Chess Metaphors

Artificial Intelligence and the Human Mind

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1 The Human Brain: Metaphor Maker

*Over the lustrous green canopy of treetops that shade the heart of the Vienna Woods, where the Austrian Alps gently expire and meet a city full of history, nobility, and misery, black crows circle. They seem to give notice that not all is well—that these woods have seen terror and madness. In the late nineteenth and twentieth centuries, everyone from every corner of the soon-to-be-dissolved Austrian-Hungarian empire could be found gathered together in Vienna—the Romantic writer who lived in those eternal cafés, his attention on the words he strung together and far away from the holes in his dirty, ill-fitting jacket; the musician who came from a village on the Italian border, Bratislava, or perhaps some forgotten town in Hungary to follow the same road as Mozart, Beethoven, Schubert, and Strauss; cultural and political figures who would change the course of history chose favorite cafés in which to nurture their dreams (musicians like Mahler and Schoenberg, scientists like Freud and Schrödinger, and politicians like Trotsky, Herzl, or the abominable dictator of Nazi Germany); and great chess players who like Wilhelm Steinizt and Carl Schlechter spent hours playing in the cafés, each one its own timeless universe, filling the chairs along with writers like Stefan Zweig, who captured the psychology of the chess player in his celebrated "*Schachnovelle*" ("Chess Story").*

But in 1999, just before the arrival of the third millennium CE, the noise of the train that I was riding overpowered the caws of the black crows waiting in the distance to seize the souls of the dead, and my thoughts continued their own course—sometimes flitting from subject to subject, sometimes following a continuous stream. We arrived at Altenberg, my daily destination for two years. The Danube River runs parallel to the train tracks, and I saw a white swan swimming solemnly, reminding me of Konrad Lorenz and his noble intellectual misery. I started to walk toward the research institute, the Konrad Lorenz Institute for Evolution and Cognition Research, and as all the familiar sensations that I had experienced in recent days washed over me, an idea about how to solve a problem that I had been thinking about all week suddenly came to me as if out of nowhere. This chain of events *is no mystery: it moved from my perception of the centuries-old trees to historical associations with the country's Nazi past, the consciousness of being in a train with its rhythmic sounds and movements, a swan on the river that suggested an image and a feeling, my own rhythmic body movement as I walked, and the sudden appearance of an idea completely unrelated to my other thoughts. No, it's no mystery: I am a mammal with a brain.*

General Introduction to Brain Structure and Function

This chapter explores the biological bases for the development of cognitive processes in the human species. I use the expression *cognitive processes* to refer to those processes, either intentional or unintentional, that involve a certain type of stimulus-response mechanism. With such a broad definition, it is immediately clear that the majority of the poorly named higher animals show cognitive processes. That should not come as a surprise, given that all of them, including primates such as humans, possess a nervous system that has an accumulation of tissue in the anterior part of the body, which is organized into numerous specialized compartments. In other words, they all have a brain. Even creatures that lack a brain but are able to react to a stimulus from the environment and create a response accordingly possess cognitive properties. Bacteria in the microscopic world, for example, will respond to different concentrations of food in a water solution by moving to areas where the concentration is higher. In the plant world, the sunflower follows the direction of the sun during the course of the day. Humans have also created mechanisms whose functioning is based on pieces of knowledge, opening the door to the possibility that these machines also possess cognitive capacities. A thermostat turns on and off in response to the temperature around it, and a supermarket door opens when it perceives a customer's footstep.

In essence, this book is concerned with the following problem: what would we learn about our minds if we concluded that machines could carry out cognitive activities? And as a corollary to that idea, it also asks: can machines think? This extraordinary possibility has been the dream of many generations, and I return to it later to analyze it in greater depth. Before turning to the mind and cognitive processes, it is necessary to look at some of the basic characteristics of the brain—its structure and biological functions. With this biological foundation, it will be easier to relate cognitive processes (especially those that are commonly understood to be human) to the brain's functioning, which in turn is completely dependent on its form, its structure, and the connections between the elements that make up the brain—the neurons.

Form and Function: Brain and Mind

As with any animal organ, the human brain can be studied from both structural and functional perspectives. Each aspect has particular points of interest and needs to be looked at separately. As the great French anatomist Geoffroy de Saint-Hilaire pointed out in the nineteenth century, function must follow from the dictates of formal structure for any anatomical part. In other words, the functions that an organ can perform depend on the structural organization that it has (including its proportions, orientations, connections, and articulations) and the materials of which it is made. In engineering, this relationship is clear. Thanks to their particular structural conditions, a hanging bridge made of wood with tensors of rope can serve as a footbridge, while a bridge of reinforced concrete with steel tensors will allow cars to pass over.

In biology, the separation between form and function is a source of intense debate, especially in evaluations of the mechanisms that have played a role in evolutionary dynamics. Even so, it seems clear that the structure of the hand lets it carry out a variety of functions, from grabbing a rock to playing the piano. To assert that the hand has evolved to play the piano and thus has a structure developed in accordance with its function (in other words, that form follows function) is absurd (although appealing from a romantic point of view). The same thing is true of the brain. The extraordinary versatility of this organ is a direct consequence of how it is organized, and so its structural characteristics need to be closely examined. The eyes—the sight organs—have evolved structurally so that they can specialize in the reception of light stimuli. Again, function follows from form. Even so, form and function are integrated, meaning that in some cases it is hard to separate one from the other.

Structurally, the brain is a complex organ that is composed of billions of neurons and other auxiliary cells that together form an astronomical number of connections. Functionally, the brain is an organ that allows sensations from the environment to be evaluated, stored, and integrated and that provides appropriate responses to any given situation. To carry out these functions, the brain needs large quantities of energy. Although it makes up approximately 2 percent of the body's weight, it consumes up to 20 percent of the oxygen and glucose that are present in the blood, which is delivered through the blood vessels of the brain. The next chapter looks at the brain's functional capacities—that is, the brain as a process that commonly is called the *mind*—to create the worlds that represent, more or less reliably, the physical reality that surrounds it. The mind is a private witness of the course of our existence for each one of us. It is responsible for creating our emotional responses and for sensations like pleasure, happiness, fear, and hate. Or is it the brain that is responsible?

Some Structural Elements: Brain Cells

Since antiquity, the brain has been considered a continuous, undifferentiated mass of unknown matter that somehow (perhaps by hydraulic mechanisms, as Galen, René Descartes, and numerous other philosophers thought) used the nerves to send information to and receive information from the rest of the body. The nerves were considered to be hollow tubes through which a liquid transmitted the pressure that was sent by the brain. Thanks to Santiago Ramón y Cajal's anatomical and histological analyses, using silver staining techniques developed by Camilo Golgi, it became clear by the end of the nineteenth century that, like all other animal organs, the brain in reality is made up of a multitude of discrete elements called *cells* and that nerves are formed by a bundle of *axons*, which are just parts of those cells. These specialized brain cells, called *neurons*, are responsible for representing the world, storing memories, distributing information, and generating thoughts. Along with neurons, *glial* cells are a fundamental component of the brain. They nourish the neurons and isolate neuronal axons (much as if the axons were copper wires and the glial cells a plastic coating), facilitating the movement of ions through the wires. On average, there are about ten glial cells for each neuron, but since glial cells are about one-tenth the size of neurons, they take up roughly the same amount of space in the brain.

