Figure 2.1 Leonardo’s self-portrait (?), ca. 1510–1513. Turin, Royal Library.
Leonardo da Vinci's powerful, insatiable, and extraordinarily visual curiosity drove him to seek meaning in both the structure and pattern of the microcosm of the body and the macrocosm of the universe. For him, to draw was to understand. Throughout most of his life he had a consuming interest in the structure and function of the eye, brain, and nervous system, and in a variety of visual phenomena such as illusions, contrast, and color. Although he was initially led to these subjects by his painting or, as he put it, "the science of painting," they soon became obsessions in their own right.

Leonardo (1452–1519) was the first great medical illustrator. His are the earliest surviving naturalistic drawings of the internal structure of the human body. Furthermore, he introduced a number of powerful techniques for portraying anatomical structures such as the use of transparencies, cross sections, exploded figures, and three-dimensional shading. Today, his anatomical drawings continue to attract huge crowds, although most are unaware of the frequent errors they contain and their dependence on traditional authority.

This chapter concerns Leonardo's drawings of the nervous system. First, I consider the background of neuroanatomy in fifteenth-century Europe, then the development of some of Leonardo's ideas on the brain and the eye, and finally, the impact of this work. Leonardo may be the paradigmatic Renaissance
genius with ideas about such things as airplanes, submarines, machine guns, and bicycles that were not to be realized until the twentieth century. However, in his neuroscience he begins solidly in the Middle Ages, blinded, or at least blinkered, by traditional dogma. Only gradually, and only partially, does he free himself from a “debased medieval Aristotelianism and a corrupted Galenism” and begin to draw with accuracy the open body before him.

**Neuroanatomy in the Fifteenth Century**

After the death of Galen in 199, anatomical dissection for either scientific or medical reasons was absent in both Europe and Islam for over a thousand years. It began again in thirteenth-century Italy, first for forensic purposes and then as a way of illustrating Galen’s anatomical works for medical students. Galen, however, did not become available in direct translation until the sixteenth century; before then his work was presented by Avicenna and other Arab scientists who never practiced dissection themselves. Not only were the accounts of Galen’s work indirect, but Galen never mentioned that his anatomical descriptions were almost always based on nonhumans, a fact that was not realized until recently. Galen’s anatomy is remarkably accurate when applied to the monkey or ox, his usual subjects, but not to humans.

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**Box 2.1 Leonardo’s Drawings and Notes**

Over 5,000 sheets of drawings and notes by Leonardo on a fantastic range of subjects have survived and are scattered in libraries around the world. In spite of his plans for a number of books, including one on anatomy, none of his drawings or texts were published until long after his death. By 1690 virtually all of his extant anatomical drawings found their way to the Royal Library in Windsor Castle, including the originals of figures 2.2, 2.3, 2.4, 2.6, 2.7, and 2.8. They are here referred to by the numbers assigned by Clark, e.g., W19097. Leonardo’s surviving texts, except for the recently discovered Madrid codices, have been translated into English and arranged by Richter and, easier to use, MacCurdy.
The first European anatomy textbook was the forty-page *Anathomia* of Mondino de' Luzzi (Mundinus) written in 1316. It was essentially a dissection guide for learning Arab accounts of Galen's words, not for learning about the actual body. Mondino's work went through many manuscript editions before it was finally printed in 1478, but remained unillustrated until an edition of 1521.20-22 It was known to Leonardo at the beginning of his dissections (around 1490) and was an important source of anatomical nomenclature for him.23-26 An earlier medieval tradition of drawing diagrams of the human body in a froglike posture was used to represent the major organs or venisection sites. However, none of the extant ones were drawn from actual dissections, but are symbolic representations of general Greek or Arab ideas about the body, its diseases, and their treatment.27-29 Accurate illustrations of the body beneath the skin began not in medical schools but in the workshops of Renaissance artists. With the growth of naturalism, artists desired more accurate knowledge of the surface musculature and used the scalpel on human cadavers to obtain it. Furthermore, there seems to have been considerable interaction between Italian Renaissance artists and medical workers. Both physicians and painters belonged to and were regulated by the Guild of Physicians and Apothecaries, as was the case for surgeons, undertakers, distillers, booksellers, and silk merchants. Painters bought their pigments at the same shops where doctors bought their medicines, and human dissections were usually open to the public.30-33

