The Discovery of the Visual Cortex

Soldiers who suffered head wounds in the Russo-Japanese War were among those who contributed to the identification of the brain’s visual center and the first description of its organization

by Mitchell Glickstein

A person who has perfectly healthy eyes can be blinded by damage to the back of the brain. The reason is simple: the rearmost (occipital) lobes of the two hemispheres that constitute the cerebrum (the uppermost part of the brain) form a major center for vision. They contain what is known as the primary visual cortex. If this cortex is destroyed, the brain will not be able to detect the vast majority of the visual signals transmitted from the eyes.

The explanation may be simple, but the fact that a discrete part of the cerebral cortex (the sheet of gray matter that covers the cerebrum) is devoted to vision was far from easy to uncover. Indeed, the process of discovery spanned more than a century. The history leading to the identification of the primary visual cortex is fascinating in its own right, mixing ingenuity, astute observation, folly and failure. It is also important for what it led to an ever increasing understanding of how the brain functions and how people see.

When a person looks at something, light coming from the object produces a scaled-down image of the object on the retina, the array of photoreceptors and connected nerve cells at the back of the eye. The retina translates the image into nerve impulses, which are carried over the cablelike optic nerve to the brain (see illustration on page 122). The primary targets of this nerve are two collections of nerve cells deep in the brain called the lateral geniculate (“kneelike”) bodies. The optic nerve transmits visual signals from the right side of the visual field to the lateral geniculate body in the left hemisphere, and it transmits signals from the left side of the visual field to the right hemisphere.

The lateral geniculate bodies then relay the signals to the occipital lobe on the same side of the brain, and specifically to the primary visual cortex, which does an initial analysis of the image and transmits selected information about it to other regions of the brain. Those regions in turn analyze the information further, interpret it and make use of it to control the movements of the eyes or limbs.

The path leading to the discovery of the primary visual cortex began in the late 1700's—about 50 years before the cell was recognized as the basic structural and functional unit of plants and animals, and more than 100 years before the specialized properties of nerve cells (the building blocks of the brain and the spinal cord) were described. Lacking such knowledge of cells, investigators in the late 18th century had little concept of how the brain functions, but they had made good headway in describing its general appearance.

For example, in 1783 the Scottish anatomist Alexander Monro II published a textbook that accurately (and beautifully) showed the major subdivisions of the brain, including the gray cortex of the cerebrum and the underlying white matter. Nevertheless, the cortex was depicted as a uniform sheet of gray without any substructure. Today the cortex is known to be divided into layers, each of which differs in the type of nerve cells it contains and the packing of both cells and nerve fibers: the long, signal-carrying “axons” that extend from cell bodies.

The image of a featureless cortex became outdated at about the same time Monro’s text was published. Seven years before the book appeared, an Italian medical student at the University of Parma named Francesco Gennari began a detailed study of the brain. Gennari, who was just 24, hardened brains with ice, examined the surface features and then cut and dissected the specimens in order to describe both superficial and deep structures. He published his observations in a 1782 monograph titled De Partiis Structurae Cerebris, printed by the famed publisher and typographer Giambattista Bodoni.

In his book, which at the time was relatively obscure, Gennari noted that the cortex is not uniform. Rather, the gray matter is divided by a whitish layer—a line in cross sections—that parallels the surface of the brain.

The Russo-Japanese War of 1904-5, depicted in this [woodcut], contributed indirectly to the understanding of human vision. During the war a Japanese physician named Tatsui Inouye examined Japanese soldiers (right) who had bullet wounds to the head and correlated the site of injury with the patient’s visual losses. He thereby determined how different parts of the visual field are mapped onto the main vision center of the brain: the primary visual cortex. Inouye’s studies were possible because the Russians had introduced rifles that used smaller, faster bullets. These penetrated the skull without shattering it, allowing many soldiers to survive their injuries and to cooperate with Inouye.
he was surprised. As he put it, “None of the anatomists I happened to read have taught that in addition to the cortical and medullary substance there is in the brain another substance which I am accustomed to call the third substance of this organ.” (The “medullary” material is the white matter under the cortex, which is now known to consist primarily of nerve fibers sheathed in a whitish substance known as myelin. The “third substance,” Gennari’s stripe, probably consists of myelinated axons as well, ones that transmit signals within the occipital lobe.)