What is referred to colloquially as gray matter is actually those areas of the brain (principally those closest to the surface) that have a high density of neuron cell bodies and lack auxiliary glial cells, while the white matter of the brain looks that way because of the white color of *myelin*, the substance that sheaths the axons. Myelin is secreted by the *oligodendrocytes* glial cells (other types of glial cells are the *astrocytes* and *Schwann cells*). This sheath is an insulating material that is broken up at regular intervals, leaving gaps called *Ranvier nodes*. In these gaps, a large concentration of protein channels is situated in the plasmatic membrane of a neuron, which allows ions carrying an electrical charge to pass through the membrane (these ions or elements with an electrical charge are fundamentally sodium, potassium, and calcium).

The glial cells are important to the correct functioning of the brain, but here I focus on the neurons, since they are involved in generating cognitive processes. In addition to their classic functions of support, protection, control of pH in the environment, and nutrition (thanks to their intimate relationship with the blood vessels), many more functions for the glial cells have been discovered. This new, more active role for the glial cells includes influencing communication between neurons by regulating the ionic concentrations on each side of a neuron membrane. This makes the glial cells an indirect part of the processing of information, a function that has always been reserved exclusively for the neurons.

Butterflies of the Soul

Even so, the unquestionable protagonists of the brain are the neurons. These are specialized cells that assist in the reception, storage, integration, and distribution of the information that an organism encounters throughout its existence. Ramón y Cajal, who dedicated his scientific career to the study of the brain and was captivated by the complexity and delicacy of the external form of neurons, referred to them as "these butterflies of the soul." The human brain is made up of approximately 100 billion neurons (the exact number is unknown, but this as reasonable an estimate as any other). It can be thought of as a data center that, in an orderly fashion, receives, stores, integrates, and transmits information in electrochemical form. The cells' shape and size fall within a fairly wide range of variation. They interact among themselves by connections between their entrance and exit structures (their *dendrites* and *axons*, respectively) across connection elements called *synapses* (a synapse resembles a button and acts as a plug or outlet, to use the metaphor of an electrical circuit, bearing in mind that synapses are actually much more complex). Each neuron has connections to approximately 10,000 other neurons, so that the final result—the connectivity structure of the brain—contains an extremely high number of connections.

The basic morphological structure of a neuron consists of three distinct parts—the neuron body, the axon, and the dendrites (figure 1.1). The neuron body houses the cell nucleus as well as various *organelles* (such as many energy-generating *mitochondria*). The axon, a filament of varying length (from a few microns up to some 150 centimeters), provides a transmission path where the *action potentials* (the electricity that is generated by the difference in charge among chemical ions, especially sodium and potassium) travel and transmit a stimulus to other neurons. Finally, the *dendrites* are filamentous structures that are shorter than axons but are present in large

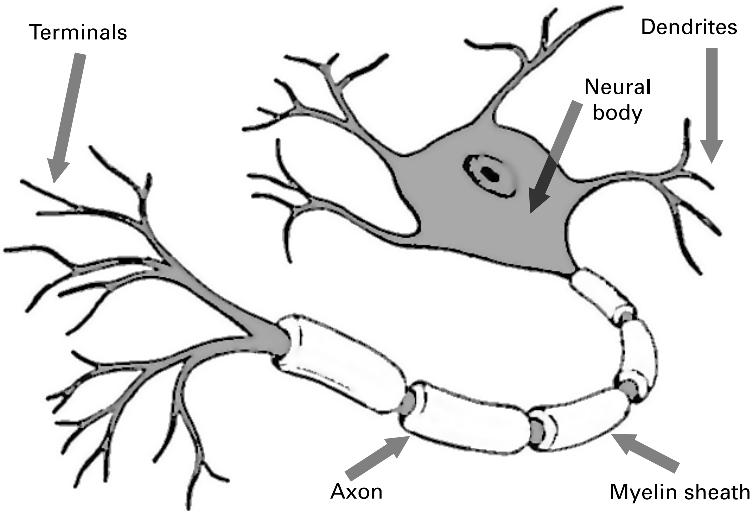

Figure 1.1
The main parts of a neuron.

numbers. Dendrites receive stimuli from the axons of other neurons. Other important elements in the neurons that should be mentioned are the *vesicles* (*microsomes*), which carry the chemical messengers (such as *neuropeptides*) that the dendrite needs to communicate with the axon; and the *membrane channels*, which are formed by diverse types of proteins and provide an entrance and exit for the chemical ions that assist in electrochemical current transmission.

There are also internal structures called *microtubules* that are found in the interior of the majority of animal cells. These filamentous structures (which are formed mostly by proteins like tubulin) confer a certain stability on the form of the neuron branches and are involved in the transport of *neurotransmitters* from their production site in the *soma* or cell body to the synaptic terminals. Roger Penrose has postulated that microtubules and information transmission among neurons are somehow related by an essentially quantum mechanism. This fascinating theory assigns a critical role to the microtubules, to the point of considering them necessary for the emergence of consciousness.

Neuron connections among the distinct areas of the brain are established during its embryonic development, partly in accordance with the spacing directives of the glial cells. In addition, specific types of neurons with distinct kinds of biochemistry, physiological conditions, or connection types

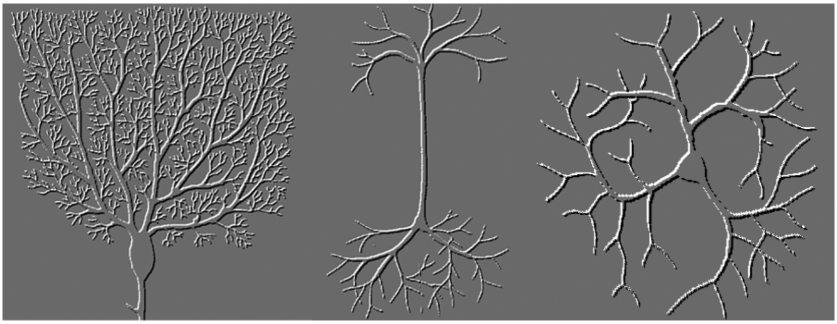

Figure 1.2
Some types of neurons—Purkinje cells, pyramidal cells, and star-shaped cells.

become differentiated from each other. Among the neuron types that are differentiated by their morphology are the pyramidal cells, Purkinje cells, motor cells, and star-shaped cells (figure 1.2).