Among the early artists who dissected human bodies to gain a more accurate view of the superficial muscles were Leonardo's teacher Verrocchio, who worked on a sculpture of the satyr Marsyas who was flayed alive for his overambition, and Verrocchio's neighbor Antoni Pollaiuolo, who displayed his anatomical knowledge particularly in his Martyrdom of St. Sebastian. Later, Michelangelo, Raphael, and Dürer all left drawings of their dissections; Dürer actually "appropriated" some of Leonardo's anatomical drawings. Leonardo's interest in anatomy presumably also began as an aid to painting, but he alone among Renaissance artists went far deeper than the appearance of the surface musculature.34-39
Chapter 2

Sexual Intercourse

One of Leonardo’s earliest anatomical drawings (ca. 1493) and one of the first to be published, in 1795, depicted sexual intercourse (figure 2.2). It is headed, “I display to men the origin of their ... cause of existence,” and consists of a contradictory collection of traditional views quite unencumbered by actual observations. Avicenna believed that semen, carrying the soul of the future person, came from the spinal cord, a view he presumably obtained from the Hippocratic work On Generation. The idea that semen derives from the brain and travels down the spinal cord is also found in Alcmaeon and other presocratic natural philosophers. To accommodate this view, Leonardo drew a hollow nerve from the spinal cord to the upper of two canals in the penis. In contrast, Galen argued that sperm came from the testes; to accommodate that view, Leonardo drew a tube from the testes to the lower canal, which was thought to be used for the passage of urine as well as semen. The two canals are shown more clearly in the two drawings in the bottom left.

Both the cervix and the uterus are shown expanded, following Avicenna, who believed both structures opened up during intercourse. Note the large sperm entering the (penislike?) open cervix. There is a nerve from the uterus to the breast, illustrating the belief that in pregnancy the “retained menses” is carried to the breast and there stimulates the formation of milk. Another nerve runs from the testes to the heart, following Aristotle’s theory of the heart as the center of sensation, a view subsequently abandoned by Leonardo and never held by Galen or most classical physician-philosophers.

This early drawing is typical in that it serves both as an uncritical “review of the literature” and as a program for investigation. Thus, Leonardo wrote beside the drawing:

Note what the testicles have to do with coition and the sperm. And how the foetus breathes and how it is nourished by the umbilical cord, and why one soul governs two bodies ... and why a child of eight months does not live. ... How the testicles are the source of ardor.
Figure 2.2 Sexual intercourse. This is one of Leonardo’s earliest anatomical drawings and is particularly replete with errors (ca. 1493) W19097. (See boxes 2.1 and 2.2).
And he criticized Avicenna:

Here Avicenna pretends that the soul generates the soul and the body the body and every member in error.

Syphilis had become widespread in Italy about this time, and at the bottom of the page Leonardo noted: "Through these figures will be demonstrated the cause of many dangers of ulcers and diseases." He returned to the subject in subsequent scattered notes. On sexual intercourse he wrote:

The act of coitus and the parts employed therein are so repulsive that if it were not for the beauty of the faces and the adornments of the actions and the frantic state of mind, nature would lose the human species. (W19009r) . . . The woman commonly has a desire quite the opposite of that of a man. That is, the woman likes the size of the genital member of the man to be as large as possible, and the man desires the opposite in the genital member of the woman, so that neither one nor the other ever attains his interest because Nature, who cannot be blamed, has so provided because of parturition. (W19101r)

He did answer his question on the role of the "testicles in ardour":

Testicles . . . contain in themselves ardour, that is, they are the augmenters of the animosity and ferocity of the animals; and experience shows us this clearly in the castrated animals, of which one sees the bull, the boar, the ram and the cock, very fierce animals, which after having been deprived of these testicles remain very cowardly.

