

The History of Reflexes Part 1

Saturday, December 15 2012, 12:09 PM

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Citation:

Clarac, F (2005) *The History of Reflexes Part 1: From Descartes to Pavlov*, **IBRO History of Neuroscience**

[http://www.ibro.info/Pub/Pub_Main_Display.asp?LC_Docs_ID=3155]

Accessed: date

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PART 1: FROM DESCARTES TO PAVLOV

Ever since the time of Descartes, reflexes have always been regarded as one of the most fundamental neural mechanisms. Even non-scientists intuitively define reflexes as very fast, reproducible reactions. In various dictionaries, the term is explained in greater detail, on the following lines: a reflex movement is an automatic response to a given stimulus, occurring after a very short delay. Reflexes can also be opposed to 'spontaneous' and 'voluntary' actions, two processes that are also quite difficult to explain scientifically (Prochaska et al., 2000).

Reflex mechanisms are of course still being extensively studied in the central nervous system (CNS). To find out whether the word 'reflex' is still attracting scientists, we consulted the PUB-MED site, using 'reflex and spinal cord' as a key-word; we found more than 6,900 references, the first of which dates back to 1949, when D. P. C. Lloyd published an article in *J. Gen. Physiol.* (1949) on posttetanic potentiation in the monosynaptic reflex. Upon enlarging our research by adding 'reflex and the CNS', we obtained more than 17,600 references, the first of which again dates back to 1949; this was a paper in Russian by V. K. Krasukii, which was published in the Pavlov Laboratory's journal.

The present review will be divided into two parts; the first, from R. Descartes (1594-1660) to I. P. Pavlov (1849-1936), corresponds to the emergence of the concept in relation to the development of the Brain Sciences (Finger, 1994). It is one of the only topics in this field that has been studied in such detail for several centuries, and research on the underlying mechanisms has involved physiologists, neurologists and psychologists. Reflexes were thought to be so crucial at the onset of the twentieth century that they seemed to be the main mechanism explaining how the brain functions. The second part will begin with the considerable contribution of Sherrington and from most of the successors. By now, however, progress in Neuroscience has become so deep and so diverse that we would suggest that the reflex concept has to be redefined as input-output circuits of a particular kind in the neural networks, which are required for adaptation to the environment.



Figure 1: René Descartes (1594-1660) and Thomas Willis (1618-1678): the two pioneers of the reflex concept.

1. From Descartes to Prochaska (studies in the seventeenth and eighteenth centuries)

Although we could start way back before the seventeenth century and mention some interesting research carried out by Hippocrates and Galen, it is generally held that the first two people who really started to throw light on reflexes were the French philosopher René Descartes and the English physician Thomas Willis (1628-1678) (Figure 1). René Descartes was born in La-Haye near Tours and educated by the Jesuits; he travelled around Europe during his youth and eventually settled in Holland at the age of 33, occasionally visiting Paris. In 1637, he published his *Discourse on Method*, containing the famous statement 'Cogito ergo sum' (see Descartes, 1953). He was not only a mathematician and a physicist specialized in optics, but also a biologist who performed numerous dissections in his cellar in Holland. Two of his works, *The Passions of the Soul*, published in 1649, the year before his death, and *De Homine*, which is entitled *Le Traité de l'homme* in French and was published in 1662, tell us what he thought about reflex functions. Descartes wrote this text long before it was published, but he feared the Church authorities and, in view of what had happened to Galileo, he took great care not to cause offence. His opinions about human consciousness were clearly 'dualistic': he made clear-cut distinctions between the workings of what he called 'the machine', corresponding to the basic mechanisms that can be reduced to physical actions, and the 'spirit', responsible for decisions, judgements and voluntary actions. This dualism seemed to have convinced contemporary scientists as well as enabling them to study nervous mechanisms without being accused of meddling with 'the soul'. It is certain that today, as Damasio (1994) has pointed out, it is an 'error' to adopt this position! But in the seventeenth century, our philosopher, in opposing the human machine and the psychological processes, opened a pathway, on the contrary, towards a highly productive scientific field. He described reflexes in two different ways: in 'Passion of the Soul', no. 13, he described the eyelid reflex:

"If someone quickly thrusts his hand against your eyes as if to strike us, even though we know him to be our friend, that he only does it by fun, and that he will take great care not to hurt us, we have all the same trouble in preventing ourselves from closing them; and this shows that it is not by the intervention of our soul that they close, seeing that it is against our will, which is its only, or at least its principal activity; but it is because the machine of our body is so formed that the movement of this hand towards our eyes excites another movement in our brain, which conducts the animal spirits into the muscles which cause the eyelids to close" (Fearing, 1970, p. 27).

