Functional organisation of the cerebral cortex: from Gall to Lashley

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ABSTRACT

Introduction. In the late 18th century, Franz Joseph Gall questioned the concept of the functional unity of the cerebral cortex, foreshadowing the advent of a new era in the study of cortical function.

Development. This review aims to provide a general view of the understanding of the functional organisation of the cerebral cortex in the 19th and early 20th centuries. This historical period is characterised by the dialectical confrontation between two factions: supporters of the parcellation of the cerebral cortex, and proponents of the functional unity of the cerebral cortex. The latter position, supported by Marie-Jean-Pierre Flourens' doctrine of cortical equipotentiality, dominated scientific thought in the first half of the 19th century. In the 1860s, it was supplanted by the theory of cortical parcellation, thanks to the contributions of Paul Pierre Broca, Eduard Hitzig, and Gustav Fritsch. During the same period, Carl Wernicke established the basis for cortical connectionism, a doctrine that conceived the cortex as a mosaic of interconnected functional centres. The early years of the 20th century saw an expansion of the anti-localisationist current, led by Pierre Marie, Henry Head, and Shepherd Ivory Franz; this current reached its greatest height with Karl Lashley.

Conclusions. In the 19th century and the first decades of the 20th century, the study of the functional organisation of the brain pivoted between two opposing epistemological positions: the localisationist/connectionist doctrine and the anti-localisationist current.

KEYWORDS

Cerebral cortex, localisationism, connectionism, antilocalisationism, equipotentiality, neuroanatomy

Introduction

Medieval understanding of the nervous system was based on the teachings of Galen of Pergamon (130-220 AD) and their interpretation by the first fathers of the Eastern Christian Church (ca. fourth century AD). Galenic theories about the brain included the ventricular doctrine[A] and the theory of animal spirits,[B] dogmas that guided the study of the nervous system for over 1500 years. The Renaissance marked the beginning of the end of the ventricular doctrine, although the transition from classical/medieval to modern medical thought did not take place until the 17th and 18th centuries. The metaphysical, theological, and philosophical debates of medieval thought gave way to medical argument based on concepts that were better aligned with anatomical and physiological reality.[1]

The collapse of the ventricular doctrine gave rise to the need to identify a new biological substrate for psychic life. In 1664, in his work *Cerebri anatome*, Thomas Willis (1621-1675)[2] theorised that the cerebral cortex is responsible for memory, imagination, and volition. In

[A]The ventricular doctrine asserted that the cerebral ventricles were the biological substrate of intellectual faculties.
[B]According to the theory of animal spirits, brain function is the product of a substance (the animal spirits) stored in the cerebral ventricles.

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the first half of the 18th century, Emanuel Swedenborg (1688-1772) published *Oeconomia regni animalis* (1740)[3]. He employed similar arguments to Willis', and incorporated the hypothesis that the cortex is made up of specialised regions, which are responsible for different functions. Soon after, in 1779, Georg Procháska (1749-1820) argued that the cortex contained numerous organs that acted in concert. The theories of Swedenborg and Procháska were the prelude to a new era in the study of cortical function.

For centuries, the anatomical structure of the cerebral ventricles had been extensively researched due to the significant interest in their function. It was only in the 19th century, when the cerebral cortex became pre-eminent as the seat of psychic life, that a detailed topography of the cortex was developed. Until then, the lateral sulcus (or Sylvian fissure) was one of the few cortical structures to have been identified. In 1663, Franciscus Sylvius (1614-1672)[4] wrote:

> Particularly noticeable is the deep fissure or hiatus which begins at the roots of the eyes […] it runs posteriorly above the temples as far as the roots of the brain stem. It divides the cerebrum into an upper, larger part and a lower, smaller part.

Johann Christian Reil (1759-1813) described the insula in 1809, and Luigi Rolando (1773-1831) described the fissure that bears his name in 1829. The terms frontal, temporal, parietal, and occipital (now used to divide the surface of the cortex) were introduced by Friedrich Arnold (1803-1890) in 1838.[C] In the 1850s, Louis Pierre Gratiolet (1815-1865) identified nearly all the gyri as we know them today. This work was completed in the following decade by William Turner (1832-1916) and Alexander Ecker (1816-1887).[5]

This review aims to provide a general view of the understanding of the functional organisation of the cerebral cortex in the 19th and early 20th centuries. This historical period is characterised by the dialectic confrontation between two opposing epistemological positions: the supporters of the atomisation of the cortex, and those who believed it to exist as a functional unit.

Gall, precursor of cortical localisationism

In 1871, Franz Joseph Gall (1758-1828) intuited that different mental faculties were located in different regions of the brain; however, he possessed no evidence supporting this hypothesis:

> Most philosophers find the opinion ridiculous that the various psychic faculties and notions have their seats in different places of the brain. But if this is ridiculous, it is also ridiculous that the different senses are placed in different parts of the body.[6(p197),D]

He dedicated several years to gathering evidence, and in 1798 he wrote a letter to Joseph Friedrich von Retzer (an official at the censor's office in Vienna) explaining the basic postulates of a new "science": *Schädellehre* (the "skull doctrine").[E]

Schädellehre, which later came to be known as phrenology, was based on the observation that the skull presents pronounced bumps in certain areas; from these, a series of specific individual talents could be derived, which were the result of uneven development of different areas of the brain. Gall proposed that, just as the body contains organs associated with specific physiological functions, the brain is also made up of mental organs, each of which is dedicated to a specific task.[6] Through external analysis of the skull (cranioscopy), Gall concluded that there were 27 mental organs or faculties, localised bilaterally across both cerebral hemispheres (Figure 1).[7]

Schädellehre was based on the following assumptions:

— The brain is the organ of the mind.
— The brain comprises a set of organs or mental faculties.
— The organs or mental faculties making up the brain are located in different brain areas, each of which has a specific function.
— As the skull ossifies over the brain during its formation, external analysis of the cranium (cranioscopy) is a method for diagnosing the state of the organs or mental faculties.

