The Study of the Wonderful

The First Topographical Mapping of Vision in the Brain

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The conception by René Descartes of the human brain, notorious as it is for placing the soul or mind in the pineal gland, had yet within it the basic idea of the brain as a highly organized mechanism with topographical sensory mapping and different functions localized in specific areas. Descartes was directly led to this idea by his appreciation of what the retinal image conceived by Johannes Kepler implied, not only for the nature of vision, but for the operation of the brain in general. The linkage between Kepler and Descartes is not widely appreciated but is one of the best examples of synergism in the history of science.

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Nature tells us one secret in terms of another, and she may refuse to disclose one secret until another has been laid bare.

T.S. Kuhn

THE ELEGANT CONSTRUCTION OF A RETINAL IMAGE

The book was a small one, with the disarmingly modest title Supplements to Witelo on the Optical Part of Astronomy (Ad vitellionem paralipomena quibus astronomiae pars optica traditur) (Witelo was a 13th century writer on optics). This book is the first one of modern optics. No one today can read any of the optical theorists that came before Johannes Kepler and understand them without reconstructing optical ideas that are largely antique and obsolete.

In a way, what Kepler did was simple, yet it had profound effects. He had been busy throughout 1603 with calculations that would eventually show the orbit of Mars to be elliptical, the first of his laws of planetary motion. This involved reams of arithmetical calculations in which he had to be aware of how the atmosphere’s refraction of starlight affected the observed star positions. For some reason, since he was so much involved with the errors created by refraction, he decided to study the refraction of light in the eye. He followed light going through the transparent media of the eye and followed where it led him, and it led him to the retina. He thus accomplished what Witelo and a host of others could not quite manage. He took what was then only a vague and tentative idea, that the retina was the true photoreceptor, and established the first convincing idea of a retinal image.

In 1583, the Swiss anatomist Felix Platter, in De Corporis Humani Structura, approached the problem of the eye as an anatomist and for the first time explicitly made the retina, as the expansion of the optic nerve, the eye’s essential light transducer. Gone was the traditional assumption that the lens, with its unique structure, was the essential element in vision. Now it was simply ‘the internal looking glass’ of the retina. Platter made no effort to solve the geometrical problems of image formation and did not mention the inverted image produced in this scheme. He ignored it. But that problem had to be faced if the intraocular refraction was to be properly appreciated. That is what Kepler did. He confronted the problem and solved it. In a model of concision, Kepler wrote: “Thus vision is brought about by a picture of the thing seen being formed on the concave surface of the retina. That which is to the right outside is depicted on the left on the retina, that to the left on the right, that above below, and that below above.” This gives us the retinal image, clearly enunciated for the first time.

Kepler’s image has “elegance,” that particular quality that Judson ascribes to the double helix: “Structure and... function are united in DNA with such ingenious parsimony that one smiles with the delight of perceiving it.” The retinal image is an elegant construction. Structure

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Kepler was well aware of Galen’s ideas and those of the medieval optical theorists before him. He had, however, the advantage of not being wedded to them. When he approached the problem of how light behaved in the eye, as an astronomer he saw it in a different way. He made the strategic decision to treat the eye as an optical instrument, pure and simple. He traced light refracting through the transparent optical media of the eye and its projection as a real image onto the retina. The inverted and reversed image is a faithful representation of the outside world because its details bear the same geometrical relationship to each other as the details of the object do. It is not the insuperable obstacle to seeing things right side up that previous writers had thought it was. Kepler could afford to treat the inverted image and the other features of perception as a different problem, a problem whose time for solution had not yet come. This is still a critical judgment in determining the success of any scientific enterprise today. Kepler’s behavior here was of as high an order as any displayed in the astronomical discoveries for which he is famous. With admirable directness, Kepler wrote: I leave it to natural philosophers to discuss the way in which this image is put together by the spiritual principles of vision residing in the retina and the nerves. For by the laws of optics, what can be said about this hidden motion, which, since it takes place through opaque and hence dark parts and is brought about by spirits that differ in every respect from the humours of the eye and other transparent things, immediately puts itself outside the field of optical laws? I leave it to natural philosophy and the study of the wonderful. Very simple, and very elegant.