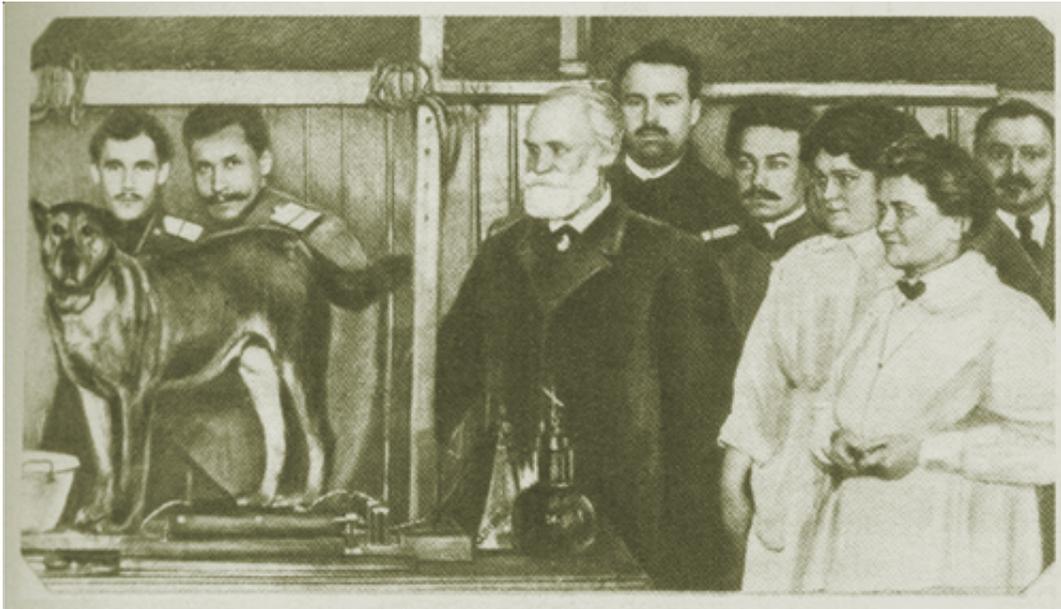


Figure 2: Figure 7 of *De Homine* (1662), showing an infant looking at a fire (A) and withdrawing his left foot (B). The 'pain' message is represented going to the pineal gland (F).

On the other hand, in *De Homine*, figure 7 shows an infant looking at a fire and withdrawing his left foot (Figure 2). The pathway involved is indicated, running from the digits to the pineal gland, which Descartes took to be the interface with the spirit. His idea of locating the soul in this very small gland can be explained by the fact that it is the sole component of the brain that is not twofold, occurring in both hemispheres. The soul must be unique! Descartes explained that when a sensation reaches that gland, it serves to orientate the 'spiritus animus' (animal spirit: nowadays we speak about 'nerve impulse') in the right direction to induce an appropriate reaction (Figure 3). At that time, the blood vessels and nerves were assumed to be more or less fused; Descartes declared that these 'animal spirits' penetrate the brain via very fine pores; but that only the most elaborate ones could conduct nervous information to the whole body.



Figure 3: Figure 33 of De Homine (1662). This figure shows how the light enters and makes images on the retina. The nervous pathway goes from the optic chiasma to the pineal gland. It moves toward the arm and induces the muscle contraction to project the arm onto the AC arrow.

Thomas Willis, a Professor of Natural Philosophy at Oxford University, was a great anatomist and an excellent clinician. To avoid having problems with the authorities, he dedicated his main work, entitled *Cerebri Anatome* (1664), to his patron, Dr. Sheldon, the Archbishop of Canterbury. Here Willis described the various parts of the brain, including the cerebral cortex, the basal ganglia (corpus striatum) and the callosal body, and distinguished between the functions of the cerebrum and those of the cerebellum. Although he was wrong in his conclusions, Willis initiated a new period, since he himself dissected his own clinical cases. Willis defined the reflex as described by Molnar (2004): "he believed that nerve impulses journeyed to and from the brain, and that 'animal spirits' were reflected back toward the periphery from the striatum." He often used the term 'reflex' when distinguishing between three types of movements, depending on the intensity of the stimulus. A weak, continuous stimulation induces automatic movements such as the heartbeat or the respiratory rhythm; these movements involve the cerebellum, which controls the vital functions of the organism. A more intense stimulation will trigger the transport of classical sensory information to the striatum, where it is integrated and where involuntary movements such as walking or the learning of adaptive activities are controlled. Very intense stimulations induce voluntary reactions involving the corpus callosum, which Willis took to be a similar structure to Descartes's pineal gland.

Willis, like Descartes, was a highly positive thinker who attempted to explain mechanisms scientifically without taking transcendental considerations into account. Canguilhem (1977) explained that one of the great differences between the latter two pioneers was their

interpretation of the heart. Descartes took the heart to be the 'primus movens', the main organ controlling the brain. According to Willis, however, the heart was nothing more than a muscle. Another of the latter author's works, *De Anima Brutorum* (1672), dealing with the soul and pathological states and emphasizing the difference between the human brain and that of other species, was also highly influential.