Leonardo was the first to realize that in erection, the penis fills with blood. On the subject of the penis he notes that it:
Box 2.2  Leonardo’s Handwriting

Leonardo’s mirror writing is very hard to decipher and not only because it is mirror writing. He had his own peculiar orthography that changed over time, he arbitrarily fused and divided words, he used no punctuation, and he had his own set of abbreviations and symbols. The mirror writing presumably reflected that he was left-handed and had been taught as a child to write with his right hand rather than any “secret code.” He did protect many of his inventions by introducing an intentional error into his plans such as an extra cogwheel.

... confers with the human intelligence and sometimes has intelligence of itself, and although the will of man desires to stimulate it, it remains obstinate and takes its own course, and moving sometimes of itself without license or thought by the man, whether he be sleeping or waking, and many times the man is awake and it is asleep, and many times the man wishes it to practice and it does not wish it; many times it wishes it and the man forbids it. It seems therefore that this creature has often a life and intelligence separate from the man and it would appear that the man is in the wrong in being ashamed to give it a name or exhibit it...

AN EARLY FIGURE SHOWING THE VENTRICULAR THEORY

As in other areas of his investigations, Leonardo’s understanding of the brain shows progression over the years. He begins with uncritical notes from contemporary sources and, finding them unsatisfactory, moves on to critical inquiry and, sometimes, to new insights.

Another one of Leonardo’s earliest anatomical drawings shows the visual input to the brain (figure 2.3) It is a curious and uncritical amalgam of Arabic and medieval sources, with a minor discovery and some new techniques thrown in. The terms for the layers from hair to brain are from Avicenna through Mondino’s text; in two cases the Arabic terms are still in use today—dura mater
Figure 2.3 An early (ca. 1490) drawing of the eye and cerebral ventricles of the brain that uncritically combines Greek, Arab, and medieval views. W12603r
and pia mater. The depictions of the dura and pia extending to sheath the optic nerve and the eyeball (center and lower right) are again derived from Avicenna. The lens or crystalline humor is shown central, as it is in virtually all Arab and European drawings until Felix Platter (1603), the first to understand its role as a lens projecting the image onto a sensitive retina.\textsuperscript{57, 58} The lens is shown as round, although Galen and most of the Arab authorities on the eye, but not many medieval writers, had described it more correctly.\textsuperscript{59, 60}

Leonardo must have been uncertain about the shape of the crystalline humor, because later, in his unpublished monograph on vision,\textsuperscript{61} he suggested and diagrammed a method for determining the shape and location of the lens:

\begin{quote}
In the anatomy of the eye in order to see the inside well without spilling its humour one should place the whole eye in white of egg, make it boil, and become solid, cutting the egg and the eye transversely in order that none of the middle portion may be poured out.
\end{quote}

He never carried out this idea, as reflected in his continuing to draw the crystalline humor (lens) round and his reminder to himself to "study the anatomy of different eyes."\textsuperscript{62}

The portrayal of the ventricles as three connected spheres is not derived from Avicenna or Galen, or any other classical text. Galen knew that the first or lateral ventricles are paired, and he provided an accurate account of the morphology of all four cerebral ventricles on the basis of his dissections of the ox.\textsuperscript{63, 64} Rather than following Galen, Leonardo depicted three circular ventricles according to the widespread medieval theory of the ventricular localization of psychological function. In the basic form of the theory, the faculties of the mind (derived from Aristotle) were distributed among the spaces within the brain (derived from those described by Galen). The lateral ventricles were collapsed into one space, the first cell or small room. This received input from all the sense organs and was the site of the sensus communis, or common sense, which integrated across the modalities. The sensations yielded images, and thus,
the first cell was the seat of fantasy and imagination as well. The second or middle cell was the site of cognitive processes, reasoning, judgment, and thought. The third cell or ventricle was the site of memory. (For a discussion of the origins, variations, and longevity of the ventricular doctrine, see chapter 1 and figure 1.7.)