WHY DID KEPLER SUCCEED WHERE HIS PREDECESSORS HAD FAILED?

Descartes wrote about the eye and brain mainly in 2 works, Dioptrique (Optics), published in 1637 and Traite de l’homme (Treatise on Man), written in 1632 and published posthumously in 1662 in Latin (De Homine) and in 1664 in French (L’Homme). Dioptrique is one of 3 works that were meant to illustrate his primary effort, the Discourse on the Method of Rightly Directing the Reason, and Searching for Truth in the Sciences, the other essays concerning meteorology and geometry (in which Descartes formulated analytical geometry). Posternity pays most attention to the Discourse of Method, but the 3 essays themselves are all substantial affairs. Dioptrique consists of 10 chapters dealing with the nature of light, its refraction (enunciating the sine law, probably independently from Snell), the anatomy of the eye, the nature of sensation and vision, and the operation of lenses in general. It even concludes with suggestions on how to fabricate new types of lenses however the soul gained understanding from the image, its organization would be crucial.

However, Galen’s concept of the brain, still largely accepted at the time, was of a mostly undifferentiated gland producing the animating principle, the “pneuma” or “spirit” of the nerves. What room was there in such a tradition for Kepler’s retinal image? Was Kepler’s representation of the outside world so carefully constructed on the retina only to be lost in its passage to the brain? No, said René Descartes in effect, it is not lost. It is preserved in a direct projection of retinal points to corresponding points in the brain (Figure 2). In one stroke, Descartes invented sensory projection and brought the physiology of sensation into the modern age. There is nowhere in all of the history of science a better example of how one man’s seminal insight led directly to the equally brilliant and powerful insight of another. For Descartes, Kepler’s image became the key to the brain.

DESCARTES EXTENDED KEPLER’S RETINAL IMAGE TO THE BRAIN

Kepler’s retinal image was a geometrical representation of the outside world inside the body. The requirements of optical theory and the constraints implicit in the rectilinear propagation of light in the formation of images ensured that for each point in the external world, there existed a corresponding point in the retinal image that bore the same relative positioning to other points as they did “out there.” The retinal image was only 2-dimensional and thus was by no means an actual replica of the object. Its geometry was far more convincing than Alhazen’s quasi-optical constructions on the lens surface. It thus was a powerful argument that
for telescopes, the exciting new invention of the time. Descartes’ discussion of vision outlines his main ideas on the eye and the brain, which are elaborated further in *Traite de l’homme*.

*Traite de l’homme* purports to describe general physiology, but it deals largely with what we now call the central nervous system. The work includes some material on hearing and smell, but the principal discussion concerns vision. It is lavishly illustrated, though its posthumous publication probably means that Descartes never saw or approved of the actual illustrations. Of 54 diagrams in the book, more than half depict the eye or the eye and brain together. Kepler’s optics is dealt with in detail. But, unconscionable as it is to the modern reader, Kepler’s name is never mentioned.

**DESCARTES DID NOT MENTION HIS SOURCES**

This failing was less egregious in the custom of the time than it is now, but raises the legitimate question of whether Descartes actually knew of Kepler’s work. Descartes consistently earns poor marks in the etiquette of attribution. Hall acknowledges that:

Descartes created a problem for historians by generally omitting any reference to his sources. This omission was in line with his goal of building biology anew, by reasoning logically from certain axioms that seemed inescapably clear. . . . But, despite this aim of disengagement, we sense . . . a thorough immersion in already existing ideas, ideas within the context of which, and not outside them, his own opinions were developed. We obtain, in consequence, a paradoxical impression: his explanations seem new on the one hand, yet strangely familiar on the other.

As Scott puts it:

It was not his custom to refer in his published works to the contributions of other writers in any field of learning; on the contrary he usually makes it abundantly clear that he is not in any way indebted either to predecessor or contemporary. There is nothing in the works of Galileo, for example, which he can envy, or which he has patience to read, and [in Descartes’ correspondence] he scornfully repudiates the suggestion that he received any hint for his ellipses or his hyperbolas from Kepler. Consequently, the uncritical reader is prone to accept many of Descartes’ observations as his own, an assumption which is usually far from accurate.