In the early 19th century, phrenology enjoyed great scientific/academic prestige; this status was gradually lost, until it was reduced to a pseudoscience. One of its main critics was Marie-Jean-Pierre Flourens (1794-1867) (Figure 2).[8,9] Flourens accepted that intellectual

[C] In 1807, François Chaussier (1746-1828) divided the cerebral cortex into three sections: the anterior or frontal, middle or temporal, and posterior or occipital lobes.

[D] Translator's note: the English translation of this excerpt is taken from: Eling P, Finger S, Whitaker H. On the origins of organology: Franz Joseph Gall and a girl named Bianchi. Cortex. 2017;86:123-31.

[E] The letter was subsequently published in the journal *Der Neue Teutsche Merkur* (Gall FJ. Schreiben über seinen bereits geendigten Prodromus über die Verichtungen des Gehirns der Menschen und der Thiere, an Herrn Jos. Fr. von Retzer. Der neue Teutsche Merkur. 1798;27:311-32).

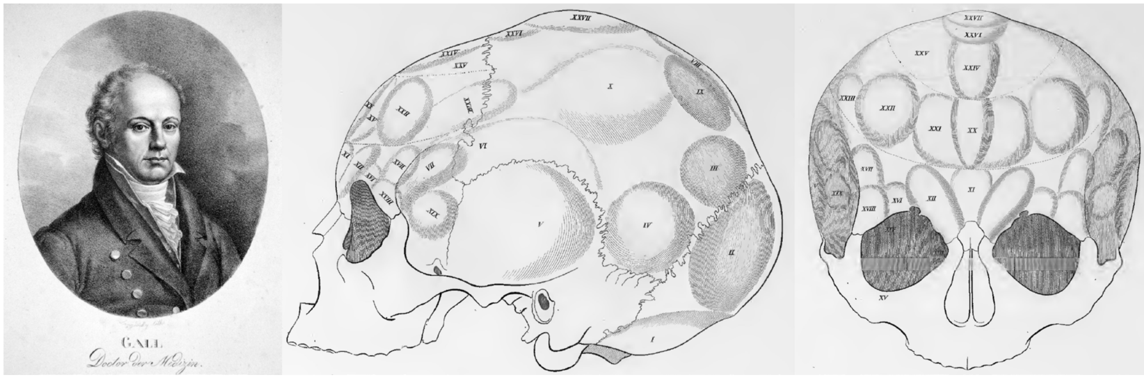

Figure 1. Left: Franz Joseph Gall (1758-1828). Centre/right: approximate locations of the mental faculties, according to Gall (*Anatomie et physiologie du système nerveux en général et du cerveau en particulier*, 1810).[7]

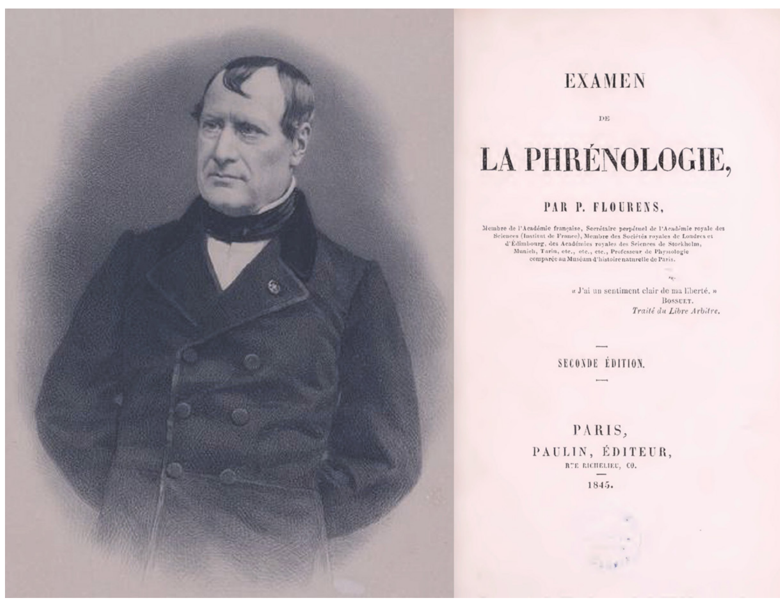

Figure 2. Left: Marie-Jean-Pierre Flourens (1794-1867). Right: title page of *Examen de la phrénologie* (second edition; 1845).[9]