In addition to discovering the myelinated stripe that bears his name, and hence recognizing that the gray matter is subdivided, Gennari also realized that the cortex looks different in different regions of the brain. In particular, he found that the white line, which sometimes appears “as a single stripe, sometimes [as] two independent parallel stripes,” is difficult to see in sections of the front part of the brain but “can be detected more and more clearly in the posterior part”—specifically in the region that is now known to be the primary visual cortex. A footnote indicates that Gennari first saw the stripe on February 2, 1776.

Thus, working with the simplest of tools, well before new staining methods opened the way to the microscopic study of the brain, Gennari initiated the field of cerebral architectonics: the study of regional differences in cortical structure. Yet because he was not well known, his role in the discovery of the variable white stripe in the brain was not widely acknowledged until a century later.

Meanwhile two others claimed, or were credited with, the stripe’s identification. Samuel Thomas Soemmerring, professor of anatomy at the University of Göttingen, insisted that he had described the band four years before Gennari had, in a book published in 1776. Soemmerring had indeed mentioned a stripe in his book, but he described it as yellowish and placed it in the cerebellum, where there is no such stripe. What Soemmerring saw was probably either one of the layers in the gray matter covering the cerebellum or an artifact of the method he employed to examine the brain.

In spite of Soemmerring’s claim, credit for the discovery of the stripe usually went to the eminent French anatomist Felix Vicq d’Azyr. In 1786, four years after Gennari’s monograph appeared, Vicq-d’Azyr described the white line and its location in his massive and beautiful Traité d’Anatomie...
BASIC PATH of visual signals through the brain is shown from the side (a) and from below (b). The retina of the eye converts light from an observed object into nerve impulses and relays them by way of the optic nerve to a collection of nerve cells deep within the brain called the lateral geniculate body. From there the impulses travel to the primary visual cortex, which is in the occipital, or rearmost, lobe of each hemisphere. Signals from the right side of the visual field (yellow) go to the occipital lobe of the left hemisphere, and signals from the left side of the field (green) go to the right hemisphere. The primary visual cortex (blue in details) constitutes a fraction of the cerebral cortex (the convoluted sheet of gray matter that blankets the hemispheres). It consists of a small part of the outermost surface of each occipital lobe (c) and a much larger part of the medial surface (d)—the inner surface, facing the opposite lobe—including a groove called the calcarine fissure.

Serious experiments into cortical function began not long after the publication of Gennari's monograph. In the typical experiment investigators produced lesions in the brain of animals and studied the resulting deficits. These experiments, combined with the observations of the deficits found in human beings who had suffered brain damage, led by 1850 to the recognition that the cerebral cortex is essential for normal movement, sensation and thought.

Nevertheless, there was as yet no compelling evidence for making the next crucial connection, namely the realization that specific lesions lead to specific functional deficits. In fact, the very idea of cortical localization was given a bad name by a pseudoscientific fad known as phrenology, which started in the first half of the 19th century. Franz Joseph Gall, a prominent anatomist who worked in Vienna and later in Paris, taught that the brain is composed of as many individual regions as there are psychological faculties. He argued that the shape of the skull reflects the form of the brain under it, and that personality and character traits—such as cruelty and a love of food—can be evaluated by palpating the head. Gall's disciple Johann Spurzheim expanded the scheme and attracted some support from physicians as well as an enthusiastic popular following.

Such experimental evidence as there was in the first half of the 1800s seemed to point away from localization. For example, the French physiologist Pierre Flourens reported that a lesion in the forebrain of animals resulted in a mixture of effects; a single lesion might leave an animal with sensory defects, difficulty understanding what it saw and felt, and difficulty initiating movement. He therefore concluded that sensation, perception and volition cannot be separated, that whatever controls them is diffused throughout the cortex. "Unity is the great principle, it is everywhere. It dominates all," he announced. "The nervous system therefore forms one unitary system."

Sensible opinion favored Flourens.