Besides this morphological division, types of neurons also become differentiated by the kind of information that they are able to process. Thus, motor neurons, sensory neurons, and interneurons are formed during *embryogenesis*. *Motor neurons* stimulate movement in some part of the body, such as the neurons that innervate the muscles that move the fingers. The bodies of these neurons are lodged in the spinal cord, but their axons can be of enormous length (up to a meter and a half) to reach the indicated part of the body (for example, the big toe). *Sensory neurons* receive information from the sense organs (touch, hearing, sight, smell, and taste) and translate (the scientific term is *transduce*) the physical stimulus that arrives through each organ's specialized receptor cells into the electrochemical signal that neurons transmit to specialized regions of the brain. In the skin, for example, the receptor cells are the nerve endings themselves, while for vision, cells (*retinal cones* and *rods*) send the information from the luminous impression to the sensory neurons' terminals. The study of how vision is structured and functions is a productive topic in neuroscience and is providing a large quantity of information about the overall functioning of the brain and the nature of consciousness. Finally, the *interneurons* are neurons that play the role of intermediary between the sensory and motor neurons. During embryonic development, they establish routes where the sensory neurons transduce the information received from the environment and transmit it to the brain. There, the information is integrated and processed, and a new type of signal is produced that heads to a motor neuron, which provokes some kind of movement or action. But there are also reflex actions that establish a circuit (the *reflex arch*) that does not pass through the brain so that the action is much faster and unconscious.

Some Functional Elements: Electrochemical Current and Communication among Neurons

The brain is like a huge, highly complicated electronic circuitry where axons and dendrites serve as the wiring along which the electrochemical current travels. Current is generated by means of action potentials, and axons and dendrites communicate chemically by means of the release of chemical messengers called *neurotransmitters*. These two functional aspects create an electrochemical language of incredible reach.

An action potential is a process that releases a flow of electrical energy, produced by the depolarization of the membrane in a part of the neuron (figure 1.3). This depolarization is carried out by a series of protein channels in the membranes that allow certain chemical ions to pass between the interior and the exterior of the cell. Thanks to the delivery of neurotransmitters, the presynaptic neurons stimulate other neurons (the postsynaptic), producing a depolarization in the plasmatic membrane of the postsynaptic cell, which then evaluates all the individual contributions of the dendrites on this portion of the neuron to determine whether to fire (carry the impulse forward) or not. To a certain extent, this is a statistical problem, where the probability that the postsynaptic cell will fire is directly proportional to the sum of the excitations and inhibitions of all the afferent dendrites (dendrites coming from other neurons). In a resting state, the interior of the neuron holds a charge of some -70 millivolts with respect to its exterior, and when it allows sodium ions to pass through, the interior charge changes to 0 millivolts; that is, it depolarizes. A different phenomenon, that of *hyperpolarization*, happens when the difference in potential increases.

A close look at the structural and functional details of neurons shows that the wiring metaphor does not hold up. Axons receive and transmit action potentials in stages, given that the axon's conductance is small and the potential needs to be generated at regular intervals to be transmitted long distances. Moreover, the action potential is not transmitted directly from neuron to neuron (as happens with regular electric wiring) but instead requires the involvement of intermediary molecules that assist the transmission by leaving signals that change the possibilities of the action potential continuing in another neuron. (In certain cases when the synaptic gap is very narrow, the potential can jump from the pre- to the postsynaptic neuron.)

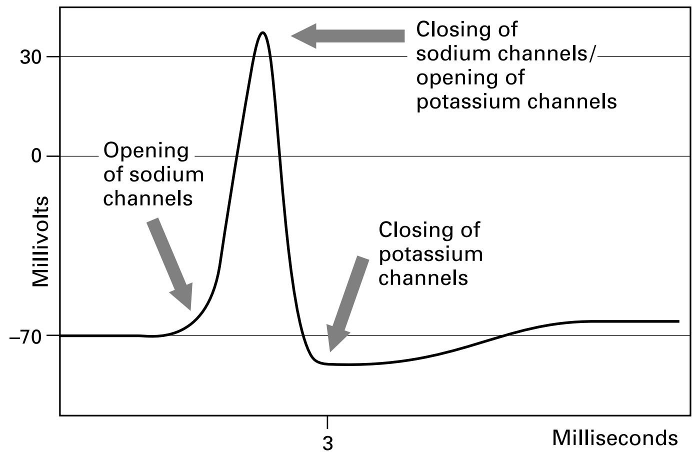

Figure 1.3
Action potential. The membrane of the neuron depolarizes, generating an electrical current with a characteristic transmission provoked by an ion flux.

This last aspect of neuron functioning is important because it constitutes the basis of cerebral functioning. Each axon possesses collateral branches where the action potential is distributed. These collateral branches connect (make synapses with) approximately 10,000 dendrites of thousands of neurons. For a neuron to be stimulated and transmit an electric current through its axon and its collateral branches, its firing *activation threshold* needs to be triggered. All the dendrites' contributions are added up to evaluate whether the neuron has passed that threshold. The sum is determined by the number of excitatory and inhibitory stimuli that are received, which in turn are determined by the type of neurotransmitter that is released. Neurons' electric functioning is also distinguished from the wire metaphor because in neurons the current moves by means of pulses. Once the neuron has crossed the activation threshold and thus fired its own action potential, it needs a period (the *refractory period*) of between 200 and 500 milliseconds to recover before it is ready again for the next firing.

One phenomenon that should be noted (and that could be behind the generation of high-level cognitive activities and even the manifestation of consciousness) is the phenomenon of *binding*, by which a group of neurons fire at the same time. This synchrony of neuron firing can be recorded using some of the methods discussed below (such as inserting microelectrodes in specific areas of the brain). Binding, or the rhythmic activity of neuron groups, could be what enables cognitive functions (such as perception and thought) to be carried out. To experience a scene consciously, its different properties need to be united in a coherent manner. This can be achieved through the neurons' action potential thanks to the phenomenon of binding. For example, when a person observes the ocean in movement, the brain must correlate different perception events (such as the color of the water, the smell of iodine, the movement of the waves, the reference to the horizon, and the sound of seagulls) and any other circumstantial phenomenon (such as the smell of sardines on the grill being prepared to end the day at the beach). All these events, sensations, perceptions, and feelings should be coded and represented in the brain as a unit, forming the conscious experience of a pleasant day at the beach.

The same thing happens within the conscious experience of a chess player. Many experiences—the color of the board, the texture of the pieces, the sound of the clock, the mental struggle to match up the positions on the board with memories of other games—should be linked with a physical presence in a specific part of a specific city and the tumultuous reality of the exterior world. All these elements together form a single, vital experience that is continually being processed, consciously or unconsciously, in the player's mind. And for that to happen, this phenomenon of firing synchrony among neurons from different parts of the cerebral cortex could be key.

Information is distributed in the brain in such a way that serial connections are scarce (and perhaps nonexistent within the brain, given the number of collateral branches of axons that also distribute information) compared to parallel connections. This means that electrical activity is spread throughout different brain areas. Neurons form particular networks that depend as much on development as on learning. These networks have specific, although not static, connection patterns and in many cases (as is shown below) can be identified with certain functional modules or parts of modules.

Depending on the type of neurotransmitter that is released in the synaptic button, the connection might contribute to the postsynaptic neuron's excitation or inhibition. This type of regulation of neuron communication (known generically as *neuromodulation*) is of great importance. Thanks to the differential action of distinct types of neurotransmitters, the brain can enter into different conscious states, such as dreaming or waking consciousness. Broadly speaking, we can distinguish between the *cholinergic* and *aminergic* systems, groups of neurotransmitters that respectively augment or inhibit neurons' excitation. Neuromodulation is important in bringing about different states of consciousness and also contributing to creating memories at a cellular level and therefore as a base for learning and memory.

