motility (Loyber, 1988).

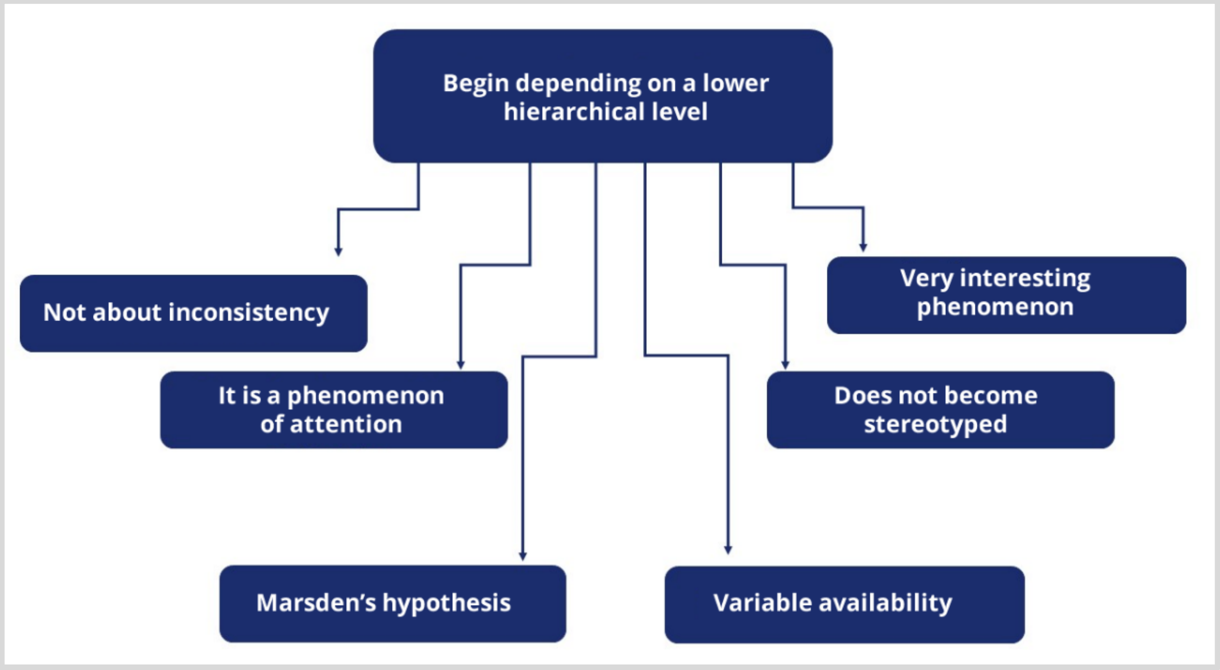
To conclude, we are able to divide the motor system into three levels:

1) **Superior level:** This is made up of the motor cortical areas, areas 6-4-SMA.
2) **Intermediate level:** This is made up of the brain stem, where the nerve pathways that innervate the spinal cord exit.
3) **Inferior level:** This is the spinal cord.

We will focus on the **superior level** given that this is where awareness of the movements is achieved. The **first level** is made up of the motor cortex which is responsible for planning movement and sending motor signals to execute them through the motor neurons located in the spinal cord. It is also connected to the medulla oblongata in order to regulate control of head movements. The cortex can act **directly or indirectly** on the (corticospinal) spinal cord. After leaving the cortex, the corticospinal tract reaches the brain stem and from there, the majority of the fibers **cross** the midline to the opposite side (lateral corticospinal tract). Only a small number of fibers do not cross, but instead travel directly to the spinal cord. The majority of the fibers of the corticospinal tract end in **interneurons**, while an even smaller number end in motor neurons (Tamorri, 2004).

The movements programmed by area 6 and executed by area 4 relayed by the motor neurons of the spinal cord are voluntary or conscious movements, while those that originate in inferior nerve centers may or may not be (Di Santo, 2015).

Figure 5: Hierarchical Levels



Source: Prepared by the author.

Unit 1.2 Giant Pyramidal Betz Cells and the Corticospinal Tract

1.2.1 Cortex, Layers, Plexus, and Columns

The **cerebral cortex** has three quarters of the neuronal bodies of the entire nervous system and, therefore, is indispensable for maintaining the conscious and voluntary functions of life. The cortex receives sensory afferent signals from different parts of the body, decodes, integrates, stores, and uses them to adapt behavior to any situation. (Rigal, 1987).