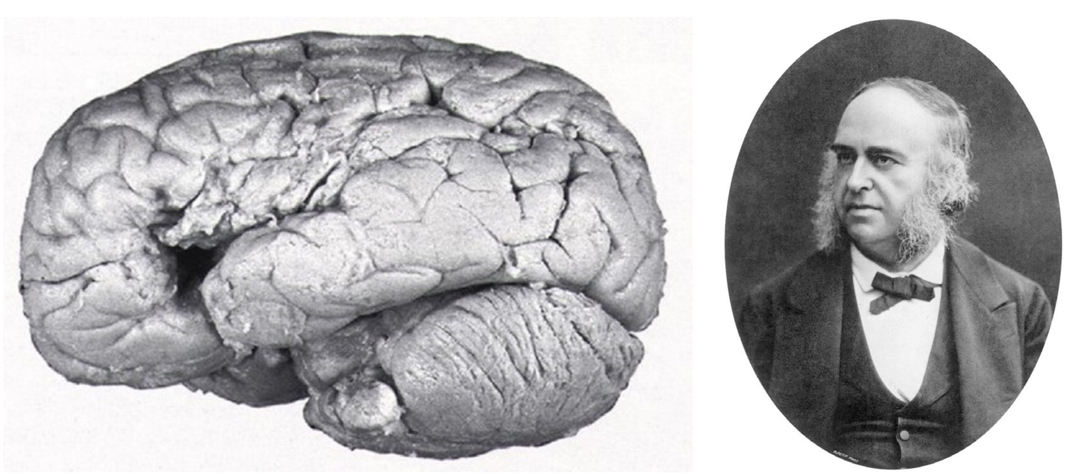

Figure 3. Left: the brain of Monsieur Leborgne, showing a lesion to the left third frontal gyrus. Right: Paul Pierre Broca (1824-1880).

functions are the domain of the cerebral cortex, but rejected the notion that the cortex was made up of a federation of organs, each of which had a specific function:

> Hence it appears, that the cerebral hemispheres concur, by their whole mass, in the full and entire exercise of the intelligence. In fine, as soon as one sensation is lost, all sensation is lost; when one faculty disappears, all the faculties disappear. There are not, therefore, different seats for the different faculties, nor for the different sensations. The faculty of feeling, of judging, of willing any thing, resides in the same place as the faculty of feeling, judging, or willing any other thing, and consequently this faculty, essentially a unit, resides essentially in a single organ. The understanding is, therefore, a unit.[9(p28-9),F]

This French physician also harshly criticised Gall's methodology, noting that it was based on the topography of the skull, rather than that of the brain. "But as to the pretended organs of the brain, are they really situated at the surface of the brain, as Gall asserts? In plain terms, is the surface of the brain the only active part of the organ?"[9(p78-9)] In another passage, he explains how:

> The cranium, especially the external surface of it, represents the superficial configuration of the brain but very imperfectly. Gall knows it. "I was the first," says he, "to maintain that it is impossible for us to determine with exactitude the development of certain circumvolutions, by the inspection of the external surface of the cranium." […] Gall is aware of all this, and nevertheless he inscribes his twenty-seven faculties upon the skulls.[9(p83)]

Gabriel Andral (1797-1876), a contemporary of Flourens, notes that:

> In the point where a lesion is discovered, the direct cause of the effects which it produces does not always reside […] If then it happened that we succeeded in discovering in the encephalon a certain number of parts, the lesions of which always occasioned the disturbance of the same cerebral act, it would not, in our opinion, be fair to object to the doctrine of localisation, that there are also other cases where this same functional disturbance is reproduced, though the lesion might be elsewhere.[10(p734-5)]

Cortical localisationism

Flourens' conception of the cerebral cortex was broadly accepted by his contemporaries, becoming dogma during the first half of the 19th century. However, some researchers, continuing along the path laid out by Gall, argued that the cerebral cortex was not a homogeneous structure, but rather was made up of multiple functional regions.

Jean-Baptiste Bouillaud (1796-1881), a dedicated follower of Gall,[G] considered cranioscopy not to be the most suitable method for studying brain function. Rather than inferring the functional role of brain regions by examining the bumps on a person's skull, he used the anatomopathological method, establishing correlations between neurological signs and structural brain lesions.[11] In May 1825, he gave a lecture at the Académie de Médecine entitled "Recherches cliniques propres à démontrer que la perte de la parole correspond à la lésion des lobules antérieurs du cerveau, et à confirmer l'opinion de M. Gall sur le siège de l'organe du langage articulé" (Clinical research aimed at demonstrating that loss of speech corresponds to a lesion to the anterior lobes of the brain, and at corroborating Gall's opinion on the location of the organ of articulate language),[12] in which he suggested that the organ of articulate language was located in the anterior lobes of the brain, an idea he defended for over 50 years.[13-15] His contributions were fundamental in the transition from Gall's theoretical speculation towards the scientific studies that supported the relationship between the cerebral cortex and specific cognitive processes.

On 18 April 1861, Paul Pierre Broca (1824-1880) presented to the Société Anthropologique de Paris the case of a patient who had lost the ability to speak (Monsieur Leborgne, also known as Monsieur Tan-Tan).[16] The post mortem examination revealed a lesion in the left third frontal gyrus (Figure 3). The same year, he presented a second case with similar characteristics, in which a lesion was detected in the same location.[17] In 1865, after analysing other cases, he concluded that the left third frontal gyrus was the neuroanatomical substrate of articulate language.[18] Broca's observations constitute the first documented empirical evidence of the correspondence between a cognitive process and a specific region of the cerebral cortex, contravening Flourens' dogma of cortical equipotentiality.[19]

[F]Flourens' assertions anticipated the concepts of equipotentiality and mass action, developed in the 1920s by Karl Lashley (1890-1958).

[G]Bouillaud was a founding member of the Société Phrénologique de Paris (the inaugural meeting of the society was held on 14 January 1831).