Cellular Mechanisms for Memory Storage

Memory is a cognitive process that is necessary for learning. It is the basic component of intelligent behavior. The brain needs to possess a means for storing and recovering information that is registered by the sense organs or created by thought. This is achieved thanks to different memory systems, such as working memory and long-term memory (see the next chapter). However, some kind of molecular or cellular mechanism must allow that storage to take place. And this can take place only within the neurons.

In the 1940s, Donald Hebb proposed a mechanism for reinforcing the connections between two neurons (*neural memory*) based on the need for both the presynaptic neuron as well as the postsynaptic neuron to activate (*fire*) in a congruent or associative manner (when one fires, it increases the probability that the other will fire). This supposes a metabolic restructuring of both cells, strengthening their relation. Another mechanism that allows for learning at the synaptic level is the modulation of a third neuron that acts to reinforce the synapse between the pre- and postsynaptic neuron. In this case, the modulating neuron reinforces only the presynaptic neuron's activity.

One type of neuron connection is directly related to the generation of memories and learning. A special membrane channel called *N-methyl-D-aspartate* (*NMDA*) depends for its activation on the presence of the amino acid glutamate (which acts as a neurotransmitter), on the depolarization of the membrane, and on the stimulation of the neuron by a second path. The NMDA channels contribute to establishing what is called *long-term potentiation* in those synapses where they appear. They have been observed to be particularly numerous in the membranes of neurons in the *hippocampus*, a region of the brain that is related to memory storage. The receptor, situated on the postsynaptic membrane, receives an electrical signal thanks to the depolarization of the membrane, which happens independently because of the action of another type of postsynaptic receptor. This depolarization induces the NMDA receptor to release magnesium and allows it at the same time to bind with glutamate, which prompts calcium to enter the cell. The entrance of calcium seems to provoke a chain of reactions that culminates in the release of nitric oxide, a gas that acts backward as a messenger from the postsynaptic to the presynaptic neuron. There is a feedback mechanism between the two cells, mediated by the glutamate and nitric oxide, that strengthens the synaptic relation (or even stimulates a greater response). This constitutes a cellular memory mechanism, and thus the name of synaptic long-term potentiation.

Basic Organization of the Brain's Functional Regions

Higher vertebrates' nervous systems are divided into central and peripheral systems. The *central nervous system* (*CNS*) is composed of the brain and the spinal cord. The brain is lodged in the head and is protected by the braincase and by a set of flat bones connected to each other by strong, rigid sutures. The brain is also protected by three membranes—the *dura mater*, *pia mater*, and *arachnoid*. These membranes (also called *meninges*) protect the cerebral mass from infections and from knocks against the inner part of the cranium bones. The brain's average cellular mass weighs approximately 1.3 (for women) and 1.5 kilograms (for men). The spinal cord also has a set of bones that protect it (the *vertebrae*) and that are distributed along the cord's length like rings placed one on the other. The nerves that communicate between the brain and the rest of the body through the spinal cord pass through the intervertebral spaces, which are protected by cartilaginous disks. These nerves form the peripheral nervous system and, connected to the spinal cord, reach every part of the body. The nerves collect information from both outside and inside the body, which is then processed in the brain to elaborate an appropriate response. This response can be of a motor type (a movement, for example of a hand moving to swat a mosquito) or not (a thought). Furthermore, control of vital organs is carried out automatically, also thanks to the coordinated action of nerves and muscles.

The brain possesses various regions that are anatomically or functionally delimited (figure 1.4). The most basic parts are the hindbrain, the midbrain, and the forebrain (the latter provides the well-known image of the brain, the *cerebral hemispheres*). The *hindbrain* (also called the *lower brain*) consists of the *brain stem*, which connects the brain to the spinal cord; the *cerebellum*, a singular structure that is immediately posterior to the brainstem; the *medulla*; the *pons*; and the *reticular zone*. Functionally, the hindbrain structures control the body's vital functions, such as breathing, heartbeats, and digestion. They are also responsible for coordinating body movement, especially the cerebellum. The pons receives information from the visual areas, and the reticular formation controls the passage from sleep to wakefulness. The midbrain rests on the lower brain and is divided into the *tegmentum* and *tectum* (with two zones, the *inferior* and *superior colliculus*). The midbrain controls motor activities and sight and hearing (although in humans, both the visual and auditory areas are found principally in the forebrain's *neocortex*). The *forebrain* (or *upper brain*) is highly developed in humans. It is formed by hemispheres with *convolutions* (also known as *sulci* or *fissures*) and *grooves* (also known as *gyri*) with important internal structures. The extensive development of the forebrain (especially the neocortex) provides the structural conditions for the high-level cognitive functions to emerge. Other structures that are found in this area of the brain include the *thalamus* (the center of coordination for various sensory areas); the *hypothalamus* (which controls primary activities like feeding, flight, fight, and sex and regulates body temperature, sleep, and emotions); and some structures of the *limbic system* (the principal center of emotions control, along with the hypothalamus), such as the *hippocampus* (essential for fixing recently formed memories), the *pineal gland* (the seat of the soul, according to Descartes), and the *basal ganglia* (responsible for motor control).

All these structures are found in the interior of the forebrain. But the structures that have had the most pronounced development in the human brain are in the *neocortex*, which lies over the rest of the brain, covering the other interior structures. The neocortex, some two millimeters thick in humans, is divided into hemispheres (left and right). The *central longitudal fissure* lies between the hemispheres, which are connected mainly by a central structure called the *corpus callosum*, although there are other connection paths that do not pass through it. The most notable characteristic of the cerebral hemispheres in humans is their rugged appearance. Their folds and grooves provide a substantial increase in surface area and thus accommodate a greater number of neurons. Each hemisphere controls the information input and output corresponding to the opposite side of the body. Thus, the right hemisphere receives stimuli from the left hand, while the left hemisphere receives them from the right hand. Externally, the

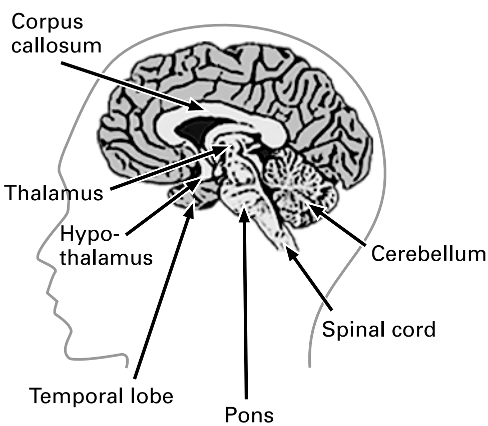

Figure 1.4
Sagittal section of the brain showing internal parts.

neocortex is divided into a series of regions bordered by fissures. The frontal and parietal regions are separated by the central fissure, while the lateral fissure separates those two regions from the temporal and occipital regions (figure 1.5).

The neocortex is diverse functionally and is where the high-level cognitive functions originate. For example, the frontal lobes (whose development has been more pronounced than the rest of the neocortex) carry out planning functions and possibly are the site of long-term memory storage, while the lateral lobes seem to be involved in decision making. In reality, the connections among the different areas, not only within the neocortex but also in the rest of the cerebral areas (especially the hypothalamus and basal ganglia), allow different cognitive elements to be integrated, producing the factors necessary to generate mental activity.