The cerebral cortex is made up of a series of **nerve fibers, neurons, neuroglia, and blood vessels.**

The cortex contains the following types of nerve cells:

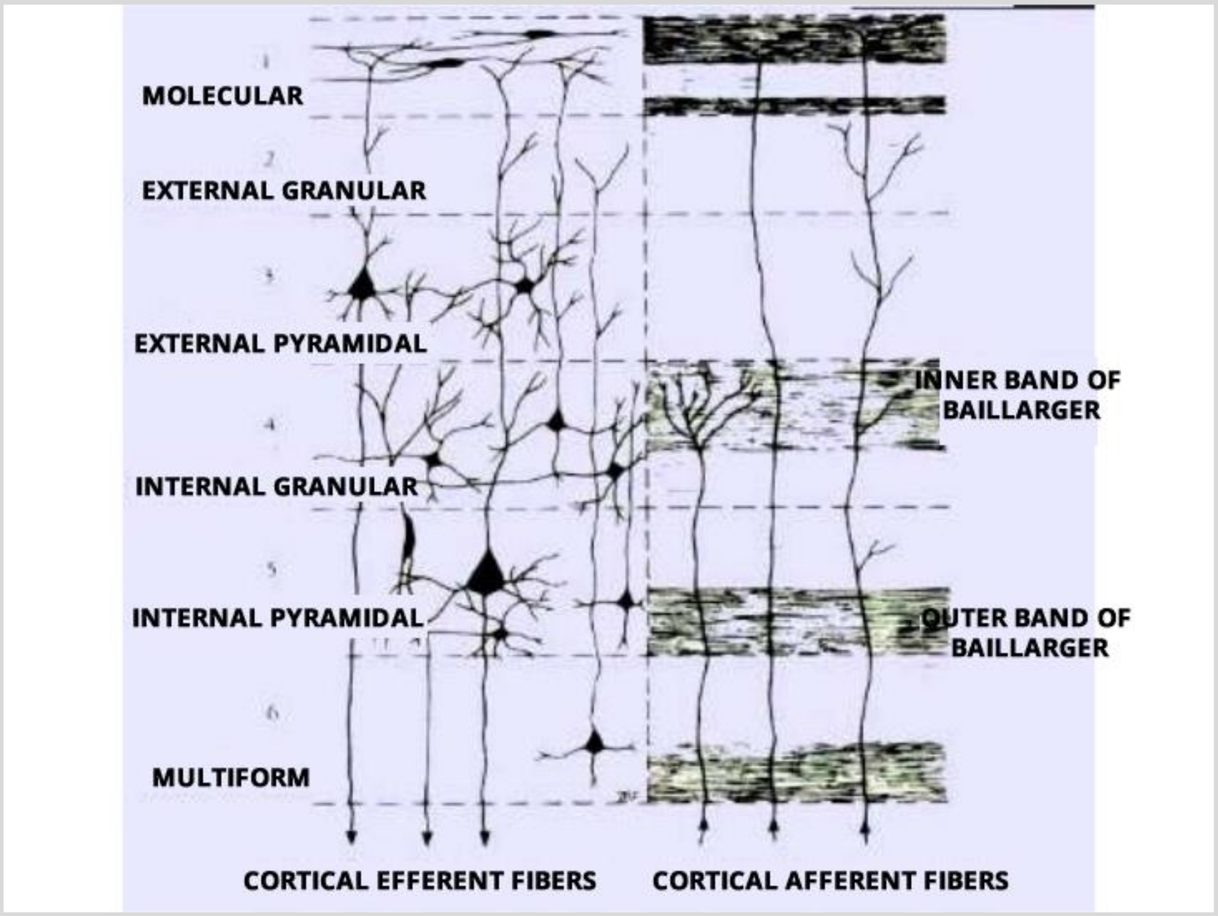
- **Pyramidal cells:** also called Betz cells, are the largest cells and can be found in the pre-central motor convolution. The vertices of these cells are oriented towards the cortex. From the apex of each cell, a dendrite extends towards the pia mater (internal layer of the meninges), where it emits collateral branches. The axon of these cells reaches the deeper cortical layers or enters the white matter of the brain as an association fiber.
- **Stellate cells:** these are polygonal shaped cells that have multiple branched dendrites and a short axon. They communicate with neighboring neurons.
- **Fusiform cells:** found in the deepest layers of the cortex, these cells possess dendrites emerging from each of their poles. The inferior dendrite branches within the same cellular layer while the superior dendrite ascends towards the surface of the cerebral cortex. The axon reaches for the white matter, much like the pyramidal cells' axon.
- **Horizontal Cajal cells:** these are small, horizontally oriented cells found in the most superficial layers of the cortex. The axon of these cells runs parallel to the cerebral cortex, making contact with the dendrites of the large Betz cells. The dendrites arise from each end of this cell.
- **Martinotti cells:** these cells are present throughout all layers of the cortex and the axon is directed towards the pia mater of the cortex (Snell, 1999).