Broca's *discovery* sparked interest among the scientific community in identifying cortical functional regions, leading to the development of an explanatory model of the neurobiological basis of mind based on the "one region, one function" axiom. Jean-Martin Charcot (1825-1893) argued in 1875 that "there are areas in the brain in which a lesion inescapably leads to the same symptoms. Beyond this law, all else is confusion."[20(p400)] He also argued that:

> The brain is not a homogenous, single organ, but rather a group, or if you wish, a confederation, composed of a number of different organs. To each of these, distinct properties, function and faculties are physiologically attached. Once the physiologic properties of each of these parts is known, it should be possible to deduce the pathologic situation, since this would only represent a modification, mild or marked, of the normal state, without any intervention of new laws.[21(p4)]

In 1883, Charcot and Albert Pitres (1848-1928) published a study describing a large series of patients with cortical lesions. Faithful to his convictions, he considered evidence against the localisationist doctrine to present "defects of form," diminishing its credibility.[22]

Animal experimentation provided new evidence in support of cortical localisationism. In 1870, Eduard Hitzig (1838-1907) and Gustav Fritsch (1838-1927) observed that application of galvanic current to the posterior frontal lobe in a dog caused movement in the hemibody contralateral to the cortical region stimulated.[23] Specifically, they identified five motor centres, whose stimulation provoked muscle contractions in the neck, abduction of the forelimbs, flexion of the hindlimbs, movement of the forelimbs, and facial contractions (Figure 4). These findings strengthened localisationist positions, and cast doubt on the idea of cortical insensibility.[H] As noted by Hitzig and Fritsch themselves, "with the results of our research, many of the conclusions about the basic properties of the brain are substantially changed."[23(p308)] Their findings brought about a cascade of experimental studies that helped to consolidate the pre-eminence of cortical localisationism: David Ferrier (1843-1928)[24] identified several cortical motor centres, Hermann Munk (1839-1912)[25] demonstrated that destruction of the occipital lobes caused vision loss, and Leonardo Bianchi (1848-1927)[26] observed that surgical lesions to the frontal lobes caused dramatic changes in complex behaviours.

In the latter third of the 19th century, experiments were also performed in humans (from today's perspective, these were ethically reprehensible). In 1874, Roberts Bartholow (1831-1904) replicated the study by Hitzig and Fritsch, performing the first documented demonstration of the excitability of the human cerebral cortex. To conduct the study, he applied direct electrical current to the left postcentral region of the brain of Mary Rafferty (which was exposed due to erosion of the scalp and skull by a cancerous ulcer).[28] Soon after, Ezio Sciamanna (1850-1905) conducted a series of experiments in which he electrically stimulated the surface of the brain in a patient who had undergone trepanation due to a traumatic brain injury. In 1883, Alberto Alberti (1856-1913) replicated Bartholow's study in a woman with an eroding tumour of the skull, allowing access to the surface of the underlying dura mater.[29]

Cortical connectionism

In 1868, Theodor Meynert (1833-1892) proposed an associationist brain model based on the premise that psychic functions resulted from the interaction between different parts of the brain. In other words, associations created complex structures that cannot be located in a specific brain region.[30] Carl Wernicke (1848-1905) recognised the importance of this model, and applied it in his analysis and interpretation of cognitive deficits secondary to neurological lesions (Figure 5). In 1874, he published his work *Der aphasische Symptomencomplex: eine psychologische Studie auf anatomischer Basis* ("The aphasia symptom-complex: a psychological study on an anatomical basis"),[31] in which he proposed a cortical associationist model based on two principles: *1)* the cerebral cortex contains centres responsible for specific functions; and *2)* these centres are connected with one another through association pathways. Thus, a particular pathological behaviour may be predicted according to understanding of how the flow of information between centres has been interrupted, or how these centres have been destroyed. To differentiate his theories from localisationism (and by extension, phrenology), Wernicke argued that "Any higher psychic process, […] could not […] be localized, but rested on the mutual interaction of these fundamental psychic elements mediated by

[H]In the 1750s, Albrecht von Haller (1708-1777) had concluded that the external surface of the cerebral cortex was insensitive to mechanical, electric, or chemical stimulation. This theory was endorsed by Flourens in the 1820s.

Figure 4. Left: Eduard Hitzig (1838-1907). Centre: drawing of the excitable area of the dog cerebral cortex.[27] Δ Contraction of the neck muscles. + Abduction of the forelimbs. +' Flexion of the forelimbs. # Movement of the forelimbs. ○ Facial contraction. Right: Gustav Fritsch (1838-1927).