In the third quarter of the 19th century three discoveries finally made the concept of localization attractive once again. In 1861 the French physician Pierre Paul Broca reported that a lesion in the left frontal lobe of one...
of his patients resulted in a permanent speech disorder. A few years later John Hughlings Jackson, a London neurologist, described a type of epileptic seizure that begins with a rhythmic movement of one body part and then spreads to neighboring regions in a definite sequence. The pattern was suggestive of a brain organization in which adjacent brain regions control adjacent parts of the body.

Then in 1870 the German physiologists Gustav Theodor Fritsch and Eduard Hitzig did an experiment that was arguably the single most important factor in initiating new investigations of cortical localization. They electrically stimulated discrete areas of cortex in the frontal lobe of a dog and found that the stimulus produced the movement of a limb or some other body part on the opposite side of the body. The surgical removal of an area whose stimulation had resulted in movement in a limb made the animal clumsy when moving the same limb. Interpretations of this experiment varied, but one reasonable explanation held that in spite of earlier claims to the contrary at least one part of the cortex is specialized for the control of a specific function: movement.

The search was on for regions that control other functions, particularly vision. The first person professing to have identified the center for vision was the British neurologist and physiologist David Ferrier, who initially worked in laboratory space made available at the West Riding Lunatic Asylum in Yorkshire and then moved to King's College London.

By systematically noting the effects of alternating current on the brains of animals, Ferrier confirmed that stimulation of certain parts of the brain resulted in specific kinds of movement. At King's College, where he concentrated on monkeys, he also found that stimulation of an area known as the angular gyrus, which is located in the parietal lobe, caused the eyes to move. The finding suggested to Ferrier that

**Strip of Gennari** a white layer (4, top) within the gray cerebral cortex, is shown in a 1782 illustration of a horizontal section of the brain. The illustration appeared in a monograph (bottom) by the stripe's discoverer, Francesco Gennari. The observation of the stripe, which is most prominent in the primary visual cortex, was the first recognition that the cerebral cortex has structural subdivisions, and it led Gennari to speculate—correctly—that the cortex in the back of the brain might have a unique function.

**Francisci Gennari**
**Parmensis**
**Medicinæ Doctoris Collegiati**
**De Peculiari Structura Cerebri**
**Nonnullisque ejus morbis.**

**Paucæ aliaæ anatom. observat.**
**Accedunt.**

**Parmae**
**Ex Regio Typographo**
**M. DCC. LXIII.**
**Cum approbatione.**
LESIONS made in the brain of monkeys initially yielded contradictory information about the location of the main visual center of the brain. In 1876 a British neurologist named David Ferrier reported that the removal of a region in the parietal lobe known as the angular gyrus (triangular shaded area, left) blunted monkeys. He suggested that the region is the seat of vision. Hermann Munk, a German physiologist, strenuously disagreed; his studies, which he discussed in an 1881 publication, indicated that the occipital lobe (area A, right) is responsible for vision. Later work ultimately proved Munk was correct.

The angular gyrus might well be the sought-after visual area of the brain. To test his idea further, he removed the angular gyrus and observed the response of the monkeys. Exciting the gyrus from only one side of the brain seemed to leave the monkeys unable to see in the eye opposite to the lesion; if both gyri were removed, the animals seemed to become completely blind.

Ferrier's evidence for the total loss of vision was largely anecdotal. He reported, for example, that one monkey, which was particularly fond of tea, seemed unable to locate a cup placed right before its eyes.

"On placing a cup of tea close to its lips it began to drink eagerly," Ferrier reported to the Royal Society of London in 1875 and in his book Functions of the Brain in 1876. "The cup was then removed from immediate contact, and the animal though intensely eager to drink further, as indicated by its gestures, was unable to find the cup, though its eyes were looking straight towards it. This test was repeated several times with exactly the same result. At last on the cup being placed to its lips, it plunged in its head and continued to drink though the cup was gradually lowered and drawn half way across the room." Lesions of the occipital lobe did not produce a comparable handicap; hence Ferrier had no reason to think that the occipital lobe was important for vision.