Jean Astruc (1684-1766), from Montpellier in France, was the first to use the term 'reflex' as a noun. F. Fearing (1970), quoting an extract from the French doctoral thesis by Jules Cayrade (1864), showed how Astruc used the metaphor of the light ray reflected by a mirror to describe the initiation of a motor response, although this author knew nothing at all about anatomical pathways. Cayrade used the old term 'nervous sympathy' and then described the mechanisms involved. A. Von Haller (1708-77), who was born in Bern and educated at the Universities of Tübingen and Leyden, made a great contribution to physiology when he defined the notion of 'irritability'. Muscles have the unusual ability of being able to contract with the 'vis insita', and they were found in some experiments to keep this property even after death; the 'vis nervosa', the stimulation involving the nerves, on the contrary, is variable. Von Haller defended the idea that involuntary actions are extremely frequent and that they occur without the will or the soul, involving only the activity of the body (Haller, 1762).

During the eighteenth century, Descartes's ideas were still quite influential. At that time, mechanical figures were highly popular; in 1738, Jacques de Vaucanson (1709-82) presented the French Academy in Paris with a fascinating mechanical flute player. He also made a duck, which was able to eat and to swim; these inventions greatly impressed the scientific community, since they corresponded to the materialization of Descartes's 'machine'. It was also the beginning of animal experiments. The idea was to work on specimens without heads, using 'cold blooded' animals such as reptiles or amphibians (turtles, salamanders and tritons, etc.); frogs were mostly used for this purpose because they survived for long enough in captivity to be used for experiments. In fact, there were two schools of thought opposing Descartes's ideas. First there were the vitalists, who felt they were too mechanistic. One of their representatives was G. E. Stahl (1660-1734), a professor of physics in Halle, who defended the 'phlogiston' theory whereby all chemical mechanisms are controlled by the soul; another was Cl. Perrault (1613-1688). On the opposite side, the materialists claimed that there was no place for the soul in the human body. One representative of this school, J. O. de la Mettrie (1709-51), who published *Man, a Machine* in 1748, stated that "the brain has its 'own muscles' for thinking, just as the legs have their muscles for walking." Since his book was said to be dangerous, he was obliged to leave France and took refuge in Prussia with Frederic the Great. The ideas of P. J. G. Cabanis (1757-1808) were on very similar lines. This scientist studied guillotine victims to ascertain whether they had suffered after being decapitated. He defined three levels of activation in the CNS, that of the reflex, a semi-conscious level and a completely voluntary one. This author's main claim to fame was the following statement: "The brain produces thought in much the same way as the liver filters bile!"

Robert Whytt (1714-66), a professor at the University of Edinburgh, made a significant contribution in 1751 when he published his monograph 'On the Vital and Other Involuntary Motions of Animals'. It is this author who developed the 'sentient principle', according to which sensory information is sometimes not perceived, since some actions are automatic and do not depend on the will. The mind may also control motions that are beyond the scope of consciousness. He defined the various types of automatisms quite aptly. Fearing (1970) has quoted the following passage about conditioned reflexes (p. 80), which seems greatly in advance of the time:

"Thus the sight, or even the recalled idea of grateful food, causes an uncommon flow of spittle into the mouth of a hungry person; and the seeing of a lemon cut produces the same effect in many people" ('On the Vital and Other Involuntary Motions of Animals', p. 280).

Whytt made some fundamental contributions to reflexology. He demonstrated by introducing a very fine needle into the frog rachidian canal that it was possible to destroy the spinal cord in this way: the frog becomes flaccid and unable to react. For the first time, this showed the presence of a true spinal centre responsible for integrating sensory information and triggering motion (Figure

4).