We can divide the cerebral cortex into six layers, from the periphery to the center:

1) **Molecular layer:** connects the surface with the lower layers.
2) **External granular layer:** receives nerve signals from other layers of the cortex.
3) **External pyramidal layer:** projects the intercortical nerve impulses.
4) **Internal granular layer:** receives the nerve impulses from the medullary and subcortical centers.
5) **Internal pyramidal layer:** projects nerve impulses to the medullary and subcortical centers.

6) **Fusiform or multiform layer:** projects the impulse to the other hemisphere (Rigal, 1987).

Figure 6: Layers of the cerebral cortex



Source: [Untitled image of the cerebral cortex layers]. (July 31, 2015). Taken from https://goo.gl/iZt3U3

As this image clearly shows, there are different types of neurons with different functions in each layer, arranged into vertical columns. Although there are many theories on how these columns work, what is known for sure is the following:

1) The sensory signal that enters first excites neuronal layer IV. The signal spreads toward the surface of the cortex and toward the deepest layers.
2) Layers I and II receive diffuse nonspecific signals from the reticular activating system. This entry perhaps controls the overall level of cortex excitability.
3) The neurons of layers V and VI project axons to other parts of the nervous system; some to different areas of the cortex, others to deeper structures of the brain, such as the thalamus and stem, and some even to the spinal cord (Guyton, 2006).

Each vertical neuronal column is responsible for interpreting a specific type of information (Guyton and Hall, 2006). In the visual cortex, a specific column would interpret visual signals caused by lines that run in a particular direction, while another column would be responsible for interpreting the information from other types of lines, of other thicknesses, etc.

These columns do not have a motor function, but instead are responsible for sensory-motor integration; therefore, the greater the sensitivity of an area, the greater the space and geographical proximity between columns (denser).

Association plexus is the name we have given to the laminae of axon neurons that separate the layers between one another and connect the different sectors of the cortex (Di Santo, 2015).

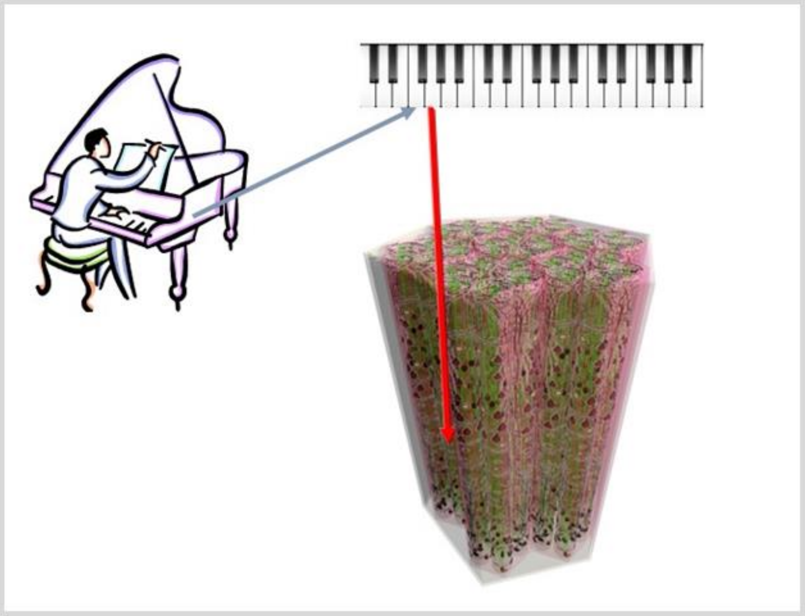
1.2.2 Spinal Organization. Intramuscular and Intermuscular Coordination

The kinesthetic melody was mentioned earlier as an example to understand the programming of the motor act and, among the musicians responsible for executing the melody, we referred to a particular pianist.