This mention of hyperbolas refers to Kepler’s 1611 text *Dioptrice*, which was written in a flurry of enthusiasm when he had just heard of Galileo’s amazing observations with the telescope. In this text, Kepler suggested the use of elliptical or hyperbolic lenses to decrease the spherical aberrations that limited Galileo’s observations. But *Dioptrice* was more than that. It was Kepler’s attempt to systematize his understanding of optics, at which he had only hinted in the *Supplements to Witelo*. All the basic concepts of modern image theory are there: real, virtual, upright, and inverted images; reduced and magnified images; the crucial relationship between the distance of object and image; refraction in 1-, 2-, and 3-lens systems; the double convex lens system for an astronomical (Keplerian) telescope; and the convex-concave lens (Galilean) telescope. Kepler also coined the words *focus* and *dioptrics*.

Not only did Descartes have no compunction in using the word *dioptrics* for his own essay on optics, but the essay contains internal evidence that he had carefully read Kepler. For instance, like Kepler, Descartes used the word *painted* to describe the action of light in forming the retinal image: “[A] picture can easily stimulate our minds to conceive the object painted there” (Kepler: “The retina is painted with the colored rays of visible things”).

More than that, Kepler’s *Dioptrice* was the reigning optics text in the period before Christopher Scheiner’s *Oculus, hoc est: Fundamentum Opticum* appeared in 1619. Scheiner extended Kepler’s retinal image by actually demonstrating the real inverted image formed on the retina in his famous experiment in which he directly viewed the image on the translucent retina of an enucleated eye. Descartes referred to Scheiner in his correspondence and illustrated the experiment in *Dioptrique* (without attribution). If Descartes was aware of Scheiner, it stretches credence to suppose that he was unfamiliar with Kepler’s *Dioptrice*, if not the *Supplements to Witelo*. Descartes may not have acknowledged it and may not have even consciously recognized it, but Kepler was leading him into the brain.

**DESCARTES MODIFIED KEPLER’S IDEAS**

At any rate, Descartes makes 2 significant improvements over Kepler in dealing with the intraocular refraction of light. Having by now the sine law of refraction, which Kepler did not have, Descartes realizes that the cornea must contribute to the overall refraction as much as, if not more than, the lens itself. Also, in changing its refractive capacity for the requirements of forming an image of a near object, the eye, according to Kepler, changed the relative position of the lenses. Descartes proposes a change in the shape of the lens as being a more feasible alternative. (Some vertebrates, especially fish, do use Keplerian accommodation.)

![](image.png)
In binocular vision, the image rests on corresponding points in the 2 eyes (the first such clear idea of binocular correspondence) (Figure 4A). Each stimulated point on the retina exerts pressure on a fiber that runs back in the optic nerve past an uncrossed chiasm and ends on the internal surface of the ventricles. The interstices between the mass of fibers on that surface can be considered a system of openings or pores. The sensory fiber controls the relative orientation of a particular pore and the degree to which it is open. This then controls the ease with which the intraventricular spirit or fluid can enter the nerve.

At this point, Descartes knows he must account for single binocular vision in particular and—in general—for the single idea generated by paired sense organs when they are stimulated simultaneously. Galen already had the blood vessels around the pineal gland as the brain’s chief source of animal spirits. In a brain that seems to be bilaterally symmetrical with paired structures, the pineal gland was conspicuous as single, central, and unpaired. So Descartes selects the pineal gland as the central structure that allows the “soul,” acting through the pineal gland, to obtain a unified sensation. This selection, sui generis in this context and unutterably quaint and wrong-headed to us, was logical to Descartes but was going to bring continuing grief to his ideas on the brain.

When the retinal image stimulates the optic nerve fibers, these fibers in turn tug on corresponding points on the ventricle surface (Figure 4B). This opens the associated pores. There is now a lessened resistance to flow toward the open pores for the spirit emanating from the surface of the pineal gland. Therefore, the pineal gland leans toward these open pores. Certain points on the pineal surface now become apposed to the open pores and there is a gush of spirit off the pineal gland into the open pores. This, so to speak, completes the circuit and vision (in humans, at least) is made conscious.