Over the past 150 years, researchers have been identifying areas of the brain. From this research, an image of the brain as a modular structure has emerged, with each module carrying out a specific activity. But the modularity of the brain has often been exaggerated, especially when considering the generation of cognitive processes. For example, pseudosciences like phrenology understand the brain as having specific parts for each cognitive process (even proposing modules for areas like friendship and morals) and also suggest that the skull's external, anatomical structure itself, with its indents and bumps, indicates the degree of development of these modules. In a less spectacular version of phrenology, Jerry Fodor and other psychologists and philosophers of the mind, using the Swiss army knife as a metaphor, insist that structural and functional modules for each type of action must exist.

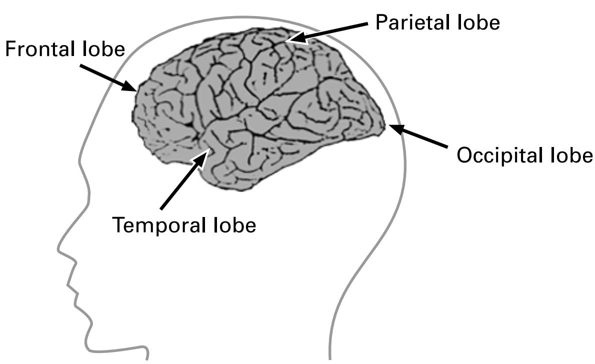

Figure 1.5
The brain in lateral view, showing the most important areas of the neocortex. Compare with figure 1.4.

They view the brain as an organ that is made up of multiple parts, each one of which is in charge of a series of specific tasks (figure 1.6). The idea of the modularity of the brain also has interesting consequences from an evolutionary point of view, given that evolution can simply add modules to those already there to generate a brain with new capacities.

Despite controversies about the modular brain hypothesis (at least in its most radical versions), the existence of specialized areas to receive particular stimuli is undeniable. This specialization is carried out during development and is largely provoked by the specific input of sensory information from both the body itself and from outside it. Some of the important areas of the neocortex are the visual areas (principally those called *V1* to *V5*), the motor areas, and some specialized areas such as those for language (Broca and Wernicke), color, face recognition, and memory (figure 1.7). Perception of an object is separated into attributes like movement, color, form, and orientation, given that each of these aspects is processed separately in different visual regions of the neocortex. Some areas of the visual cortex are organized in a way that represents the stimulus in a topologically equivalent manner. This means that if we could watch the activation of the neurons in those areas, they would form an image that was basically the same as the perceived object. However, other areas work in a much more diffuse way, and the equivalence is lost.

In the *motor cortex*, which is located in the most posterior part of the frontal lobe, the body is represented with an almost topological equivalence, and the same is true in the *somatosensory cortex*, which is just behind the motor cortex in the most anterior part of the parietal lobe. The most interesting part of these projection areas is that although the body's topological

Figure 1.6
The brain as a modular complex, like a Swiss Army knife.

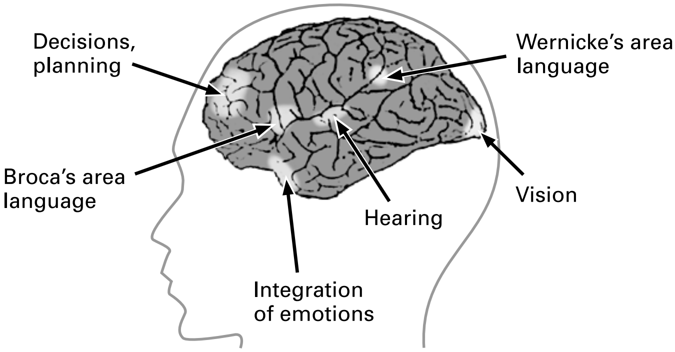

Figure 1.7
Some of the brain's functional areas. Even though the existence of these modules has been sufficiently demonstrated, cognitive functions need the joint action of several areas of the brain.

representation is almost equivalent (after the hand comes the forearm, which is followed by the upper arm, and so on), the relation between the real size of each body part and the size or proportion of the area as it is represented is completely different. Thus, the large area dedicated to the face and the hands stands out, reflecting the control of the many functions that these body parts can carry out. The relation between the motor and somatosensory cortices and the body is often represented by drawing a distorted human figure (called *motor homunculus* and *sensory homunculus*) on a section of each brain area (figure 1.8).

Besides the functional areas, which are concentrated in specific sites of the brain, the neocortex is stratified, with a cross-section showing six morphologically distinct layers with different connectivity patterns. These six layers, which extend across the whole surface of the neocortex, also have distinct specializations from a functional point of view. For example, layer II is composed mostly of pyramidal neurons with far-reaching axons, which make synapses with nonadjacent zones.

For an organism to survive, it needs diverse regulatory systems that are independent to a certain extent from the brain's integrated control. Thus, various systems contribute to keeping the body's interior in a dynamic equilibrium that is maintained always within a constant range for properties such as temperature (around 37 degrees Centigrade in adult humans) and pH (the ionic concentration that determines the acidity of the blood and other liquids inside the body and that varies from one organ to another; for example, the stomach pH is much more acid than the blood pH). This capac-

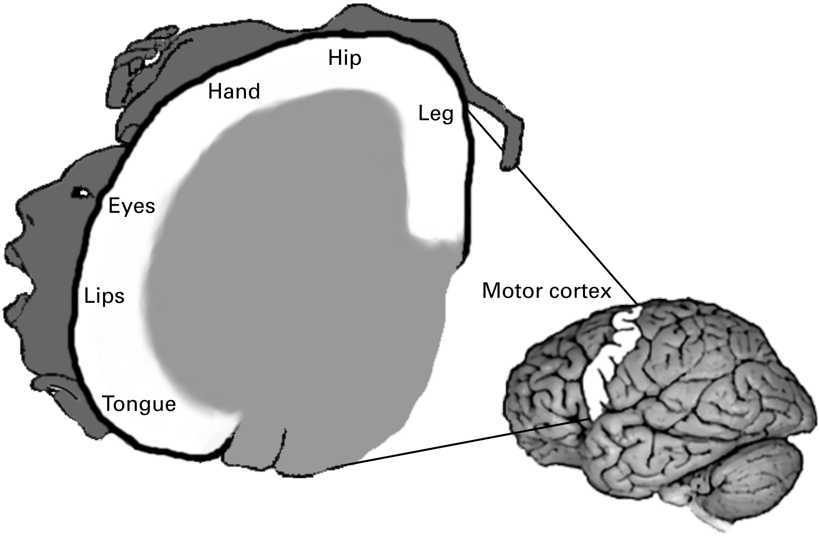

Figure 1.8
Spatial representation of body parts on the motor cortex. This topological relation between body parts and the brain has been traditionally drawn as a homunculus around the transversal section of the motor cortex. This kind of diagram shows that some anatomical parts are more represented (and hence controlled to a greater extent) than others in the motor cortex. Hands, which have built civilizations, are a significant example.

ity of the body to maintain a dynamic equilibrium is called *homeostasis* (the mid-nineteenth-century French physiologist Claude Bernard discovered the existence of this self-regulated *milieu interieur*, or internal environment). Another type of important regulation affects the automatic movement of muscles that control the body's vital organs. The brain's conscious control is not needed for the heart's *systolic* and *diastolic movements* (contraction and expansion) or for the diaphragm's movements that make breathing possible. These movements are controlled by the *autonomic nervous system*, which is divided into *sympathetic* and *parasympathetic systems*. The autonomic nervous system starts being formed during the first phases of embryonic development, and any defect in it has catastrophic consequences.