Taking this pianist as a reference, we can imagine that the keyboard is located in the 1MC, and that each one of its keys corresponds to a column. The motor act and, particularly, its harmony will depend on the continuity with which the musician plays the correct keys.

The number of columns of a muscle does not depend on its size, but rather on the quantity of motor units that neurally make it up and regulate it. Consequently, the greater the muscle's fine motor coordination, the greater the size in the 1MC and a greater number of columns (not to be confused with the aforementioned neuronal layers).

Figure 7: The Pianist



Source: Prepared by the author.

When discussing the quality or the harmony of the movement, these will depend on two aspects: **intramuscular coordination** and **intermuscular coordination.**
Following the example of the pianist, we can define these as:

- Intramuscular coordination: the pianist's capacity to strike the largest number of columns that correspond to a muscle.

Considering the ideas of Tous Fajardo (1999), intramuscular coordination is the ability to **recruit motor units** of the same muscle, which will depend on the following characteristics:

  - *Spatial recruitment:* refers to the quantity of fibers recruited. This in turn can increase or decrease muscle tension, as required by the activity.
  - *Temporal recruitment:* deals with the frequency with which the muscle fibers are active. Muscular tension can vary depending on how frequently fibers are recruited.
  - *Motor unit synchronization:* "motor units normally activate asynchronously (so that the movement is smooth), although it appears (as it does in weightlifters) that when it is time to perform a maximum voluntary contraction, activation is synchronous" (Fajardo, 1999, p. 47).

- Intermuscular coordination: the pianist's ability to play the notes in perfect harmony while, at the same time, avoiding playing irrelevant columns.

From this we can understand that intermuscular coordination is our ability to **activate relevant muscle fibers**, not only in the agonist muscle, but also synergists. In turn, it is necessary for the pianist not to hit the columns corresponding to antagonist muscles, which limit the activity of the main column responsible for a movement.

It is vital that there be proper sequencing and synchronization in the different muscle groups, some of which are activated (agonist or synergist) and other inhibited (antagonist).

These coordination processes will depend on the capacity of inhibition or facilitation that the nervous system is able to exercise, which are related to different nerve reflexes (Di Santo, 2015).

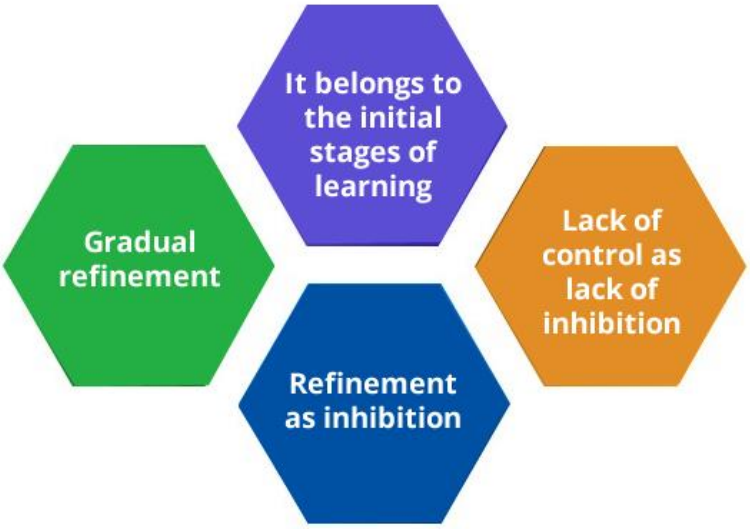
1.2.3 Irradiation and Parasitic Motions. Motor Refinement

Proximal Irradiation

Imagine that the pianist does not hit the exact notes, but instead his finger inexpertly strays to keys that correspond to other muscles.

As a result, columns that do not correspond are activated. This phenomenon of irradiation and motor parasitosis accounts for a large part of motor performance failures.