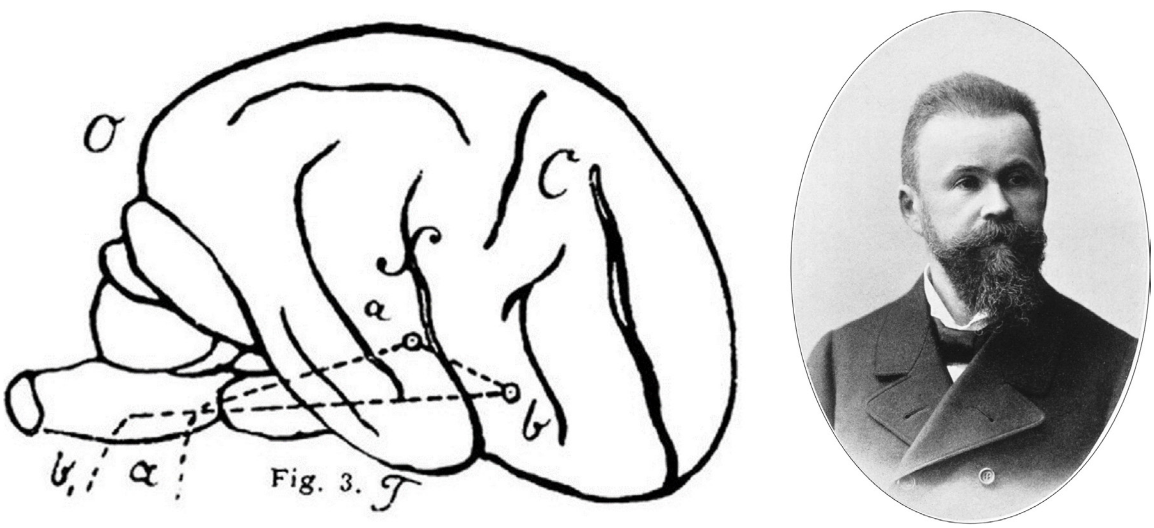

Figure 5. Left: a diagram by Wernicke depicting the sensory and motor language areas and their connections.[31] Right: Carl Wernicke (1848-1905).

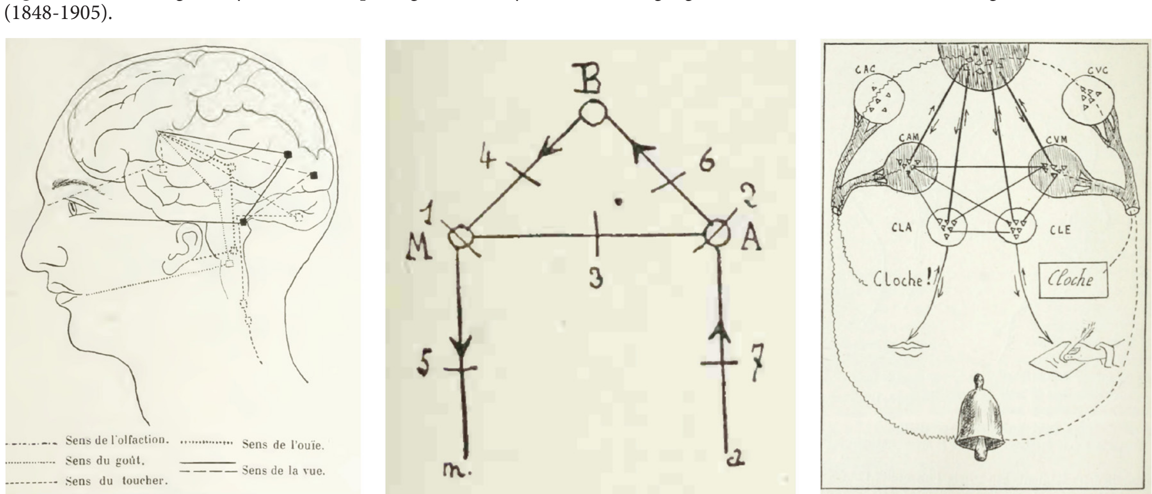

Figure 6. Left: a diagram by Magnan (1881). Centre: a diagram by Lichtheim (1885). Right: Charcot's bell diagram (1885). Source: Moutier, 1908.[36]

means of their manifold connections via the association fibers."[32(p824)] Although Wernicke's proposal is an adaptation of Meynert's associationist model, it constitutes the starting point for a *new* model of cortical physiology: the connectionist doctrine.

The connectionist doctrine offered a working methodology that was useful both in research and in clinical practice. The elegant system of centres and connection pathways brought order to the *chaos* of symptoms observed in patients, helped to classify symptoms within a limited set of syndromes, and enabled individualised neuroanatomical examination of each patient's deficits. Connectionism was adopted, adapted, and disseminated by various disciples of Wernicke's.[33] Other authors who embraced this doctrine include Henry Charlton Bastian (1837-1915), Charles K. Mills (1845-1931), Joseph Grasset (1849-1918), and Jules Dejerine (1849-1917), among others.

Henry Head (1861-1940) was a harsh critic of the connectionist doctrine, and particularly of authors who created graphical representations of their functional architectures (Figure 6), whom he dismissed as "diagram-makers." He believed that physicians ran the risk of considering the diagram to be more important than the patient. Clinical reality, argued Head, was richer, more varied, and more complex than diagrams, and did not fit the categories generated on the basis of a framework of centres and connections.[34] Similarly to Head, Pierre Marie (1853-1940) believed these graphical representations to be of no value as they oversimplified the clinical reality and illustrated the prejudices and obsessions of their authors.[35]

The anti-localisationist current

The localisationist-connectionist doctrine became the frame of reference for neurology and neurophysiology in the latter third of the 19th century and the early years of the 20th century. However, many authors believed that it offered only a crude, ingenuous explanation of cortical physiology. In this context, the anti-localisationist current comprised a heterogeneous group of physicians and researchers who rejected the principles of the localisationist-connectionist doctrine.