Another fundamental system of internal control is the *endocrine system*, a collection of organs that are located in different parts of the body and that secrete chemical substances (*hormones*). The pituitary gland or hypophysis, the thyroid gland, the adrenal glands, the ovaries, and the testicles are examples of hormone-producing organs that contribute to the regulation of vital functions. The brain and the hormonal system are closely related. A hormonal gland (the *pituitary*) is lodged within the brain. This gland is directly related to the hypothalamus, creating what is called the *hypothalamic-hypophyseal axis*. This axis controls all the vital processes that are carried out in the organism (such as breathing, heartbeat, blood regulation, and body temperature). The relation between the hypothalamus and the pituitary gland also regulates many basic behaviors (such as hunger, thirst, fear, reaction to cold, and sexual desire).

Although the brain is essentially not involved in the control of the regulation of the autonomic systems, there is a close relation between the autonomic systems and certain areas of the brain such as the limbic system, which is involved in the control of emotions. In this way, the basic physiological functions are directly connected to what we feel in a given moment. This point is fundamental for theories of consciousness and of formation of the mind because at a certain level, it is impossible to separate autonomic activities from conscious activities. And likewise, the vital functions can conclusively determine the kind of behavior that we carry out in a specific situation.

The brain's organization is separated into regions with structurally and functionally delimited areas, and it responds to criteria that are related to the laws of *bilateral symmetry*. This principle of organization is one of the fundamental characteristics of animal architecture. The phenomenon by which functional symmetry is broken in the brain hemispheres is called *lateralization*.

Vertebrates are organized according to principles of bilateralism. Fundamentally, *bilateralism* refers to the process of development by which the embryo grows in a symmetrical manner, which is a way to conserve resources during *embryogenesis*. These development processes are so fundamental that they are shared by a large group of animals (as disparate as worms and humans) called *Bilateria*. In an adult animal, bilateral symmetry can be easily recognized because the parts of the body on each side of an imaginary middle line are mirror images. The clearest example is the organization of the skeleton in vertebrates, which possess bilateral symmetry with respect to the middle axis that passes through the spinal cord: the hands, arms, legs, and ribs on one side of the body are the mirror image of those found on the other. Additionally, organs such as the kidneys and the cerebral neocortex (which has two hemispheres) fulfill the criteria of bilateralism. The heart, stomach, intestines, liver, and pancreas do not follow these rules. They are unmatched organs that lie on one side or the other of the body.

In spite of the symmetrical organization of vertebrate bodies, left and right differences can be seen even in the skeleton. The length of the legs, for example, is a well-known example. The same thing happens with the brain. Each cerebral hemisphere possesses a series of modules that are functionally distinct to such an extent that sometimes a person is spoken of as having a left- or right-dominant brain. The right hemisphere has been shown to specialize in spatial representation, among other cognitive activities, and the left to contribute to the understanding and expression of language. This difference could be behind a person's capacity to become a grand master in chess and the differences between men and women in the practice of the game. There are no conclusive studies in this respect, but activities such as mathematics, music, painting, architecture, and even chess, which require good spatial representation, are chosen by more men than women.

On the other hand, instead of an innate difference based on the asymmetric structure of the cerebral neocortex, these differences could reflect differences in education that foster the appreciation of certain activities above others. Thus, in chess, the appearance of the three Polgar sisters (Susan, Sofia, and especially Judit, who is one of the strongest grand masters on the worldwide roster) in current competition seems to confirm that education is sufficient to generate any type of cognitive activity at highly specialized levels.

In any case, male and female brains have different characteristics, which, to a large extent, are influenced by hormonal levels, particularly *testosterone* and *progesterone*. If these differences are added to those that appear because of the different ways that children are educated in the family and in schools, the result is fundamental differences that necessarily will be reflected in the habits, tastes, predilections, and actions of each sex.

An additional problem for evaluating the differences between the sexes (the scientific name is *sexual dimorphism*) is the enormous variability among individuals of the same sex. Thus, the structural and functional characteristics of the brain vary in such a marked way among males as a group and females as a group that it is difficult to propose an average type that characterizes each sex. No conclusive studies have been carried out to determine to what extent lateralization influences men and women in their chess skills. Two recent excellent books, one by Susan Polgar (four-time women's world chess champion) and the other by Jennifer Shahade (two-time U.S. women's chess champion), explore the issue and offer numerous personal insights from the point of view of female chess professionals.

Techniques for Analyzing Brain Activity

The classic tool for evaluating the activity of the brain as various mental tasks are carried out is *electroencephalography*. One or more electrodes are placed on specific parts of the scalp to register electrical current, normally on the body of a neuron, and produce an *electroencephalogram* (*EEG*). Thanks to the EEG, numerous properties of the brain and its electrical activity have been identified in both wake and sleep states. Different types of electrical frequencies depend on the global activity of the brain. The 1 to 2 hertz (Hz) of the delta band that is identified with deep sleep is located in the lowest wavelength, and the gamma frequency of 35 to 40 Hz is identified with the wake state. This last frequency is behind the *synchrony* phenomenon that might play a fundamental role in the generation of different cognitive processes.

In recent years, sophisticated techniques of image analysis have identified areas of the brain that are active in a certain moment or as a result of a specific activity. The most important techniques are *functional magnetic resonance imaging* (*fMRI*), *positron emission tomography* (*PET*), and *magnetoencephalography* (*MEG*). The first two take advantage of the fact that active areas of the brain consume more oxygen than passive areas and therefore demand a greater blood supply. They can recognize isotopes that have been previously ingested and that are then found in the bloodstream to generate a three-dimensional map showing the regions of the brain that have more blood. The third, MEG, is a sophisticated technique that can detect in real time the magnetic fields that are created by electrical currents between neurons. The data contributed by these techniques will in the near future delimit functionally specific zones of the brain (especially in the neocortex) and describe a cerebral structure that shows that the brain acts in a collective and integrated way to carry out specific higher cognitive functions in a given situation.

Diverse studies have examined the brain's functioning during chess. This type of information is beginning to contribute important data about differences in information processing among players of different strengths. It has been discovered that during a chess game, the occipital lobe (which corresponds to visual processing) and the parietal lobe (which corresponds to attention and spatial control) are strongly activated during the cognitive processes that are involved in decision making. Other studies have verified that a player without experience shows an active hippocampus and medial temporal lobe, suggesting the analysis and processing of new information (use of short-term memory), and that an expert player shows predominantly activation of the frontal lobe, suggesting a superior order of reasoning where attention is centered in the use of already well-known mental schemas and not in trying to look for new solutions (figure 1.9). I return to this fascinating subject below.