Ferrier's conclusions were controversial. His most bitter opponent was Hermann Munk, a German professor of physiology at the Berlin Veterinary School, who had begun his own experiments soon after Ferrier started his. Munk correctly reported that damage to the occipital, not the parietal, lobe is responsible for blindness. He found that removal of the occipital cortex from one side of the brain made monkeys hemianopic unable to see one side of their visual field. Because each eye lost half of its vision, Munk concluded that both eyes must be connected to both the right and the left hemispheres of the brain. He also reported that removal of the occipital cortex on both sides of the brain produced total blindness.

Munk was not gentle to his opponent. In an 1881 publication he records two sets of comments he had made earlier to the Physiological Society in Berlin: "In my first communication on the physiology of the cortex which I made in March of last year I did not say anything about Ferrier's work on the monkey because there was nothing good to be said about it."

When he was asked to express his views at a later session, however, Munk seems to have had quite a bit to say. He first listed several of Ferrier's conclusions, including not only his assertion that the angular gyrus is the visual center in the monkey but also his idea that the occipital lobe is the seat of hunger. Then he stated that Ferrier's declarations "are worthless and gratuitous constructions since the operated animals were examined by Mr. Ferrier in quite an insufficient manner and only at the time of general depression of brain function. If I have gone too far in this statement which is based on a general survey of Mr. Ferrier's experiments it was up to me to restore the injury, the sooner the better. However, as the experiments show now I have said... rather too little than too much. Mr. Ferrier had not made one correct guess, all his statements have turned out to be wrong."

The acrimony between these two investigators was so strong that the psychologist and philosopher William James noted in his 19th-century psychology textbook that "the subject of localization of functions in the brain seems to have a peculiar effect on the temper of those who cultivate it experimentally... Munk's absolute tone about his observations and his theoretical arrogance have led to his ruin as an authority."

Munk, as it turns out, escaped ruin, and he continues to be recognized for having demonstrated clearly that the occipital lobe has a unique role in vision. Even so, Ferrier's work merits further attention, both because questions remain and because the results he obtained did provide a clue to the visual organization of the brain.
Why is it that Ferrier did not see a clear loss of vision after lesions were made in the occipital lobes of monkeys, and what was happening to the animals that seemed to be blinded by lesions of the angular gyrus? Ferrier's failure to blind his monkeys by damaging the occipital lobe in both hemispheres is not hard to explain. In almost every instance he removed a large part of each lobe—the section found behind a deep groove known as the lunate fissure. This would have eliminated most of the primary visual cortex but not all of it. Even if just a few millimeters of cortex remained, the animal would have retained a good deal of its vision because, as will become clear below, relatively small amounts of the primary visual cortex map a rather large extent of the peripheral visual field.

Ferrier's monkeys probably lost certain vision, then, but they would not have been blind. Presumably they compensated for their visual losses to a great degree. Monkeys quickly learn to exploit whatever sight remains after a brain injury, and they are aided in this effort by their ability to move their eyes and head quickly. Munk, for his part, probably produced blindness by including in his lesions more of the medial face of each lobe: the inner surface that faces the opposite hemisphere. Much of the primary visual cortex is on the medial surface.

As to why monkeys that lacked angular gyrus seemed to be blind, Ferrier's descriptions of the animals' activity indicate that he had unwittingly discovered not the visual center of the brain but a region that is of major importance for the control of visually guided movement: the faculty that enables one to, say, reach accurately for a raspberry on a bush or walk down a busy street without bumping into anyone or anything. Ferrier's monkeys could no longer guide their movements according to what they saw, and that is why they had difficulty reaching food placed in front of them.

Ferrier himself must have eventually recognized his mistake. In his first experiments he had allowed his monkeys to live only three or four days after surgery because infection was inevitable. Later, when he adopted the sterile surgical procedures of Joseph Lister, which allowed the monkeys to survive and heal, he realized the monkeys did not stay "blind." His description of the monkeys as they recovered makes it clear that the major effect of his operation was to produce deficits in visually guided movement.

While Ferrier pursued his studies of the angular gyrus, Munk's conclusion that the occipital lobe is the seat of vision gained support. By 1890 Edward Albert Sharpey-Schafer, professor of physiology at University College London, had replicated Munk's results, and physicians had reported many cases of patients who suffered partial blindness following damage to the occipital lobe.