Figure 8: Proximal Irradiation



Source: Prepared by the author

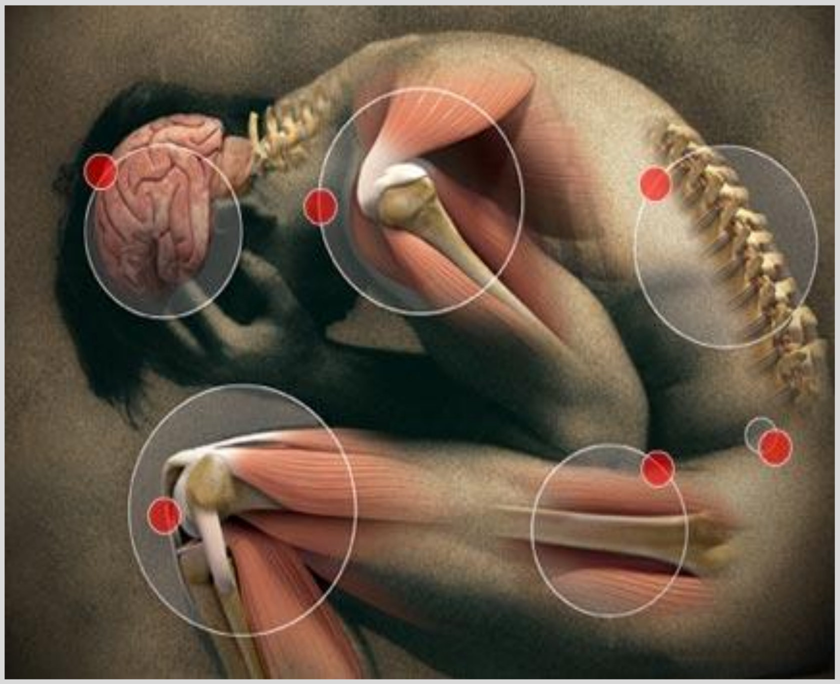
Synkinesis has a cortico-cortical explanation:

a) There are parasitic activations that are generated from the very 1MC due to proximal irradiation.
b) The wrong sectors are activated which then innervate muscles that should remain inactive.
c) They can be static or dynamic, and therefore affect the quality of execution and economy of movement.
d) Synkinesis generally involves the activation of the antagonists at the inappropriate time and in poorly effective regimes.

Synkinesis is also related to injuries and the phenomenon of “anti-economy”:

- They cause dysfunctional movement patterns, also called **aberrants**.
- These are also called **defective movement syndromes.**
- They cause **myotendinous injuries** of different kinds.
- Above all, they cause **considerable energy losses** that may worsen *performance*.

Figures 9 and 10: Proximal irradiation and synkinesis



Source: [Untitled image of proximal irradiation and synkinesis]. (Undated a). Taken from https://goo.gl/ECqoIu

[Untitled image of proximal irradiation and synkinesis]. (Undated b). Taken from https://goo.gl/EO0FAy

Refining them results from the following:

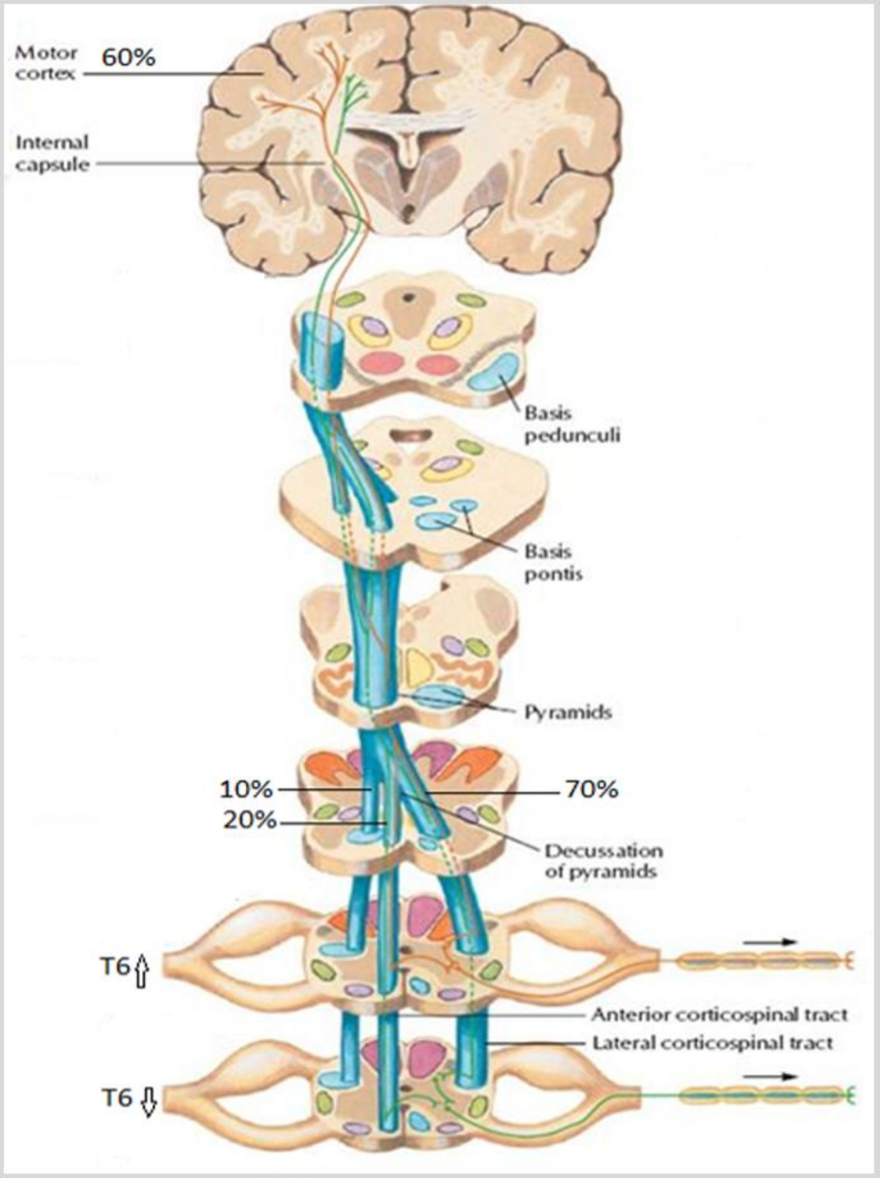
- There is a progressive elimination of the synkinesis, both static and dynamic, with precision in protagonist activations.
- Possible mechanism: pre-synaptic inhibition before the descending discharges arrive at the giant pyramidal body on the association sector between the PMC and 1MC; in short, before the efferent orders reach the 1MC. This can occur in the tracts of the 1MC itself.