Consciousness is a manifestation of the human’s God-given immortal soul and distinguishes us from animals, which are mere automatons without souls. The soul is not strictly localizable, but interacts with the body at the pineal. The conscious mind is made aware of the retinal pattern by the pattern of the spirit as it leaves the pineal surface. The conscious idea is accurate because there is a point-to-point correspondence between the patterns on the retina, the ventricle, and the pineal gland.

In modern parlance, this correspondence is “topographical mapping,” but its configuration bears no other physical resemblance to the object. “Correspondence” effectively buries any persisting echoes of the ancient Greek idea of some tangible replica of the object entering the eye to effect vision.

**THE PINEAL GLAND IS AN ACTIVE PART OF THE PROCESS**

The pineal gland has the ability to alter its position relative to different locations on the ventricular walls. It can tilt toward motor areas on the wall, thus initiating voluntary motion through the muscles. For instance, when we wish to touch a point (Figure 5), the pineal gland, as the seat of volition, orients itself so that the spirit flows off toward the pores whose nerves serve certain muscles. The spirit fills the active muscle, causing it to contract, and there is a primitive type of reciprocal innervation of agonist and antagonist. The pineal gland can also move closer to the input from one sense organ rather than another, and this allows us to fix our attention on that particular sensation (Figure 6).

**THE CRUCIAL POINTS ABOUT THE BRAIN**

Certainly this is very odd anatomy. It is, in fact, quite literally fantastic—a fantasy springing out of Descartes’ imagination. Voltaire called

![Figure 4. A, René Descartes’ concept of points in the retinal image of one eye corresponding to points in the other eye, and each set of points projecting in turn to other corresponding points on the wall of the ventricles. B, The corresponding points on the ventricle surface in turn correspond with points on the surface of the pineal, yielding single binocular vision. The pattern of points on the surface of the pineal gland from which the “spirit” comes corresponds to the pattern of pores on the ventricle surface. Because point A on the pineal surface serves point 2 from each eye, etc, single binocular vision becomes possible.](image-url)
it a “novel of the soul.”17 But if we let the anatomy distract us, we will miss the point. Something else comes through all of this: Descartes’ single-minded, determined, relentless insistence on treating the brain as a complex mechanism. The following is the crux of Descartes’ idea of the brain11:

1. The brain has an intricate structure.
2. Important elements of this structure are on a level too minute to be seen, but are located in specific locations that have specific functions.
3. The elements interact with each other in such a way as to form a model of the external world within the brain.
4. This model then actuates the motor system in an organized way so as to deal with that external reality.
5. Consciousness is closely related to this process.

The French Jesuit philosopher Nicolas Malebranche later wrote that when he first read Descartes, he was forced by palpitations of the heart to put the book down for awhile, as he realized the implications of the brain as a maker and manipulator of symbols.1

It is true that we get impatient with Descartes for what Hall15 called his “gratuitous precision” in constructing the body, describing things we know he could not have seen. (We do know that Descartes dissected animal parts, including sheep brains, obtained from his neighborhood butcher.18 When a visitor to his bachelor quarters asked to see his library, Descartes pointed to a leg of veal he was dissecting at the time.)

DESCARTES WAS CONSTRUCTING A HYPOTHETICAL MODEL

Then we realize that Descartes is being coy in his biological writings. He uses phrases such as “suppose that” or “if you now consider that,” and he explicitly tells us that he is not actually describing the body but rather a machine that could simulate all the activities of the body. This indirectness may partly have been a safer way to challenge Aristotle’s ideas, so as to avoid condemnation by the Church (an effort that was unsuccessful).19 On the other hand, it seems to be on par with his frequent use of comparisons as an explanatory tool (for instance, the use of bouncing tennis balls to describe the laws of reflection and refraction).20,21 He seems to realize that biology is not about to yield to his method of deducing laws of nature from a few basic axioms. Life is too diverse, too complex. So he describes a hypothetical model. Blake22 writes:

Sometimes, indeed, for certain limited purposes, and on certain occasions, Descartes is content to offer particular mechanical explanations as mere hypotheses such as would suffice to explain the given phenomena if they were true, but which, for all we know to the contrary, may be pure fictions. On such occasions Descartes claims for the hypotheses he offers not truth, but merely possibility...an abstract way of viewing things which, may...well be false, but which will enable us to think more clearly.