The Swedish neuropathologist Salomen Eberhard Henschens of the University of Upsala summarized the clinical story in 1892. He assembled all the available papers meeting two criteria: they described cases in which brain damage had led to the loss of the right or the left half of the visual field, and they included an autopsy report on the site of the brain damage in the affected hemisphere. In every case the damage included the region of the occipital cortex that surrounds and includes a groove prominent on the medial surface of both hemispheres: the calcarine fissure. This region contains the part of the cortex in which Gennari's stripe is most visible.

Thus, after more than a century, Henschens confirmed Gennari's early suspicion that the cortex with the dominant stripe—the striate cortex—has a unique function. Indeed, Henschens had finally demonstrated that the striate cortex is no less than the primary visual center of the brain.

If the visual world is mapped onto the striate cortex, how is the map arranged? Henschens correctly observed that the lower visual field is mapped onto the upper bank of the calcarine fissure and that the upper visual field is mapped onto the lower bank. He also proposed that the center of the visual field is mapped onto the forward part of the striate cortex and that the periphery of the visual field is mapped onto the rearward parts. This proposal was incorrect.

Henschens came to the wrong conclusion because the data at his disposal were not fine enough; the patients on whom he had based his conclusions had large lesions. What was needed was a series of patients who had partial damage to the striate cortex and who had lost the ability to see one or another region of the visual field. Such cases are a by-product of wars, and the next war arrived in due course.

In 1904 and 1905 troops of the Imperial Russian Army fought the Japanese in several bitter campaigns in Asia. The war involved more than 500,000 soldiers, and its casualties provided a young Japanese physician named Tatsuji Inouye with enough data to develop the first reasonably accurate scheme showing how the visual field is represented in the human brain. Inouye eventually reversed Henschens's proposed mapping pattern; he showed that the central part of the visual field projects to the back of the visual cortex and the periph-

SITE OF BRAIN DAMAGE (shaded regions) in partially blind patients was mapped by a neuropathologist named Salomen Henschens in 1890. These drawings, showing the medial surface of the occipital lobe, represent a few of the many cases he studied. His work helped to confirm Munk's suggestion that the vision center of the human brain is in the occipital lobes.
INOUE'S SCHEME showing how the visual field is mapped onto the primary visual cortex—that is, onto the lips (blue) and banks (pink) of the calcarine fissure—was published in 1909. (Here the right side of the visual field is mapped onto the occipital lobe (a) of the left hemisphere.) Inouye described locations in the visual field (not shown) by a coordinate system in which the horizontal axis is calibrated in degrees of "azimuth," from -90 degrees on the left to 90 degrees on the right; and the vertical axis shows "elevation," from zero degrees at the top to 180 degrees at the bottom. The center lies at zero degrees azimuth and 90 degrees elevation, and the right side of the visual field corresponds to the points to the right of the vertical axis. To make the scheme Inouye spread the fissure (b), revealing its banks; he then mapped azimuth (red) along the fissure's horizontal dimension and elevation (black) along the vertical axis (c). The diagram shows that the center of the visual field is represented at the rear of the occipital lobe, whereas more peripheral parts are represented toward the front of the lobe. It also reveals that a disproportionately large amount of the visual cortex is devoted to central viewing.

ANOTHER SCHEME showing how the visual field (color) maps onto the visual cortex in the occipital lobe was developed by Gordon Holmes in 1918. (The center of the visual field lies at the center of the grid.) The images are Holmes's, although his symbols have been redrawn and color and new labels have been added for extra clarity. His scheme quickly supplanted Inouye's because it is easier to grasp and shows that the area of cortex devoted to the center of the visual field is disproportionately large in the vertical as well as the horizontal direction; Inouye's diagram showed only horizontal magnification.
eral visual field projects to the front.

In spite of his contribution to neuroscience, Inouye has been virtually ignored for many years, an oversight that David Whitteridge, a colleague of mine from the University of Oxford, and I hope to correct. We recently tracked down the 1909 monograph Inouye wrote in German and translated it into English: we also got in touch with his family in Japan to learn more about his personal history.