Finally, the study of brain diseases and injuries in humans has yielded important data about the relationships between cognitive functions and the

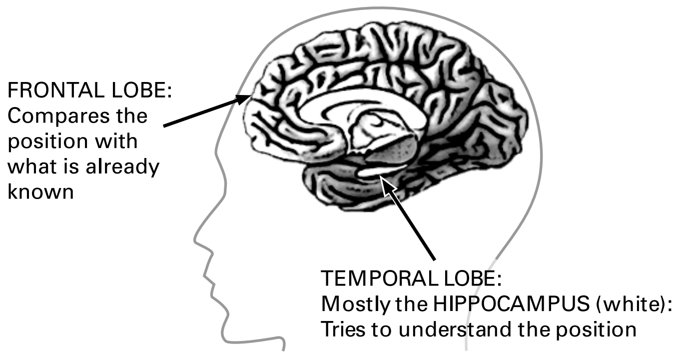

Figure 1.9
Brain activity during a chess task. Players with an Elo rating of more than 2400 use the prefrontal cortex, while novices make more use of the medial temporal lobe and the hippocampus.

regions of the brain. Think of Broca's area (located in the left frontal lobe), whose deterioration provokes the loss of the capacity to articulate language (although these patients understand what they hear), and Wernicke's area (located in the auditory cortex of the temporal lobe), whose deterioration provokes the loss of coherent speech. Numerous areas of the brain have been located and related to corporal or mental dysfunctions from this type of studies. Another valuable source of information is patients who have suffered strokes, where specific parts of the brain have been rendered useless. Thanks to these patients, it is possible to determine the kinds of cognitive processes that are associated with certain areas of the brain.

Acquisition of Functional Capacities in the Brain

The brain is not initially prepared to carry out complex cognitive functions but acquires those capacities as a result of an elaborate developmental process. Without the cultural environment in which a baby develops, neither language nor the reasoning capacity that is characteristic of humans as cultural beings will appear. The neurons' functioning is intrinsic in the sense that the structure and morphology of these cells determine their use to communicate action potentials between axons and dendrites using neurotransmitters as intermediaries. But the brain needs a full development process to configure functionally specific areas, such as the visual area of the occipital region. (It would also be possible to argue that neurons pass through a period of determination and differentiation until they reach a mature and fully functional state.) This means that, as an organ, the brain is not prepared to carry out cognitive tasks but rather needs to generate a series of relations among the neurons and with the sensations coming from its own body and from the outer world to be functionally ready.

This whole process begins very early during gestation as the brain develops. The crucial step takes place in the first weeks of development when the *neural tube* is formed from cells of the outermost layer of the embryo, called *ectodermic cells*. The closing of the neural tube marks the beginning of the development of the spinal cord as well as the brain. The *notochord*, a structure that is common to all vertebrates during development, aids to a great extent in the correct formation and later differentiation of the neural tube, as has been shown in studies carried out following specific proteins.

Once both the spinal cord and brain have closed, the true challenge of development begins. The most anterior part of the neural tube divides into five compartments as a result of a series of constrictions. The most anterior (the *telencephalon*) will become the cerebral hemispheres. It is followed by the *diencephalon*, *mesencephalon*, *metencephalon*, and *myelencephalon*, which will give rise to the rest of the structures of the adult brain. While this is happening, the neurons are starting to differentiate themselves and to emit dendrites and axons that will follow specific paths. Although dendrites establish connections only with the axons that are in their vicinity, axons will travel distances that are spectacular on the embryonic scale to innervate areas throughout the body. Axons grow to reach specific target zones by following the chemical trail left by a family of proteins called *semaphorins*, which attract and repel the axon membrane in a differential way according to their type. At the same time, many neurons die during development following a normal mechanism present in almost all tissues. Because overabundant raw material (cells) is generated, the excess then must yield its space so that the rest can grow without difficulties. This type of strategy has been taken to suggest the hypothesis of *neuronal Darwinism*, where a kind of fight for survival exists among neurons. The defender of this thesis is Gerald Edelman, who won a Nobel Prize in medicine.

Much later, each movement, each organ of the embryo, leaves its impression on the developing brain. In the human species, little by little through the nine months of gestation, the brain begins to generate a map of the world—the feet, the hands, the arms, the legs, the liver, the heart, the stomach, the muscles of the eyelids, the tongue. The whole body begins to be represented in the brain, as do certain sensations from the exterior. The mother's heartbeats are a permanent rhythm that generate a certain rhythmicity in the brain, for example, and lights coming from the outside stimulate visual responses and sounds. Everything contributes to the development of the connections among neurons, creating a map of astounding complexity that in some way is able to codify such disparate information in cellular form. The result of this cerebral representation of the body establishes proprioception, thanks to which we can determine the spatial positioning of each part of the body in an unconscious manner. Finally, for the brain to begin to carry out cognitive tasks such as perception, language, attention, or memory, it first must receive a whole series of stimuli during the first years of life. For example, visual perception is impossible if during the first months visual stimuli do not cause the cells of the retina to develop and make appropriate connections to the occipital regions of the brain.

Some Notes on the Evolution of the Brain

To analyze the evolution of the brain in primates is to analyze the origins of our species as a result of the changes that it has undergone throughout millions of years. More fascinating still is that social relations and the origin of culture and language are causal agents, found behind the evolutionary dynamics themselves affecting our species. Since evolutionary processes continue operating on any species, including humans, the effect from social relations implies that contemporary cultures throughout the planet with their different ethical and moral values exert their quota of influence on the future of the species from the anatomical and physiological point of view. But as shown above, both anatomy as well as physiology influence individual behavior, and in the final reckoning, individuals are responsible for the development of culture.

Lamentably, this circular biological-cultural relationship has been used in an abusive manner on many occasions to support totalitarian ideas and at the same time to provide a pseudoscientific basis to justify the exploitation or genocide of entire groups of humans. As an example, there are the ideas developed by Konrad Lorenz, a winner of the Nobel Prize in medicine for his work in *ethology*, the science that studies animal behavior. One of the theories proposed by Lorenz at the end of the 1930s postulated the degeneration of civilization as a result of its distance from nature and its excessive cult of urban culture. Carrying out an analogy between the phenomenon of domestication and the phenomenon of civilization, he looked for biological and evolutionary bases to justify the notion of ethnic society, without hiding his affection for the Nazi ideals that possessed, in the eyes of Lorenz, the essential characteristics for saving humanity from the degeneration into which he felt that civilization was falling. Lorenz continued to insist throughout his life on this point, consolidating himself as a defender of the ecological cause as a new strategy against urban dangers instead of promulgating, in the purest and most abominable Nazi language, the need for purity of blood in the nation-ethnic group. Evolutionary arguments lend themselves to this type of absurd analogy and the dangers that this entails. A new interpretation of Lorenz under the name of *social biology* has since the 1960s presented images of the cultural and social evolution of humans as a reflection of evolution in terms of the "fight for existence." Without losing sight of the undeniable relation between evolution and culture, I try here to keep away from this type of argument, indicating only the biological bases necessary for evolution.