In the bottom figure Leonardo reflects the standard medieval concept of the location of common sense in the first ventricle by showing input to it from the eyes and ears. Note the absence of the optic chiasm, although it had been noted by Aristotle, discussed in detail by Galen, and diagrammed repeatedly in the Arab literature, including in Alhazen’s *De Aspectibus*, which was the standard textbook on optics in Europe until Kepler in the sixteenth century (see figure 1.6).65-68

The new and correct anatomical feature, if somewhat exaggerated, is the frontal sinus, shown above the eye in the central and lower left figures. The three ways of labeling the layers of the scalp and the “unhinging” of the skull in the lower right drawing are apparently new illustration techniques.

**Injecting Wax to Reveal the Ventricles**

A few years later, Leonardo returned to the ventricles with brilliant success, using the sculptural technique of wax injection to reveal their shape (figure 2.4). As he instructed69:

Make two vent-holes in the horns of the great ventricles, and insert melted wax with a syringe, making a hole in the ventricle of the membra and through such a hole fill the three ventricles of the brain. Then, when the wax has set, take away the brain and you will see the shape of the ventricles. But first put narrow tubes into the vents so that the air which is in these ventricles can escape and make room for the wax which enters into the ventricles.

The shortcomings of his wax cast of the lateral ventricles seen in figure 2.4 were probably due to the absence of air vents in the posterior horns and
the use of an unpreserved brain. This method for revealing the shape of internal biological cavities was not used again until Frederick Ruysch in the eighteenth century, an achievement the French Academy of Science thought equal to Newton's.\textsuperscript{70}

The ventral view shows a rete mirabile, a vascular structure found in the ox, where Galen described it, but not in humans. The sulcal pattern is also that of an ox, whereas the location of the cerebellum and the form of the ventricles are closer to that of a human brain. Perhaps Leonardo injected both species and this is a composite figure.\textsuperscript{71}
As Leonardo began to study the brain itself, his attribution of functions to the ventricles became somewhat contradictory and was eventually abandoned. In the period of this drawing, he had been dissecting the cranial nerves and observed that the trigeminal and auditory nerves entered the central portion of the brain rather than the anterior portion. Therefore, in contrast to tradition and his previous drawing (figure 2.3), he put the common sense in the middle ventricle, now the third ventricle since the anterior ventricle was paired. The auditory and trigeminal inputs to the middle ventricle are diagrammed in the small horizontal section in the middle right of figure 2.5. The visual input still went to the first ventricle before proceeding to the common sense. Now he put intellect and *impressiva* into the first ventricle. Leonardo's placement of intellect at the target of the optic nerves underlies the dominant role he gave to this sense. By "impressiva," a term never used before or after Leonardo, he meant something like sensory processing or sensation. Although the impressiva is never described as only visual, note that in this figure it receives only visual input. Leonardo again contradicts his idea that it initially processes all the senses by having the tactile input come to the fourth ventricle:

Since we have clearly seen that the fourth ventricle is at the end of the medulla where all the nerves which provide the sense of touch come together, we can conclude that the sense of touch passes to this ventricle. (W19127r)

He never resolved these tensions between his anatomy and his functional localizations, and there is little effort to relate the sensory input to the ventricles in later drawings (e.g., figures 2.4 and 2.5). He did return to the medulla in the only experiment that he is known to have carried out on a living animal (he was an antivivisectionist and a vegetarian):

The frog suddenly dies when its spinal medulla is perforated. . . . It seems therefore that here lies the foundations of motion and life. (W12613v)
Box 2.3 Leonardo on the Role of Anatomical Illustrations

"Dispel from your mind the thought that an understanding of the human body in every aspect of its structure can be given in words; for the more thoroughly you describe, the more you will confuse the mind of the reader and the more you will prevent him from a knowledge of the thing described; it is therefore necessary to draw as well as describe . . . I advise you not to trouble with words unless you are speaking to a blind man." 74