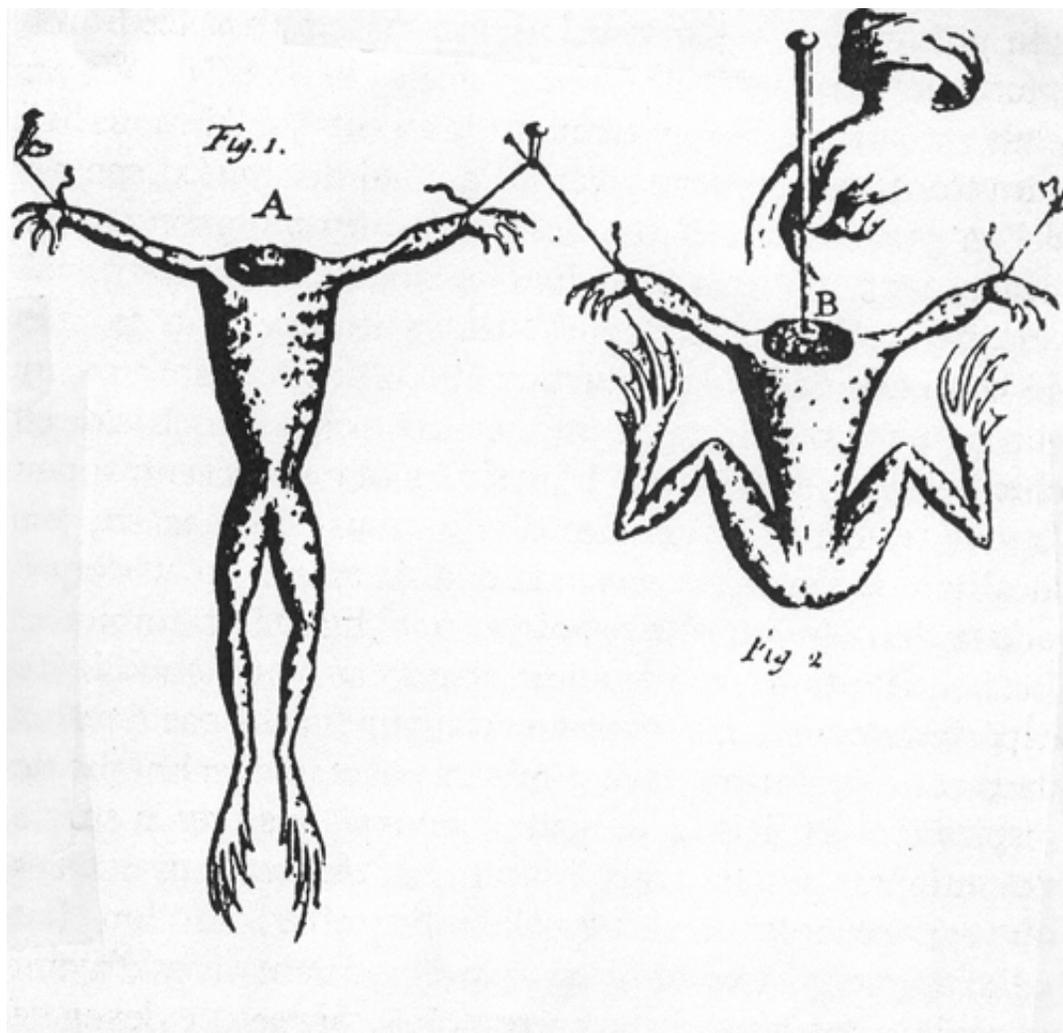


Figure 4: Experiments demonstrating the role of the spinal cord. (A) A decapitated frog stays without movement. But a mechanical stimulation of the spinal cord induces a flexion reaction. (B) After the destruction of the spinal cord, the animal is definitively flaccid. (Experiment presented by Whytt and cited by Jeannerod, 1983, p. 43.)

In fact, the first complete scientific description of a reflex was given by J. A. Unzer (1727-99), a professor working in Halle, and by G. Prochaska (1742-1820), Professor of Anatomy and Ophthalmology in Prague. In 1775, Unzer published a book entitled *Principles of Physiology*, in which he stated that the movements of animals cannot be reduced to physical and mechanical laws. He was a vitalist using a rational approach to the CNS. He provided some useful complementary data on the sensory and motor pathways involved in reflexes. In 1784, G. Prochaska from Moravia published a 160-page book called *De functionibus systematis nervosi. Commentatio* (Dissertation on the functioning of the nervous system), explaining the main principles underlying reflexes. This author added two new important principles, that of the 'vis nervosa', which corresponds to the latent nervous power transmitted in the nerves, serving to connect the different parts of the CNS. Its strength depends on the intensity of the stimulus and the vis nervosa continues to exist in the nerves even if they are isolated from the central structures. The second principle focused on the 'sensorium commune', the meeting-point between sensory and motor nerves, which is present in the various centres of the CNS from the brain to the spinal cord.

"The external impressions which are made on the sensorial nerves are very quickly transmitted along the whole length of the nerves, as far as their origin; and having arrived there, they are reflected by a certain law, and pass on to certain and corresponding motor nerves, through which,

being again very quickly transmitted to muscles, they excite certain and definite motions" (Ch. IV, Sec. I, p. 429, cited from Fearing, p. 95).

2. The concept of reflexes during the nineteenth century

The transition from the eighteenth to the nineteenth century saw the advent of a new method of nerve stimulation based on the use of electrical current. This method was a great improvement on those previously available, since it made it possible to vary the duration and intensity of the stimulus. L. Galvani (1737-98), who was familiar with B. Franklin's writings and with the principles of electrostatic conduction, used primitive condensers such as the Leyden bottle. Galvani, a professor at Bologna University, worked at home with his own electrical machine. He carried out a famous experiment on 16 September 1786, using a frog leg hanging on a copper hook placed on an iron wire grid. The difference between the two metals induced an electrical event evoking a muscle contraction. According to Brazier (1959), this was the beginning of electrophysiology! The term 'spiritus animus' was soon dropped by the theorists in the field of animal electricity; this theory immediately gave rise to much debate with A. Volta (1745-1827), who challenged the Galvanic idea. It is only more than thirty years later that C. Matteucci (1811-65) confirmed the validity and the great value of Galvani's experiments. Matteucci proposed a 'galvanoscopic' frog where both hind limbs were isolated with a dissection of the sciatic nerve and the muscles de-sheathed (Figure 5).