- The refinement is not just cortical, but involves numerous processes that transcend cortico-cortical belonging and involve central and peripheral sensory functions (Di Santo, 2015).

1.2.4 Corticospinal Tract. Cross Education

The **corticospinal tract pyramidal system** is made up of nerve fibers that run from the cerebral cortex to the ventral horn of the spinal cord, where it joins with the motor neurons. The function of the corticospinal tract is exclusively a **motor** function. The majority of the fibers come from the frontal cortex (areas 4 and 6), followed by fibers of the parietal cortex (areas 1, 2, 3,5 and 7).

Figure 11: Corticospinal Tract



Source: [Untitled image of the corticospinal tract]. (n.d.). Taken from https://goo.gl/aGacBt

The corticospinal tract originates in the **giant pyramidal Betz cells** of the motor cortex. The neurons of the motor cortex send their axons to the motor nuclei of the cranial nerves, to the medulla oblongata, and the protuberance, but the majority of these nerve structures descend to the spinal cord.

The pyramidal cells project collaterals toward the red nucleus, basal ganglia, the ventral lateral nucleus, reticular formation and the bulbar olive (Rigal, 1987). These tracts can help optimize motor control, given that **information circulates in loops** through them, indispensable for performing unconscious movements. In turn, the rubrospinal tract helps the pyramidal tract; it does this sometimes by covering its tasks if necessary.

To introduce this topic, let us differentiate certain concepts that can lead to confusion:

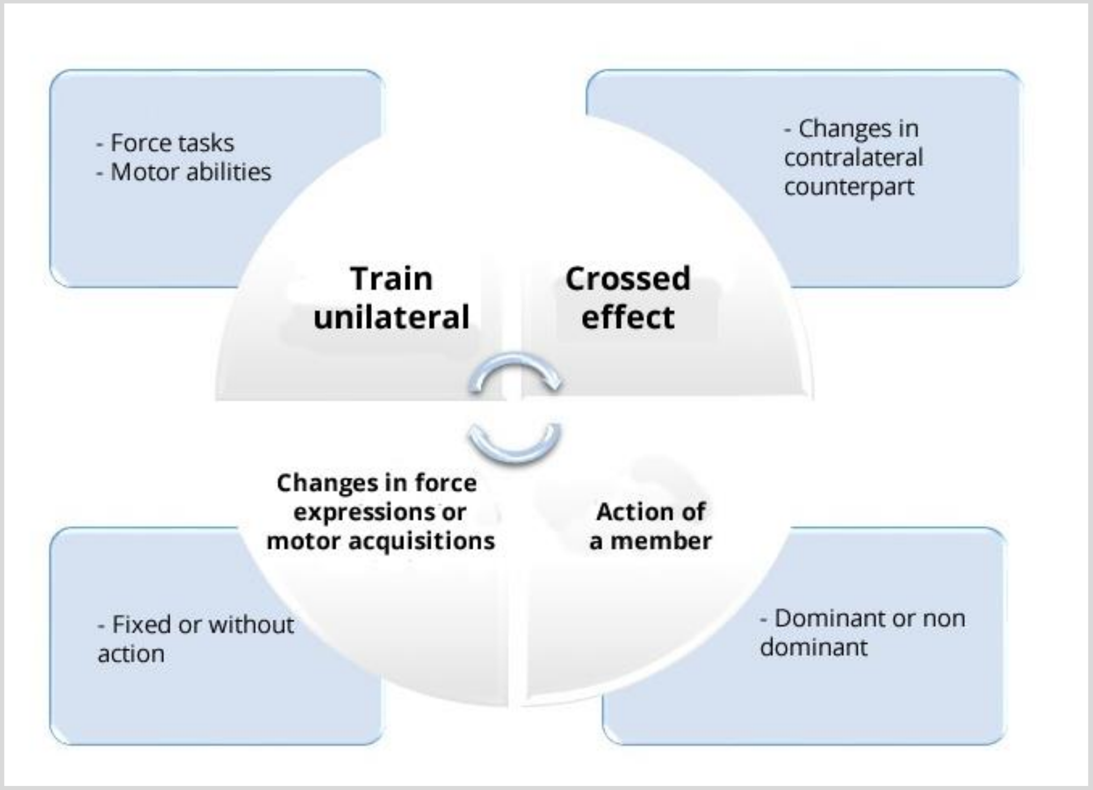
- **Cross education:** this is about improving performance in an untrained limb athlete in response to a training period of unilateral exercise in its contralateral.
- **Interlateral transference:** this refers to the bilateral transference of a motor skill.
- **Transfer of Force:** this is about the transfer of force from the untrained muscle counterpart to the trained limb.

One of the first reports of **cross education** was in 1894 when Emily Brown pressed a rubber button a maximum of 10 times for 13 days using only her right hand. After the last day, they reevaluated strength using the maximum voluntary contraction (MVC) method, but in her other hand and, surprisingly, the strength in her left hand had increased by 43% percent. The phenomenon by which training of one side of the body increases the strength of the other hemibody is known as contralateral strength training, also known as cross education or *crosstraining*. Cross education can include the transfer of muscle force to the untrained muscle counterpart following a period of unilateral training and the transfer of learning of motor skills in the untrained muscles (Zhou, 2000).

Effects of Cross Education on Strength

Several studies confirm the transfer of force from one trained limb to its untrained contralateral following maximum isometric contractions. Munn, Herbert and Gandevia (2004) performed a meta-analysis of 17 studies which revealed that the increase in strength was on average 7.8% compared to the initial strength in the contralateral limb. The increase is real although, in some cases, the researchers stated that cross education can be used to diminish strength loss or increase it when there is limb immobilization. Most articles on cross education reveal no morphological changes (hypertrophy) in the untrained limb.

Figure 12: Cross Education



Source: Prepared by the author.

In relation to **unilateral actions** and cross education, studies in lower limbs (LL) have revealed that there is greater muscle activation during bilateral execution in comparison with unilateral contractions (Behm, 2003). Bilateral facilitation of the activation could be due to the increase of excitatory reflexes, with stronger descending supraspinal *inputs* or greater inhibition.

The effect of cross education can depend on the **direction of the transference**. The study by Farthing (2005) was the first to examine the effects of the direction of the transference in cross education strength training. The most important finding was that this effect was produced after only training the dominant hand in right-handed individuals and that there were no significant changes in strength from the non-dominant left hand to the dominant one. One of the possible mechanisms is that one extremity is more competent at acquisition or learning a new motor task than the other and, therefore, more information can be transferred. Thus, the greatest transference is observed only from the dominant extremity to the non-dominant one (Farthing, 2010).