Inouye, who was born in Tokyo in 1861, completed his medical studies at the University of Tokyo and began work under a prominent ophthalmologist in the year before the Russo-Japanese War broke out. He became a physician in the army, where he examined a number of Japanese soldiers who had lost some vision as a result of head wounds from bullets. He also examined soldiers referred to him by other physicians, and he studied one Japanese soldier injured in the Boxer Rebellion of 1900 in China.

The creation of Inouye’s scheme was facilitated by the fact that the Russians had introduced an entirely new rifle, the Mosin-Nagant Model 91, which shot bullets that had a higher muzzle velocity (620 meters per second) and a smaller diameter (7.6 millimeters) than the bullets of earlier wars; the new bullets often penetrated the skull without shattering it. The patients lost consciousness for periods lasting from a few hours to several days after they were injured, but they recovered enough to cooperate in Inouye’s studies. (They had a personal reason to do so: their pensions were based on how much visual damage they had suffered.)

Inouye based his description of the cortical map on data from 29 patients. For each patient he made a careful plot of the visual field of each eye (the right eye normally saw a slightly different image from the one the left eye saw) and pinpointed the site of injury on the skull. In order to determine exactly which part of the brain was damaged, he identified each bullet’s entry and exit points and calculated the area of brain that would be damaged assuming a straight trajectory through the brain tissue. He had satisfied himself that the assumption was reasonable by analyzing cases in which a soldier had been hit while firing from a prone position. The bullet entered and left the skull and then traversed the body in the shoulder or the forearm. In such cases the three wounds were consistently in a straight line—another consequence of the high-velocity Russian bullets.

In addition to correcting Henschel’s error about the orientation of the map, the scheme that resulted from Inouye’s efforts revealed a fundamental fact about the organization of the striate cortex: the proportions of the image are not preserved when the image is mapped onto the cortex. Inouye did not depict the mapped proportions entirely correctly, but he did recognize that a disproportionately large fraction of the striate cortex is devoted to the central visual field, as might be expected from the fact that the macular region of the retina (the region of central focus) has a high concentration of visual cells.

Inouye died just 12 years ago at the age of 96, but his work has long been overlooked, in part because during World War I the renowned British neurologist Gordon Holmes and his colleague William Tindall Lister produced a more accessible and refined diagram of the way in which the visual cortex maps the visual field. That figure has since been widely reproduced.

Holmes and Lister developed their scheme in much the same way as Inouye had: they were assigned to British military-base hospitals, where they studied the visual losses that followed injury to the occipital lobe. Although their findings for the most part agreed with Inouye’s, they disagreed with him on one major point. Inouye, along with a number of investigators before and since, found that patients rarely lost a complete half of the visual field when they had widespread damage to the left or right occipital lobe. Rather, they continued to see a small region in the center—the part that falls directly on the macula—suggesting that the central region is mapped twice, once on each side of the brain.

Holmes and Lister vigorously denied that such ‘‘macular sparing’’ occurred; they believed all cases of apparent macular sparing were caused by incomplete damage to the occipital lobe. Who was right? Macular sparing probably does exist, but no single explanation accounts for all cases.

In the years since the introduction of Inouye’s and Holmes’ schemes, much has been learned about the organization of the cerebral cortex in general and the striate cortex in particular. For instance, the areas of cortex adjacent to the striate cortex and beyond it on the temporal and parietal lobes are now known to have a predominantly visual function and to receive their major input directly or indirectly from the striate cortex. In monkeys and human beings roughly half of the cerebral cortex is devoted to processing the visual image.

The study of the brain’s role in vision is by no means complete. One major task for the future is to elucidate the specific functions of the extrastriate areas: How does the visual system process color, form and movement? How is such information used to recognize familiar objects and to guide body’s movements?

Many workers look more to the future than to the past as they pursue such issues, and yet a knowledge of history helps to keep the often frustrating process of investigation in perspective. As is true in almost every new research area, progress was slow initially, before technical and theoretical advances made many of the fundamental discoveries possible. Laboratory research with animals then clarified a previously chaotic view of brain organization. That research sometimes led to erroneous conclusions, but further experiments confirmed the facts and resolved the puzzles. The results have led clinicians to a better understanding of their patients’ disorders and ushered in an era of prolific research into the remarkable workings of the human brain.

**Further Reading**

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