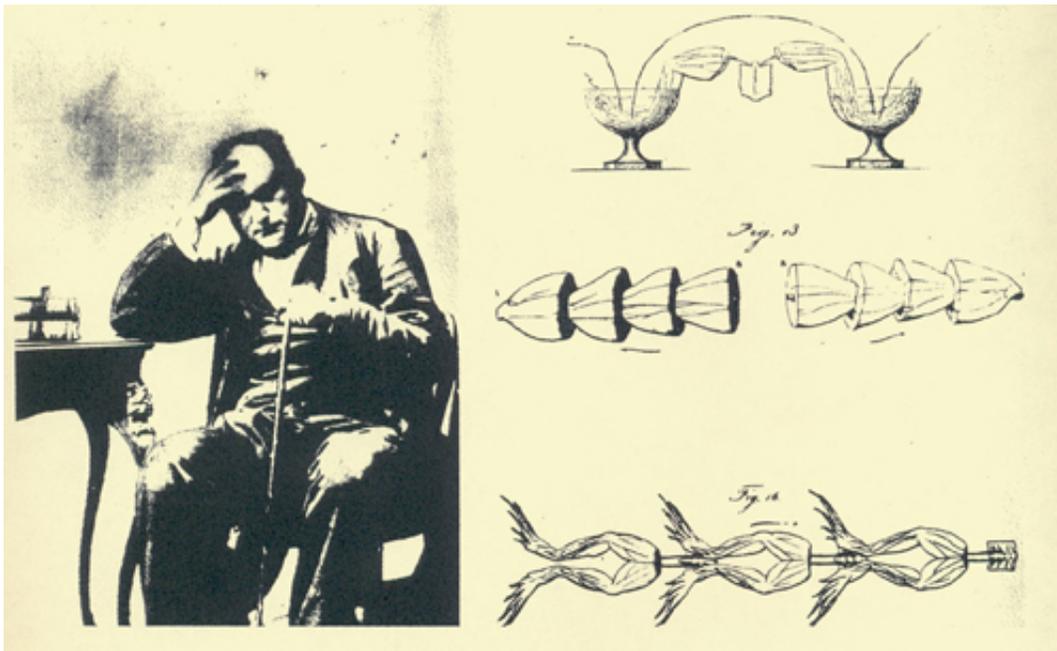


Figure 5: C. Matteucci and animal currents. Left: from an old photograph of the 'scuola Normale superiore' in Pisa. Right: Three experiments from C. Matteucci to prove the presence of 'muscle current'. At the top: an experiment inspired by Nobili where two frog legs can be in contact; in the centre and below, experiments demonstrating that muscle tissues are imitating the piles from Volta. In the picture below are represented 'three galvanoscopic frogs'; the stimulation of one induces the contraction of the others. (From M. Brazier, 1988, fig. 15, p. 30.)

In the nineteenth century, nerve conduction speed was measured by H. von H. Helmholtz (1821-94) in the frog sciatic nerve; E. du Bois-Reymond (1818-96) later built a trolley equipped with two bobbins to obtain a finely modulated induction current. At the same time, the Bell-Magendie laws proved that the sensori-motor CNS is functionally 'oriented'. In 1811, C. Bell (1774-1842) wrote an account of an experiment showing that in the spinal cord, the ventral roots alone induce a motor response. These data were presented in a very confidential form, in a letter to his brother! In 1821, F. Magendie (1783-1855), in a study on eight young dogs, showed that the dorsal roots are specialized in dealing with sensory messages and confirmed that the ventral roots drive the motor command. In his publication, he never mentioned C. Bell, since he knew nothing about his first

publication (Figure 6).



Figure 6: Charles Bell (1774-1842) and François Magendie (1783-1855): the controversy on the ventral and dorsal root functioning.

Flourens (1794-1867) divided the properties of the CNS into three different classes: (i) the properties of sensing, perceiving and willing, (ii) the property of excitability, (iii) the property of coordination. He opposed the brain, which is capable of sensibility and volition, to the cerebellum, which controls the muscle contractions (see Fearing 1970, pp. 126-8). During the years 1832-3, another discussion arose between Marshall Hall (1790-1857), an English physician, and Johannes Müller (1808-58), the German physiologist, on their respective work on the reflex. Hall's findings, despite his claims to the contrary, were not very new (he used to boast that he had spent as many as 24,000 hours on his experiments!). His main idea was that the reflex mechanisms are limited to the spinal cord and that the psychic processes occur only in the higher structures (Figure 7): "I conclude then that there is a property of sentient and motor system of nerves which is independent of sensation and volition" (Cited in Bennet and Hacker, 2002, p. 24).