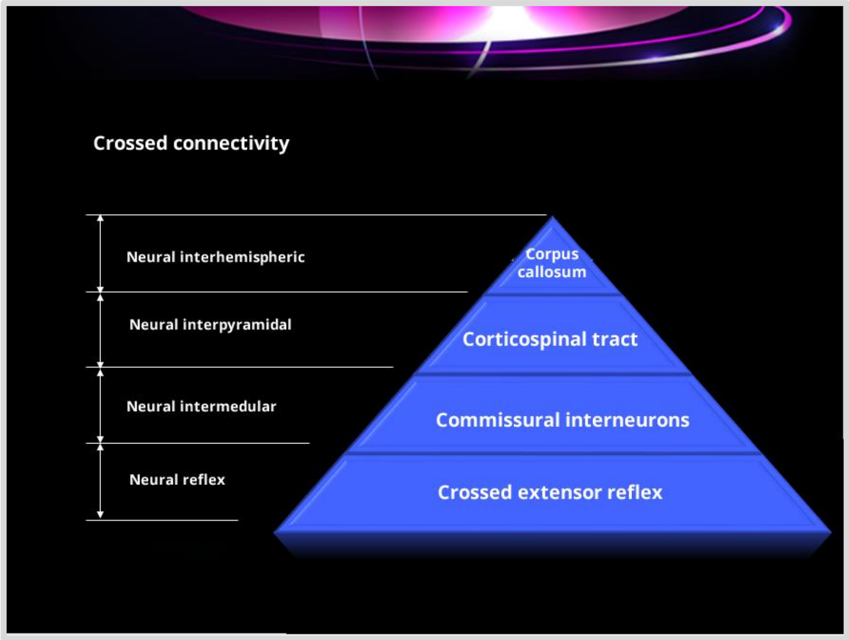
The complexity or familiarity of the task is a determining factor for cross education strength and motor skills training. If the task is unfamiliar to both extremities, the transfer of force is likely to occur in any direction.

In what area do we find the production of adaptations that support the change in the opposite side while training?

Adaptation levels:

- Cortical.
- Subcortical.
- Descending tracts.
- Medullar.
- Muscular.

Figure 13: Cross Connectivity



Source: Prepared by the author.

Other Concepts of Cross Connectivity

Transcallosal Connectivity

The term **motor irradiation** describes the bilateral corticospinal activity that is produced during a unilateral movement. The corpus callosum, which connects both hemispheres, may be a contributor to this process. The horizontal motor connections between the right and left hemispheres of the primary motor cortex can act to transmit excitatory and inhibitory activity, thereby regulating the activity of the motor cortex.

Corticospinal Connectivity

The corticospinal fibers travel through the internal capsule to the ventral portion of the mesencephalon. Some three quarters cross, while the others that do not cross descend to form the ventral corticospinal tracts. These fibers (although minimal in numbers) involve a sufficient representation of the central motor impulses that remain as **ipsilateral stimuli** which can intercede in the activation of the untrained limb.

Repercussions of Cross Education on Other Mechanisms

Muscle Mechanisms

These include changes in muscle mass, in muscle enzyme concentrations, hormonal changed and modification in the composition of contractile proteins. However, scientific studies suggest that these peripheral adaptations are much less likely in crosstraining (Carrol, 2001).

Spinal Cord Mechanisms

Although there is a complex network of neuronal circuits in the spinal cord, there is no evidence that they produce any medullary changes in the untrained hemibody. Although no variations have been found in the H-reflex, remember that there is connectivity through the commissural interneurons that cross the midline to inhibit or excite, but it is yet to be demonstrated that these mechanisms contribute to cross education (Fimland, 2007).

Cortical Mechanisms

Most studies coincide that the transfer of skills is a response to motor learning controlled by cortical adaptations. Motor learning has been associated with plasticity in the brain including the regions of the primary motor cortex, premotor cortex, and the supplementary motor cortex.

The neural adaptations are deduced from the fact that the transversal transfer of force is produced in the absence of hypertrophy. Changes are generated in brain activation of both cortical hemispheres and the somatosensory cortex, cross education is controlled by cortical adaptations with the 1M playing a fundamental role.

Figure 14: Possible Applications of Cross Education

Therapeutic Exercise

- Possibility of working the unaffected limb to transfer strength or skills to its counterpart
- Paresthesia, spasticity or hemiparesis

Rehabilitation

- In response to immobilizations or unilateral injuries
- Possibility to diminish strength loss
- Rest?

Sports

- Acquisition of motor skills
- Transfer of learning

Source: Prepared by the author.

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