In 1874, John Hughlings Jackson (1835-1911) warned that localisationists committed the error of equating the localisation of symptoms with the localisation of functions. Specifically, he noted that to locate the lesion destroying speech and to locate speech were two different things.[37] Similarly, Veniamin Mikhailovich Tarnovsky (1837-1906) argued that it is impossible to conclude, as many do, that post mortem evidence of the destruction of the left frontal gyrus in an aphasic patient means that said lesion is the sole cause of the aphasia and that, as a result, the ability to speak is located in that brain region.[38]

Although Hughlings Jackson's critiques were eclipsed by the success of the connectionist approach, his hypotheses played an important role in the development of alternative explanations about cortical functional organisation. The turn of the century saw an increased emphasis on theses that questioned the clinical-anatomical associations defended by localisationists and connectionists. Friedrich Goltz (1834-1902), Jacques Loeb (1859-1924), and Karl Lashley (1890-1958), who subscribed to the theory of equipotentialism, alleged that all cortical areas were equivalent from a functional perspective (Figure 7). The holists, in turn, believed that the brain acted as an integrated functional unit. They argued that mental processes did not result from the independent activity of individual parts of the brain, but rather from the interdependent activity of the brain as a whole. This school of thought included Pierre Marie (1853-1940), Henry Head (1861-1940), Charles Sherrington (1857-1952), Shepherd Ivory Franz (1874-1933), and Kurt Goldstein (1878-1965).[I] Outside the field of medicine, we should also note the organicist ideas of Karl Ludwig von Bertalanffy (1901-1972).[J] This Austrian biologist declared that organisms were open systems, which were in constant interchange with other, nearby systems by means of complex interactions. With respect to the brain, Bertalanffy questioned the premise that it was a set of *centres*, and proposed that focal dysfunction results in a general alteration to the functioning of the brain.[39]

The term "anti-localisationist current" encompasses highly varied propositions; one of the most unique was

[I]Analysis of Goldstein's work reveals a transformation in his thinking: his early texts (written in his youth) are based on essentially localisationist-connectionist ideas, whereas his later works present holistic positions. This conceptual evolution took place in line with the growth of his clinical experience.

[J]The functional system concept proposed by Alexandr Romanovich Luria (1902-1977) is based on Karl Ludwig von Bertalanffy's (1901-1972) biological systems theory, Alexei Alexeievich Ukhtomsky's (1875-1942) dominant system principle, and Pyotr Kuzmich Anokhin's (1898-1974) functional systems theory. Luria established that mental functions were organised in systems of brain areas, with each area playing a specific role within the system. A lesion to one area would alter the function of the system as a whole (but with specific characteristics).

the theory set forth by Constantin von Monakow (1853-1930) in his 1914 work *Die Lokalisation im Grosshirn und der Abbau der Funktion durch kortikale Herde* (The localization in the cerebrum and the degradation of the function by cortical foci).[40] The author argues that the brain is organised in constellations of synchronous networks, producing chronogenic localisations. The dynamic-functional concept of chronogenic localisation emphasises the importance of the temporal dimension in understanding brain physiology, transcending the topographic/spatial visions of the localisationists and anti-localisationists of the day. Historically, the temporal properties and chronotopic distribution of cerebral processes have played a marginal role in research into the functional organisation of the brain.[K]

One of the many arguments employed by the anti-localisationists against localisationism-connectionism is the so-called problem of recovery (evidence of the brain's capacity to regain lost or impaired functions). The localisationist-connectionist doctrine gave the impression that the cerebral cortex is a rigid, non-malleable structure lacking the capacity for functional reorganisation after an injury. Thus, from this perspective, the structural alteration of a brain region (or its connections) would necessarily lead to loss of the associated function. According to proponents of the holistic doctrine, the fact that many patients were able (to an extent) to compensate for lost brain functions indicated that one brain region was able to take on the function of another. This suggested that the cortex presented a dynamic adaptability, or plasticity. This view collides head-on with the mechanistic conception of the nervous system, in addition to undermining the principle of strict localisation, an essential pillar of the connectionist theories popularised by Wernicke and his followers.

The concept of dynamic cortical adaptability had previously been hinted at by Flourens. In *Recherches expérimentales sur les propriétés et les fonctions du systéme nerveux dans les animaux vertébrés* (Experimental researches on the properties and functions of the nervous system in the vertebrate animal),[8] he wrote that "it is possible to remove a certain portion of the cerebral lobes without destroying their functions completely. However, it is even more than that. The lobe can recover these functions in their entirety after having lost them completely."[8(p101)] In another passage he notes that:

> As long as not too much of the lobes is removed, they may regain in due time the exercise of their functions. […] if one sensation comes back, all come back. If one faculty reappears, they all reappear.[8(p102)]

A century later, Lashley reported that the functional impairment observed in experimental animals subjected to cortical ablation was related to the amount of cortex removed, not to its location (Figure 8). This finding led him to formulate the general principles of cortical equipotentiality and mass action.[41] According to Lashley, all brain regions were functionally equivalent; however, this equipotentiality was not absolute, but rather was subject to the principle of mass action (the efficiency of functional performance is determined by the extension, rather than the localisation, of the cortical lesion). The mass action principle is alluded to by Flourens[8] in his *Recherches expérimentales*, in which he explained that it was possible for the cerebral lobes to lose a certain portion of their mass, from the front, back, top, or side, without losing their functions, although function was lost if the amount of substance removed exceeded a certain level.[8]

At the 7th International Medical Congress, held in London in 1881, Goltz launched a ferocious attack against the localisationist doctrine. If there is no renewal of the extirpated tissue, he argued, then the functional recovery observed after the ablation results from the activity of undamaged regions, constituting reliable evidence that the brain is equipotential: "If a centre that has a specific function is able to assume the function of another, destroyed centre with a different function, then the same section of the brain performed different functions at the same time."[43(p220)] Subsequently, he ridicules Hermann Munk's (1839-1912) hypothesis explaining post-lesion recovery:

> [Munk] supposes that each centre with a specific function is to some extent surrounded by a fallow field made up of virgin cortical matter, which only begins functioning when the

[K]In the 1860s, Franz Cornelius Donders (1818-1889) proposed that reaction times could be used to measure "the speed of mental processes." (Donders FC. Over de snelheid van psychische processen. Onderzoekingen gedaan in het Physiologisch Laboratorium der Utrechtsche Hoogeschool, Tweede reeks. 1868;2:92-120).