The Optic Tract and Cranial Nerves

Figure 2.5 shows major advances in both illustration technique and anatomy. The upper figure uses transparency to show the relations among the cranial nerves, and the lower figure is an exploded view. Both techniques were used here for the first time. Anatomical drawings did not surpass the clarity of these for centuries.75, 76

Galen had described only seven cranial nerves, including the oculomotor but neither the trochlear nor the abducens. As shown in figure 2.5 and rather more clearly in figure 2.6, Leonardo's account of the cranial nerves is an advance over Galen. Here the optic chiasm is illustrated and the olfactory nerves are shown above it. The other nerves appear to be the oculomotor, the abducens, and the ophthalmic branch of the trigeminal,77, 78 although one observer contends that the latter is the troclear.79

Typically, the cranial nerve sheets contain ambitious programs for future research80:

- Draw the nerves which move the eyes in any direction, and in muscles; and do the same with their eyelids, and with the eyebrows, nostrils, cheeks and lips, and everything that moves in a man's face.
- Let the whole ramification of the vessels which serve the brain be made first by itself, separated from the nerves, and then another combined with the nerves.

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Figure 2.5  The ventricles, optic chiasm, and cranial nerves and (below) exploded view of the skull and brain, ca. 1504–1506. Detail, Schlossmuseum, Weimar.
Figure 2.6  The optic and oculomotor nerves, ca. 1504–1506. Detail of W190525.

**The Vagus and Hand of an Old Man**

Figure 2.7 is a drawing of the right vagus in an old man. How this centenarian came to be his most famous anatomical subject is described by Leonardo as follows:

And this old man, a few hours before his death told me that he had passed one hundred years, and that he found nothing wrong with his body other than weakness. And thus while sitting upon a
Figure 2.7 The vagus nerve and its recurrent branch innervating the larynx, trachea, and stomach, ca. 1504-1506. W19050v
bed in the hospital of Santa Maria Nuova in Florence, without any
movement or other sign of any mishap he passed out of his life.
And I made an anatomy of him in order to see the cause of so
tsweet a death. This I found to be a fainting away through lack of
blood to the artery which nourishes the heart, and other parts
below it, which I found very dry, thin and withered. This anatomy
I described very diligently and with great ease owing to the absence
of fat and humors which greatly hinder the recognition of the parts.
(W19027v)

Galen had described in accurate detail the right and left branches of the
vagus nerve, known in Leonardo’s time as the reversive nerve.81 Figure 2.7
shows the right branch innervating the larynx, trachea, esophagus, and stomach
Leonardo’s interest in the vagus may have been stimulated by Galen’s brilliant
demonstration that cutting the innervation of the larynx by the recurrent branch
of the vagus eliminated vocalization in the pig. (See the bottom panel of figure
1.5.) In the adjacent text Leonardo mentions that the left nerve may innervate
the heart. This gives him the occasion to withdraw his earlier Aristotelian belief
that the heart is the beginning of life (W19034v):

The heart is not the beginning of life but is a vessel made of dense
muscle vivified and nourished by an artery and vein as are the other
muscles. It is true that the blood and the artery which purges itself
in it are the life and nourishment of the other muscles.

The rest of the text is mostly questions for future research:

Note in what part the left reversive nerve turns and what office it
serves. And note the substance of the brain whether it is softer or
denser above the origin of the nerve than in other parts. [According
to Galen the sensory nerves and the sensory parts of the brain were
softer and the motor nerves and the motor parts of the brain were
harder. Thus, Leonardo is asking whether the nerve is sensory or motor]. Observe in what way the reverseive nerves give sensation to the rings of the trachea and what are the muscles which give movement to the rings to produce a deep, medium or shrill voice. Count the rings of the trachea.

Leonardo is unique up to his time and beyond for constantly counting and measuring in his anatomical studies.

Figure 2.8, also from the centenarian, shows the distribution of the median and ulnar nerves to the palmar aspect of the hand. Unlike the more complicated situation in figure 2.7, this drawing is very accurate.