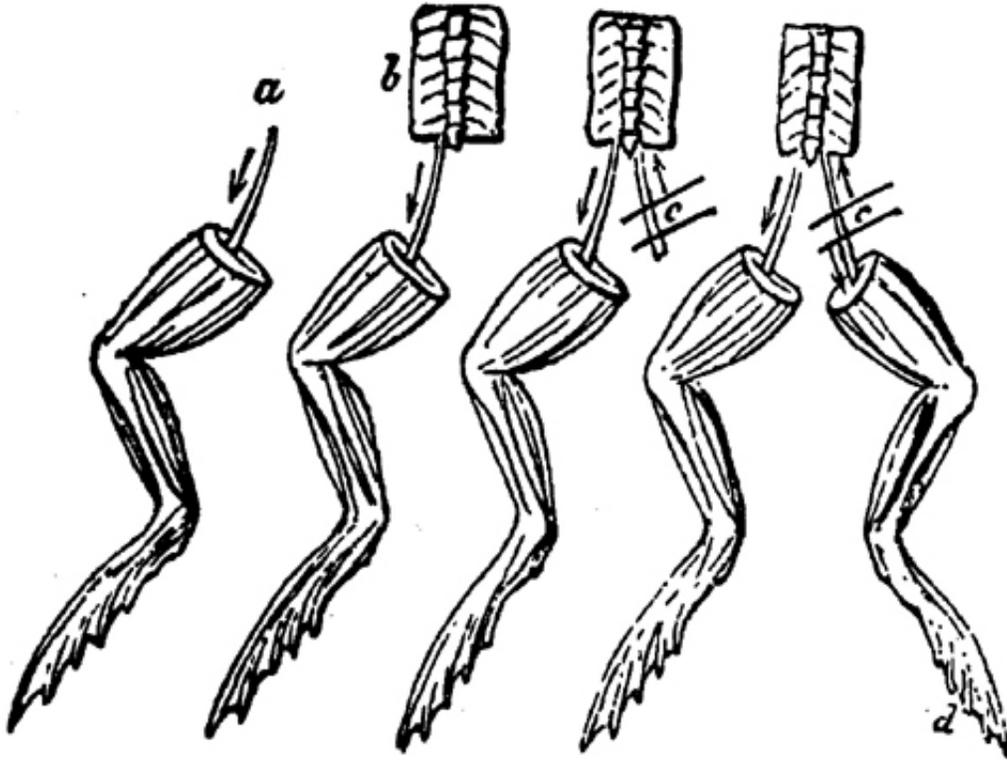


Figure 7: Marshall Hall's Experiments (1850), demonstrating the pathway of the reflex arc: a stimulation of the sciatic nerve (a) or of the spinal cord (b) induces a flexion of the isolated frog hind limb a 'galvanoscopic frog'. A contralateral isolated nerve stimulation (c) or a contralateral entire leg stimulation (d) induces a contraction of the opposite leg. (Presented in Jeannerod, 1983, p. 47.)

This strict opposition between the cerebral functions and the spinal cord was something of a throwback to Cartesian dualism (Clarke and Jacyna, 1987); whereas J. Müller, in his *Handbuch der Physiologie* (1838), linked reflex activity up with all the other brain mechanisms. A similar clash occurred some time later in the form of the 'Pflügger-Lotze controversy'. Fearing (1934) and Jeannerod (1983) have described this controversy in detail and concluded that its effects continued up to the end of the nineteenth century. E. Pflügger (1829-1910), a Professor of Physiology in Bonn who ended his career in Berlin, considering the locus of the stimulus which induced the response, proposed in 1853 the four laws of reflex action:

- "(1) The reflex movement occurs on the same side on which the sensory nerve is stimulated, while only those muscles contract whose nerves arise from the same segment of the spinal cord.*
- (2) If the reflex occurs on the other side, only the corresponding muscle contract.*
- (3) If the contractions be unequal upon the two sides, then the most vigorous contractions always occur on the side which is stimulated.*
- (4) If the reflex excitement extends to other motor nerves, those nerves always affected which lie in the direction of the medulla oblongata. Lastly, all the muscles of the body may be thrown into contraction"* (from Swazey, 1969, p. 48).