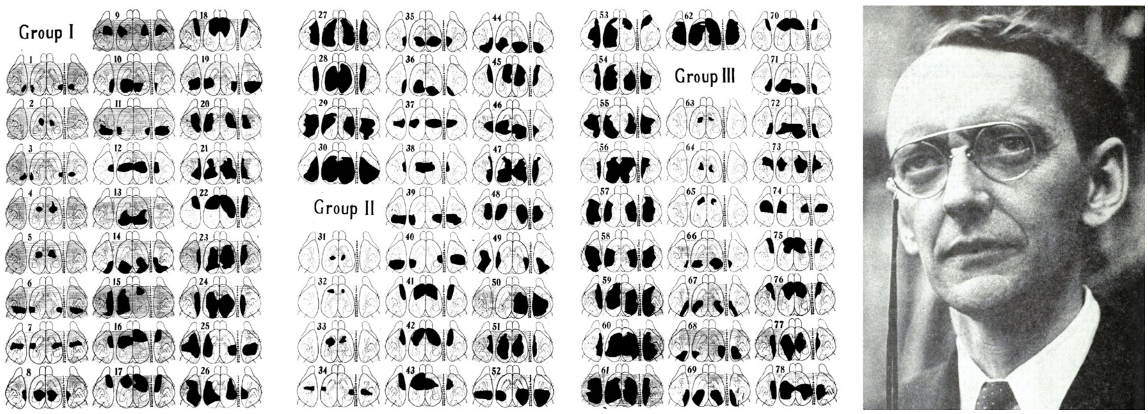

Figure 7. Left: diagrams showing the lesion localisation and extension used in different groups of rats in Lashley's experiments.[42] Right: Karl Lashley (1890-1958).

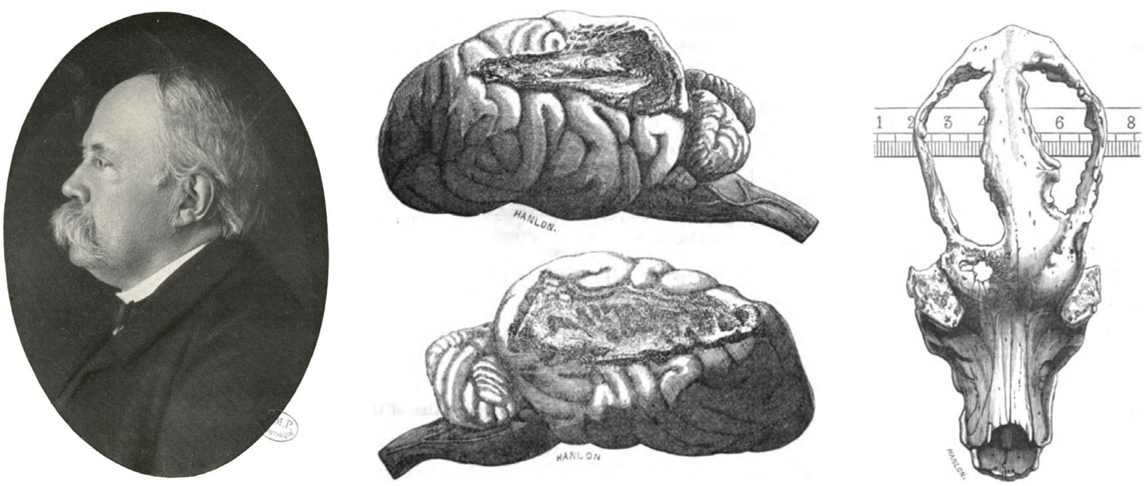

Figure 8. Left: Friedrich Goltz (1834-1902). Centre: drawings showing the amount of cortical matter removed from the dog presented by Goltz at the 7th International Medical Congress (1881). Right: illustration of the brain of said dog. The centimetre scale shows the size of the openings cut in the bone.[44]

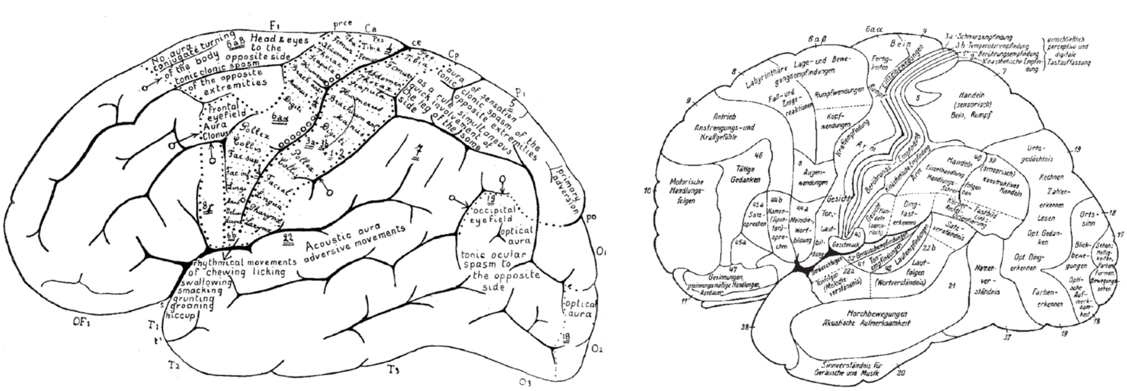

Figure 9. Left: diagram of the localisation of various cortical processes identified by Foerster (1931).[50] Right: diagram of the localisation of functions in the cerebral cortex, according to Kleist (1934).[51]