Evolution is a phenomenon that operates on systems that offer fundamentally two types of characteristics—reproduction and variation. These two qualities are necessary, although not sufficient, for certain mechanisms to operate so that starting from system A one can arrive at system B. The way the dynamic works is that system A reproduces itself, giving rise to new systems that are type A but that possess a certain variation. Eventually, the variations between the original system and one of its descendants are such that a new system, of type B, is created. The phenomenon of life and biological processes on earth has generated systems that we denominate *species*. Although how to define the concept of species is an open debate, one definition is of a set of organisms that are able to reproduce among themselves. This biological definition of species means that a cat and a dog, since they cannot generate a viable descendant that at the same time could reproduce itself, are considered to belong to two different species. Species satisfy all the requirements for the evolutionary dynamic to take place: the individuals that compose a species reproduce, giving rise to more individuals of the same species.

However, reproduction generates variation in multiple ways. One way depends on genetic information, which is found encapsulated within DNA molecules. Another way of creating difference comes from the type of cellular machinery that is inherited with the *oocyte* (the maternal cell that originates the new living being when it is united to the paternal spermatozoid). It can specify different ways to carry out embryonic development, determine how the oocyte of the daughters will develop its cellular machinery, and so forth. The accumulation of variations in a gradual way, generation to generation, is called *population dynamics* or *microevolution*; the changes responsible for a species differentiating itself from its ancestral species are called *macroevolution*; and the process responsible for that change is *speciation*. In the evolutionary history of all species (including the hominid lineage that gives rise to the human species), both types of dynamics have been important.

The evolution of the brain in terrestrial vertebrates is a process that runs parallel to the evolution of other anatomical structures in the distinct lineages of this animal group. The comparative study of the brain in other animals can establish hypotheses and theories about how the brain functions that can be generalized to the human species. A large part of our knowledge about the brain is due to experiments and analysis in other mammals (mainly mice, rats, cats, dogs, and monkeys). Nevertheless, the mammal brain evolved from the brain of reptiles at some point about 250 million years ago, at the beginning of the Mesozoic era. And that brain evolved from the brain of amphibians some 350 million years ago, during the final period of the Paleozoic era. Thus, the evolutionary chain can be followed back to one-celled organisms, although with regard to brain formation, it is sufficient to begin with the chordates (figure 1.10).

Chordates (phylum *Chordata*) take their name from the presence, at least during the first stages of development, of a structure called a *notochord* that extends dorsally with respect to the longitudinal axis of the body (discussed above). This structure has a distinct construction that includes large cells of connective tissue and constitutes a kind of guide around which an organism's bilateral symmetry is organized. In vertebrates (fish, amphibians, reptiles, birds, and mammals), the notochord is lost during development, becoming part of the vertebrae. The other primary characteristic of chordates is a *nervous cord* that is dorsal to the notochord and largely formed by it. The first chordates possessed an elongated body with an anterior portion where the mouth was located and a posterior portion containing the anus. In

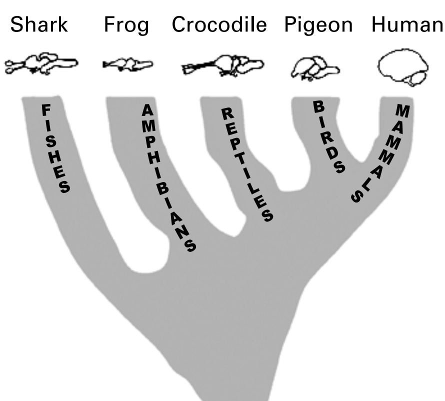

Figure 1.10
Kin relationships of the main vertebrate groups showing brain diagrams (not to scale).

this basic type of corporal architecture, nerve tissue and sense organs (such as those for hearing, sight, and taste) were accumulated in the anterior part of the body, constituting what we can consider a protobrain. The first link with a recognizable brain structure as such in the vertebrate lineage is the fish. From there, other vertebrate groups have modified or added new parts to those that already exist. Thus, the most characteristic parts of the brain, which have been described above, appear, developed to a greater or lesser extent, in the different vertebrate groups.

The area of greatest development in the brain of mammals, especially in that of primates, is the *neocortex*. In fact, the evolution of the mammal brain could be considered as the transformation and increase in complexity of the neocortex. The cerebral neocortex in humans holds three-quarters of all the synapses in the whole brain and two-thirds of the total brain mass. Here is where the associative processes and high-level cognitive functions take place. From the evolutionary point of view, the surface of the neocortex has increased considerably in the primate lineage. In addition, new areas have been added that do not correspond to areas in ancestors. New characteristics that appear are called *novelties* in evolutionary biology, and they constitute the base on which the process of change is manifested. In the aardvark (a small mammal of the African savannah), the olfactory lobe in the anterior part of the hemispheres is prominent, which has allowed this animal to adapt to situations in which the sense of smell (for enemy reconnaissance) is crucial for its survival. However, in the human species, the olfactory lobe is little developed. The same is true of the lateral optical lobe, which is present in other mammals but whose functions have been replaced in humans by the occipital cortex.

The most obvious change in the brain of the human species is its relative volume compared to the total mass of the body. The comparative study of the relative sizes of anatomical parts is called *allometry*, and thanks to this type of analysis, rules of relative proportions among different parts of the body have been discovered. These laws of proportionality are due to an increase or decrease in the speed with which a determined area develops during embryonic development in the maternal uterus (in the case of the mammals). This set of laws is called *heterochrony*, and it has been shown that the brain of *Homo sapiens* has evolved with respect to the rest of the hominid primates according to a law of heterochronic proportionality denominated *neoteny*. This law of proportionality indicates that the speed of growth of the human brain during the uterine stage (and through approximately the first year of life) is relatively much greater than that of any other primate. As a result, humans have brains that are much greater in volume than what would correspond to us by the size of our body. This has translated into an extraordinary development of the cerebral hemispheres and especially of the neocortex, with a totally unexpected secondary effect—the appearance of high-level cognitive processes.

Summary

In the structure and function of the brain, the neurons are the main protagonists of the brain's capacity to process information. Mechanisms operate inside the neurons to transmit electrical impulses and to generate memories—that is, to strengthen the relations among neurons in the synaptic connections that are made between dendrites and axons. The neocortex is the central processor for decision making, and the limbic system, especially the hippocampus, is the fundamental station for attention and working memory. All human activity has an inescapable biological base that is impossible to transcend and that influences, channels, restricts, and gives form to our cognitive capacities.

Nevertheless, within this biological straightjacket, the human brain has generated societies and civilizations based on the transmission of culture, as if this were an extension of the capacities of a brain that dreams of freeing itself from the biological yoke. Thousands of years after the appearance of the human species, as we sit down in front of a chessboard and our mental reality pauses to focus on generating thoughts based on our knowledge of the game, behind this cognitive curtain is a network of organs, cells, and molecules that allows us to construct this reality and plan our next move.

This brief explanation of the biological bases of the human mind has set out the principles and structures on which our thoughts, our critical sense, and our capacity to respond in the face of the unknown—in short, our behavior when faced with a chessboard—all rest. This concludes the first metaphor of the book—the brain as an organ whose structure allows it to construct a model of the surrounding reality. That representation constitutes a metaphor of reality that is personal and not transferable and that conditions the human mind, the subject of the next chapter.