**Optics of the Eye**

Leonardo wrote extensively about light, vision, and the optics of the eye in both an unpublished monograph and in many scattered notes and drawings. Although the camera obscura or pinhole camera had been known since late antiquity and was used by Renaissance artists, Leonardo was the first to note its similarity to the eye. He vehemently rejected the implication of this similarity, however; namely, that an inverted image was projected onto the back of the eye and conveyed to the brain. To avoid this unacceptable inversion he tried to develop an optical scheme in which the image was inverted twice in the eye, thereby ending up veridical and ready to be transported to the brain. In fact, he developed about eight such schemes, two of which are shown in figure 2.9. Leonardo actually proposed to build a model to test the lower optical arrangement with his own eye at the site of the optic nerve head of the model.

It is ironic that Leonardo, who presumably easily read his own left-right reversed writing, found it inconceivable that the brain could interpret an inverted image. One hundred years later, Kepler was the first to accept that the image on the black of the eye was indeed inverted since "geometrical laws
Figure 2.8 The median and ulnar nerves of the hand, ca. 1504–1509. Detail of W19025v.
Box 2.4 Leonardo on the Difficulties of Anatomy

"And if you have a love for such [anatomical] things, you will perhaps be hindered by your stomach, and if this does not prevent you, you may perhaps be deterred by the fear of living during the night in the company of quartered and flayed corpses, horrible to see. If this does not deter you, perhaps you lack the good draughtsmanship which appertains to such demonstrations, and if you have the draughtsmanship, it will not be accompanied by a knowledge of perspective. If it were so accompanied, you lack the methods of geometrical demonstration and the method of calculation of the forces and power of the muscles. Perhaps you lack the patience so that you will not be diligent. Whether all these qualities were found in me or not, the hundred and twenty books composed by me will supply the verdict, yes or not. In these pursuits I have been hindered neither by avarice nor by negligence but only by lack of time. Farewell."

(W19070v)

leave no choice," and, anyhow, he said, what goes on beyond the retina was not his concern but that of "philosophers."91

Influence of Leonardo on the Course of Neuroscience

Leonardo had planned to publish his "120 anatomical notebooks" (see box 2.3) first alone and then as part of a textbook in collaboration with Marc Antonio del Torre, an anatomist and professor of medicine at Padua and later Pavia. However, del Torre died in 1511, before their text was finished (or, as far as we know, started). Leonardo’s anatomical drawings had to wait over 200 years for publication. A number of his contemporaries, however, are known to have seen and admired them.92 Dürer copied several of them, as did several less well-known artists.93, 94 Leonardo’s fame as an artist-anatomist spread throughout northern Italy, and today he is credited with "spearheading the new creative anatomy,"95 and developing the naturalistic techniques that were made use of by Vesalius (1514–1564) and led to the birth of modern anatomy.96–99
Figure 2.9  Two of Leonardo's attempts to have a double inversion of the image in the eye in order to obtain an upright image at the back of the eye for veridical transmission to the brain. In the lower figure, the eye at the right symbolizes the start of the optic nerve going to the brain (Strong, 1979).
Notes

1. Clark, 1939.
5. Boring, 1942.
7. McMurrich, 1930.
11. Herrlinger, 1970. These techniques, however, were common in contemporary treatises on architecture and mechanics that must have been very familiar to Leonardo.
22. Locy, 1911.
29. Locy, 1911.
30. Clark, 1939.
34. McMurrich, 1930.
42. O’Malley and Saunders, 1952.
43. Avicenna, 1930; Longrigg, 1993. Curiously, in Taoist sexual theory, semen, conserved by controlling ejaculation, travels in the opposite direction up the spinal cord to the brain (see chapter 1, note 14).
44. Galen, 1956.
45. See chapter 1.
47. McMurrich, 1930.
54. McMurrich, 1930.
57. Boring, 1942.
60. Galen, 1968.
64. Galen, 1968.
70. O’Malley and Saunders, 1952.
72. Clark, 1939.
74. McMurrich, 1930.
77. O’Malley and Saunders, 1952.
84. Ackerman, 1978.
96. McMurrich, 1930.