Crombie1 feels that Descartes’ use of a hypothetical model was in itself an outstanding contribution to the scientific method. All in all, Descartes gives us the impression that he would not be disconcerted in the least if one were to sit down with him in a quiet cafe with a bottle of good French wine and discuss neurons and synapses, nuclei and fiber tracts. When Descartes deals with the central nervous system, he has a recognizably modern sensibility.

THE MISCHIEVOUS “SOUL” AT THE PINEAL

Today, the idea of the brain as a complex mechanism is wholly natural to us. What bothers us is this mysterious, nonphysical “soul” at the pineal gland, this ghost in the machine. What is it, exactly? How can something immaterial interact with the material? Descartes is vague. He keeps promising to discuss it in more detail (there may well have been another manuscript that was lost). In his private letters, he admits that there is no conscious thinking and no sensory awareness without the body.19 On the other hand, he completely rejects the idea that matter could be sentient or that the mind could be reduced to matter.23 Although he continues to distinguish 2 basic components to reality—res extensae or dimensional, quantifiable matter, and res cogitans, or the mind—Descartes appears to be groping for a better understanding of this relationship even up to the time of his premature death in 1650.24
THE “MASK OF THEORY” WAS CHANGING

Descartes lived at a time when the established wisdom was Aristotle’s idea of the soul, and Aristotle’s soul, after all, encompassed the whole body. It was the all-pervading activating feature of all body functions, of all life. This was upheld even as late as the 17th century by men of the caliber of Harvey, Glisson, and van Helmont. Modern physiology—physical, chemical, molecular physiology—would have been impossible under it. Descartes at least takes the soul out of the heart (where Aristotle at one time had it), the blood (where Harvey had it), the pyloric end of the stomach (where van Helmont had it), and even out of the brain itself. As an immaterial entity, the soul is not strictly localizable, but interacts with the body—and this interaction is limited to one small gland. This allows the body itself to be understood in material, mechanism terms and overcomes a great philosophical hurdle. From this point on, Aristotle’s soul began to wither away. “There is a mask of theory over the whole face of nature,” said the 19th century philosopher of science William Whewell.27 Now the mask was changing. The terms of the problem were being redefined.

WAS DESCARTES’ DUALISM A FAILURE OF NERVE?

It is a paradox in the history of philosophy that Descartes is remembered largely as the great advocate of dualism, the separation of mind and body. Perhaps this was the price he had to pay for his devotion to a structured, mechanistic brain. Cartesian metaphysics and epistemology constitute an entire subdiscipline in philosophy and it is beyond the scope of this article (and my temerity) to review it. Yet in some ways, like his occasional statements that ideas and sensation are innate, Descartes seems not to recognize the implications of his idea of the brain. Perhaps it was a failure of nerve: he could go on only so far and no further. In an extended, carefully reasoned discussion of Descartes’ ideas of mind and body (in which the word brain is mentioned rarely), Curley28 notes that “the topic of consciousness is certainly not one in which Descartes can be accused of a foolish consistency.” According to Watson,29 “Dualism is the seat of the difficulties which infect Cartesian metaphysics,” and in the opinion of Bertrand Russell,19 “modern philosophy has very largely accepted the formulation of its problems from Descartes, while not accepting his solutions.”

OPTICS WAS A WAY OF APPLYING MATHEMATICS TO THE BRAIN

Descartes’ great ambition was to create a new universal philosophical system. He felt that of all the traditional schemes of thought, only mathematics seemed to remain valid. Perhaps his greatest talent was in mathematics; his creation of analytical geometry was a great achievement. When it came to applying mathematics to physical phenomena, he found optics to be an effective way to do it, and in applying mathematics to physiology, he found optics by far the best approach. It led him directly to a theory of sensation and of the brain.