> normally occupied centre is accidentally destroyed. According to this strange doctrine, we would have an extraordinary amount of excess brain matter available that would be spared in the event of mutilation in the brain.[43(p220)]

On 28 December 1911, Franz presented his ideas on the localisationist-connectionist doctrine at a meeting of the Southern Society for Philosophy and Psychology.[45] In his presentation, he questioned the evidence from architectural neuroanatomy in support of the localisationist-connectionist doctrine. While he conceded that Korbinian Brodmann's (1868-1918) cytoarchitectonic studies had revealed that the left third frontal gyrus differed structurally from the surrounding areas, he maintained that:

> The criticisms of von Monakow and of Marie are, however, too trenchant to be disregarded, and the negative cases which they have cited are sufficient evidence that neither the mental processes connected with motor speech nor the supposed cortical speech mechanisms are definitely located in the part of the brain to which they were assigned by Broca, by Wernicke and by their followers.[45(p326)]

In 1917, Franz wrote a short article entitled "Cerebral adaptation vs. cerebral organology."[46] Citing the research of Vitzou,[47,48] he explained that:

> Assuming that the destructions [performed by Vitzou] were complete, it is not possible to understand these recoveries from the standpoint of cerebral organology, for the cortex is looked at as a locus of certain physiological processes which give rise to or which are coincident with the mental states.[46(p138)]

After describing various cases that cast doubt on the straightforward relationship between region and function, and supporting the possibility of post-injury functional recovery, he concluded:

> The destruction of a part of the cerebrum which is followed by an obvious defect does not mean that that part of the cerebrum is solely concerned with that function […]. When these facts are admitted, as they must be admitted, the whole structure of cerebral organology breaks down. The histological localization of function which has been in vogue takes its true place as a histological differentiation of an anatomical nature, without the functional implications which have been assumed.[46(p140)]

Despite the obstinacy of such authors as Salomon Henschen (1847-1930),[49] Otfrid Foerster (1873-1941),[50] and Karl Kleist (1879-1960) (Figure 9), anti-localisationist thought became the frame of reference for understanding cortical functional organisation in the first half of the 20th century.

Epilogue

Lashley's ideas had a profound impact on the understanding of the precepts governing behaviour, favouring the consolidation of American behaviourism thanks to Edward Chace Tolman (1886-1959), Clark Leonard Hull (1884-1952), and Burrhus Frederic Skinner (1904-1990), among others. It was not until the 1940s that various experimental researchers began to disprove many of Lashley's anti-localisationist assertions. This group included a follower of Lashley at the Yerkes Laboratories for Primate Biology, Roger Wolcott Sperry (1913-1994).

Sperry conducted various experiments to study the reorganisation of the motor and sensory nerves, as well as the sensory organs (particularly the eye). He concluded that nerve fibres were not interchangeable and that, contrary to popular belief (and Lashley's hypotheses), neural circuits were established very early in the course of development, and appeared to lack any capacity for modification.[52] Later, he studied the functional repercussions of interhemispheric disconnection by surgical section of the corpus callosum (the "split-brain experiments"), reporting that the experimental animals presented behavioural changes.[53,54] These findings contradicted those conducted by Andrew Akelaitis (1904-1955) in human subjects,[L] as well as the results of his old mentor at the Yerkes Laboratories for Primate Biology. Lashley argued that the corpus callosum was a merely skeletal structure, since he "could find no function for them."[55(p132)]

Sperry's split-brain experiments sparked the interest of the American neurologist Norman Geschwind (1926-1984).[M] Geschwind was very critical of the clinical value of anti-localisationist approaches, and considered the possibility that the disconnection syndromes observed in animals could be extrapolated to humans (see his

[L] In 1939, the neurosurgeon William Perrine Van Wagenen (1897-1961) conducted the first corpus callosotomy procedures to treat drug-resistant epilepsy. Van Wagenen's colleague, the psychiatrist Akelaitis, observed no remarkable cognitive changes after the procedures, concluding that surgical section of this set of nerve fibres could be performed without fear of adverse effects.

[M] Geschwind was the master and mentor of brilliant neurologists including Marsel Mesulam, António Damásio, Frank Benson, François Boller, and Albert Galaburda.

description of the patient PJK[56]). In 1965, he published an influential article in two parts, entitled "Disconnection syndromes in animals and man." In the first part, he proposed that aphasias, apraxias, and agnosias be reinterpreted in terms of anatomical disconnections.[57] In the second, he argued that knowledge of anatomical-clinical correlations was essential to understanding cortical physiology, and defended the localisationist-connectionist doctrine:

> For the past forty years there have been schools of thought which have stressed the importance of thinking of the patient as a whole, of seeing his responses as those of an integrated unitary structure […]. I have attempted to show that many disturbances of the higher functions of the nervous system, such as the aphasias, apraxias, and agnosias may be most fruitfully studied as disturbances produced by anatomical disconnexion of primary receptive and motor areas from one another.[58(p637-40)]

This marked the birth of the so-called neo-associationist school, a theoretical school of thought that recovered (and updated) the connectionist doctrine of Wernicke and constitutes the foundations of contemporary behavioural neurology and neuropsychology.

Conflicts of interest

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