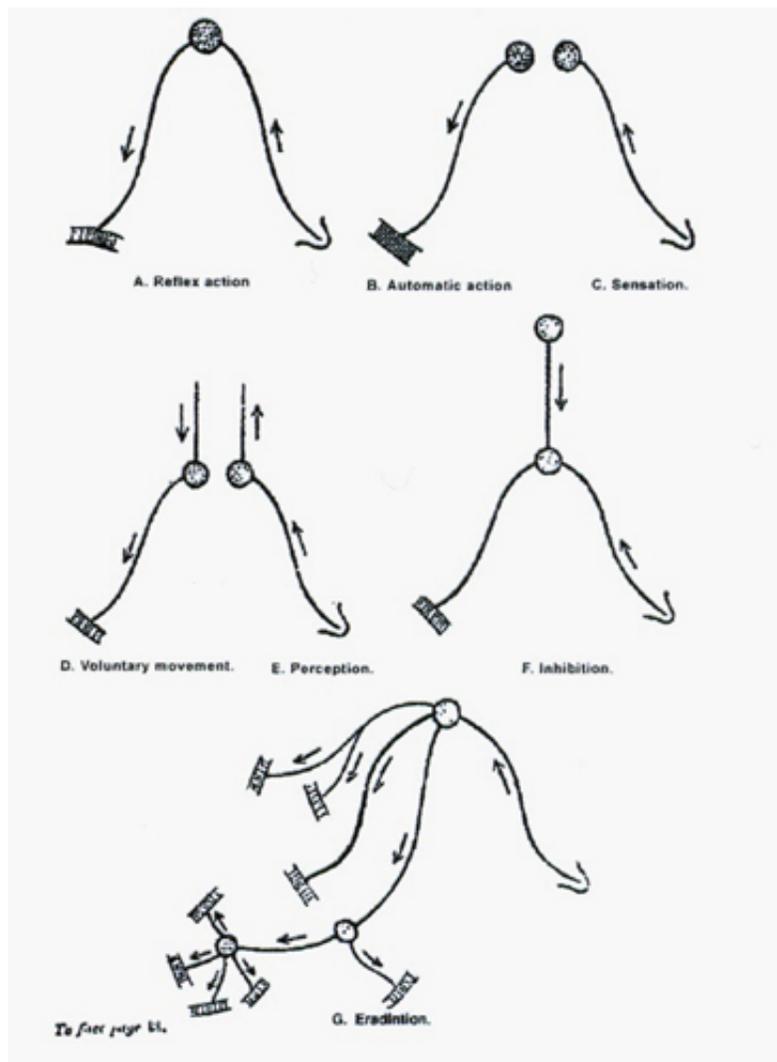


Figure 8: Connections of the nervous system illustrating excitation, inhibition and reflex action: A, reflex action; B, automatic action; C, sensation; D, voluntary movements; E, perception; F, inhibition; G, 'Eradication'. From P. H. Pye-Smith (1885), *Syllabus of a course of lecture on Physiology*, delivered at Guy's Hospital. Churchill, London.

Moreover, E. Pflüger claimed that the spinal cord, where reflex activity is organized, possesses some similar psychic properties to those existing in other central structures. He described the CNS as a single control unit running from the cortex to the spinal cord. According to R. H. Lotze (1817-81), on the contrary, the spinal cord is entirely under the control of the brain and has no independent properties, and the reflexes correspond to the first level of integration (Figure 8). C. Sherrington adopted exactly the same point of view some decades later. In fact, the controversy focused mainly on the psychic attributes of the spinal cord. Lotze observed that medullary action was not 'intelligent': after being decapitated, a frog has a very limited repertoire of activities, although they are quite complex. These activities simply result from a kind of 'persistent memory' based on the previously established neural connections.

During the middle of the nineteenth century, psychologists took great interest in this question, including H. Spencer (1820-1903) in his crucial book, *The Principle of Psychology* (1855), reviewing the development and organization of the CNS in relation to the evolution of the animal kingdom. Spencer explained that the CNS is composed of various stages of growing complexity, the lowest of which are always identical and rigid, whereas the higher levels are more independent and capable of more complex functions (nowadays, we would say they show much greater plasticity). The psychological properties are in keeping with this hierarchy; at the lowest level of organization, there is the reflex, the system which functions in the simplest way:

"S. 183: Reflex action being the lowest form of psychical life, is, by implication, that which is most nearly related to the physical life - that in which we see the incipient differentiation of psychical from the physical life (p. 534) . . . S. 184: From that lowest kind of reflex action, in which a single impression produces a single contraction, the ascent is by gradual steps to complications in the stimuli and the acts resulting from them" (p. 534).

Up to the Darwinian revolution, most physiologists and psychologists were influenced by Lamarck's ideas and took a more dynamic approach to the living world. They intended to play quite a strong role and believed that in the CNS there are no separate levels, but a continuum running from the simplest patterns of organization to the most complex ones. The workings of the CNS were thought to undergo a linear evolution, from the simple reflexes occurring in invertebrates to the reasoning, feeling and will of which humans are capable. Spencer, discussing various ideas about the emergence of actions and their great complexity, declared that however complex actions may be, they are governed by simple reflex laws:

"But, as I need hardly say, this seeming indeterminateness in the mental succession is an illusion consequent upon the extreme complication of the forces in action. The composition is so intricate, and from moment to moment so varied, that the effects are not calculable. Nevertheless, these effects are really as conformable to law as the simplest reflex actions." (Spencer, 1855, *The Will*, p. 619.)

At that time, thinking in the field of psychology was dominated in England by the 'associationism' favoured by Locke, James, Bain and Mill, who viewed the brain mainly as the site of sensory-motor associations (R. M. Young, 1990). The great neurologist J. Hughlings Jackson, who applied Spencer's theories, classified movements depending on how automatic they were; the reflex pattern of organization dominates in the lowest forms of automatic activity; whereas in the most highly evolved animals, such as humans in particular, the CNS controls the most complex activities, subject to the dictates of the will. Pathological psychic conditions were said by this author to correspond to a 'dissolution' and a 'regression' of evolutionary events: patients with psychic disorders show a behavioural regression and a return to more primitive automatic activities. I. Sechenov (1829-1905) was also a disciple of Spencer. Since he was trained by Cl. Bernard, he understood the importance of 'homeostasy', an equilibrium of the body. He took the reflex to be a sort of defence mechanism corresponding to a homeostatic adaptation to the external medium, where the responses produced result from the conservation of instincts. In 1863, this author published *Reflexes of the Brain*, where, in line with Spencer's ideas, he explained that the brain is responsible only for reflex reactions, as well as insisting on the importance of the surrounding world and the various types of sensory perceptions:

"All psychical acts without exception, if they are not complicated by elements of emotion . . . develop by way of reflex. Hence, all conscious movements resulting from these acts and usually described as voluntary, are reflex movements in the strict sense of the term . . . (p. 80) . . . Thus, man not only learns to group his movements through the frequent repetition of associated reflexes, he at the same time acquires (also by means of reflexes) capacity to inhibit them" (p. 86).