PRIOR CONCEPTS WERE POETIC METAPHOR

Our present understanding of the brain has many roots and no one can say the brain was “discovered” by a given person at a given time. But to what extent was Descartes’ complex brain a departure from the models of prior writers? Pre-Vesalian anatomists, including even Leonardo da Vinci, had drawn pictures of the brain localizing 3 attributes—sensation, memory, and judgment—in 3 spherical ventricles.8,10,12,30 This localization is so uncertain, so ill-defined and nebulous that it belongs to an entirely different class from Descartes’ model. It is a poetic metaphor rather than serious anatomy. Vesalius himself,31 famous for breaking Galen’s hold on anatomy, agrees with him most of the time on brain physiology:

1. . . . ascribe no more to the ventricles than that they are cavities and spaces in which the inhaled air, added to the vital spirit from the heart, is, by power of the peculiar substance of the brain, transformed into animal spirit. This [animal spirit] is presently distributed through the nerves to the organs of sensation and motion, so that these organs . . . perform their office.

This brain is an enigma. In comparison, Descartes’ model is a breath of fresh air.

TO WHAT EXTENT DID DESCARTES’ MODEL ACTUALLY INFLUENCE OTHERS?

Thomas Willis took some delight in pointing out how prominent the pineal gland was in supposedly soulless animals, like the sheep. (Dog-loving Englishmen probably took special umbrage at the Cartesian denial of a soul to animals.) Willis then speculated on functions for specific brain parts himself and is often regarded as the author of functional localization.12,30 Willis’ De Cerebri Anatome was published in 1664, 2 years after Descartes’ Traite de l’homme was printed in Latin, some 30 years after Traite de l’homme was actually written. In a contest, Descartes should be given priority, though, of course, Willis’ anatomy was far superior. What is more, Willis was impressed by Descartes’ use of visual optics. In his De anima brutorum of 1672,32 he used optical metaphors himself:

It is possible to conceive of a middle part of the brain, a kind of interior chamber of the soul equipped with dioptric mirrors; in the innermost of which images or representations of all sensible things, sent in through the passages of the nerves, like tubes or narrow openings, first pass through the corpora striata as through a lens; then they are revealed upon the corpus callosum [i.e., the entire white matter] as if on a white wall, and so induce perception and at the same time a certain imagination of the things sensed.

This scheme caused a contemporary of Willis to criticize his “Cartesian temerity.”33

THE HOLY GRAIL OF NEUROANATOMY

For a time, associating the thinking soul with a specific but limited brain structure became the holy grail of neuroanatomy. Even among Descartes’ admirers, however, there were few who could defend the pineal
glánd for very long. Sir Kenelm Digby, the common-sense English soldier-scholar and contemporary of Descartes, found it hard to say where the mind lay, “Show me the soule and I will tell you where it residieth,” Digby wrote, but if an unpaired midline structure was required, why, there was the septum lucidum! Other candidates over the years were the corpus callosum, the striate body, the corpora quadririma, the thalamus, the spinal cord, and ventricles.18

Whatever some of its more visible aspects may be for us today, the Cartesian model was part of the intellectual matrix of the time, usually unacknowledged or forgotten, wrong in the details but still a program for thinking about the brain. The implicit promise of this program was that if the brain only could be broken down into all its constituent parts, it could be understood in its entirety. In a field still bubbling with controversy, there is a consensus that Descartes’ ideas had great influence on the development of physiology and psychology.34

HISTORY DOES NOT ADEQUATELY RECOGNIZE THE KEPLER-DESCARTES INTERACTION

Histories of neurophysiology and psychology have largely given their attention to Descartes’ ideas of involuntary movements and reflex action and to his use of the pineal gland to solve the mind-body problem (today, commonly referred to as the neural correlate of consciousness). Relatively few writers12,18,19 recognize Descartes’ topographical mapping in the projection of the retina to the brain as the departure it was. For the most part, however, even when Descartes’ intricate, organized brain is acknowledged,30,35-38 Kepler’s crucial influence is unappreciated. (Crombie’s superb but underread monograph1 is an exception to the rule.)

Would Descartes have developed his ideas about the body-as-machine without Kepler? Probably so. Would he have solved the retinal image problem without Kepler? Perhaps. Would he have conceived of the brain as he did without visual optics to guide him? Probably not.

Kepler’s influence on Descartes was too significant to remain so widely unappreciated, and Descartes’ brain was a revolutionary idea. What we have been doing since then is changing the details. Let us allow Descartes his pineal gland. We recognize him as a colleague, avid to understand the eye and brain, engaged in a search we are still bound on, for answers that still elude us.

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