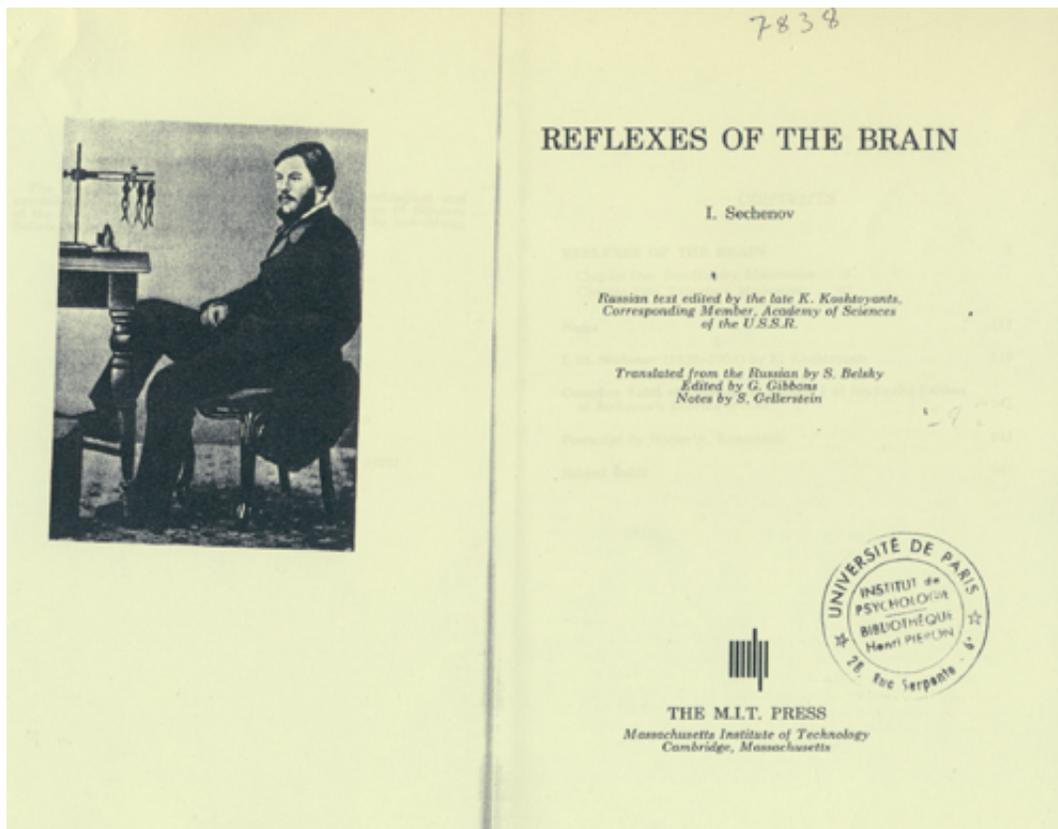


Figure 9: Sechenov (1829-1905) and the frontispiece of his fundamental publication, *Reflexes of the Brain*. English translation from the Russian, S. Belsky (MIT, 1965).

I. Sechenov was convinced that voluntary movements do not differ from reflex movements (Figure 9). He suggested that their initiation, which is immediate in the case of reflexes, is mostly triggered by a previous stimulus that has become part of our mental repertoire. All actions are determined by a previously encountered external stimulation. At the end of the nineteenth century, the concept of reflexes seemed to provide a complete explanation for the workings of the CNS. The role of reflexes was further emphasized in 1903, when I. P. Pavlov (1849-1936), a specialist in the digestive tract (for which he obtained the Nobel Prize in 1904), described conditioned reflexes. Pavlov was interested in experiments on chronic animals and, unlike Cl. Bernard, he refused to analyse the activity of separate or isolated organs, and performed a gastric fistula on his animals in order to study the complete reaction. He noted that dogs, when presented with an unconditioned stimulus (US) in the form of food, begin to salivate, but that when a neutral stimulus (NS), such as a bell ringing, is regularly associated with the food, they soon begin to salivate in response to this stimulus in the absence of any food (Figure 10). These findings opened an important new field of research that served as the basis of the Russian school's brain activation theories. According to Pavlov, the brain is composed of a set of analysers that decipher the complexity of the external world. 'Spontaneous actions' were not thought to exist, since all actions were taken to depend on sensory stimuli.



Figure 10: I. Pavlov (1849-1936) and his staff during an experiment of dog conditioning.

On the other side of the world, psychologists were about to propose another approach, which was also closely related to reflex theory, but based on another point of view. Here we are talking about Watson's 'behaviourist' approach (1913). This theory states that for obvious physical reasons, it is impossible to study the psychological brain processes such as reasoning, the will or 'impressions' such as the mind or consciousness. The followers of this school concluded that since the internal state of each individual is as hermetic as a 'black box', the only solution available was to analyse it from the outside by applying stimulus-response procedures to obtain reactions to stimuli of various kinds.

At that time, reflexes corresponded to the only mechanism able to explain the central nervous system functioning.

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