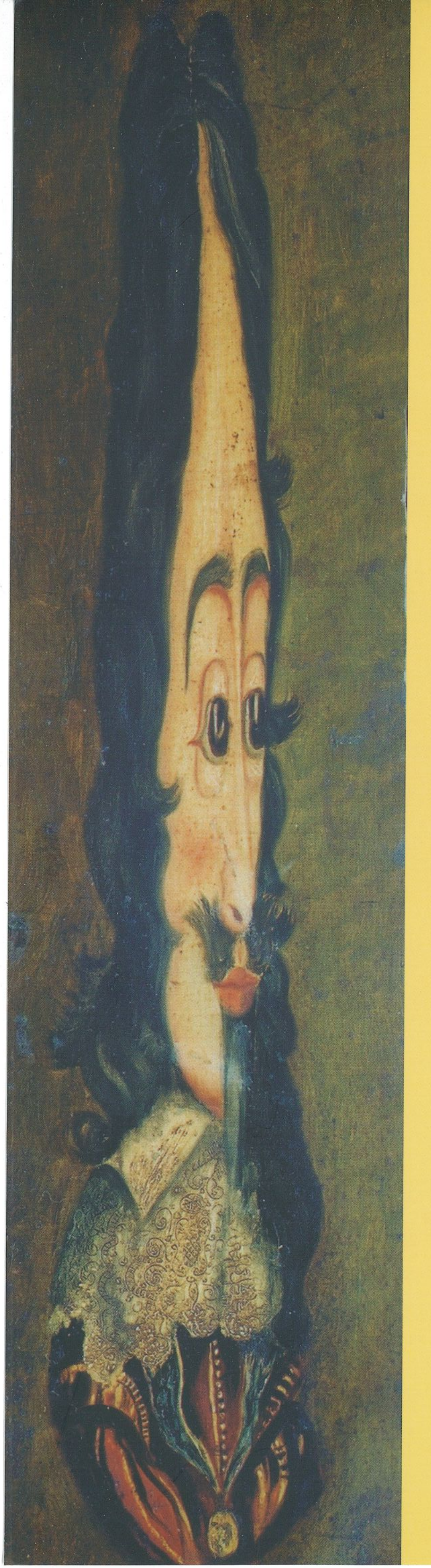

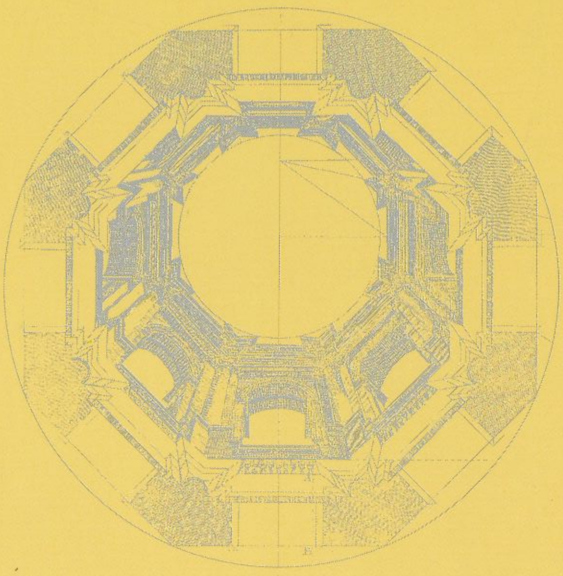

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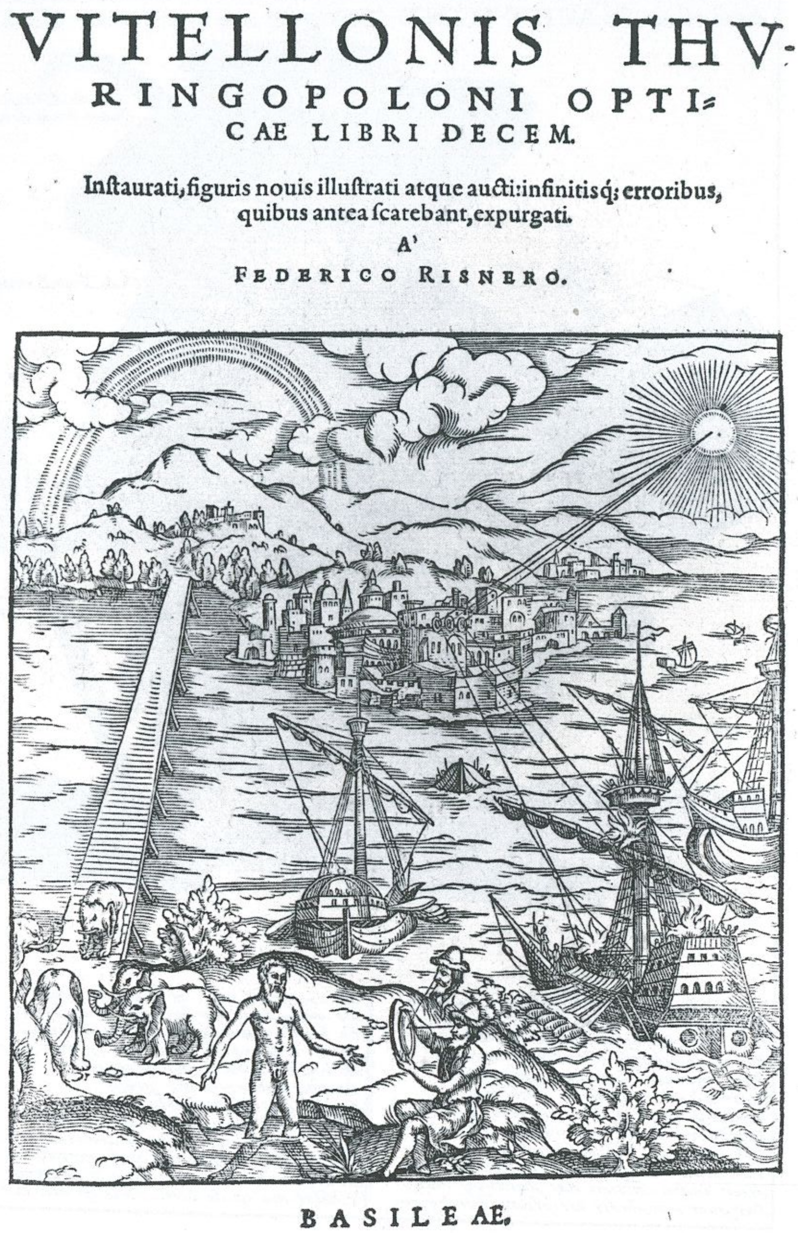


VITELLONIS THV-
RINGOPOLONI OPTI-
CAE LIBRI DECEM.
Inſtaurati, figuris nouis illuſtrati atque aucti: infinitisq; erroribus,
quibus antea ſcatebant, expurgati.
A'
FEDERICO RISNERO.

BASILEAE.

fig. 1: Vitello; Opticae libri decem, Basel 1572. Frontispiece.
It represents the three classical divisions of optics (direct vision), catoptrics (reflections), and dioptrics (refractions).

Nicholas Wade

The Art of Science: Visualizing concepts in visual science

The art of visual communication is not restricted to the fine arts. Scientists also apply art in communicating their ideas graphically. It is often the case that the development of ideas can be traced through their graphical representations and it is this that I propose to explore in the context of concepts of visual science. The illustrations employed will be taken from books in the collection of Werner Nekes.

Visual science can be subdivided in a variety of ways. The classification I will employ is in terms of optics, anatomy and physiology, and visual phenomena. Each of these can in turn be subdivided, as will be evident in what follows. First, optics can be considered in terms of the nature of light and its transmission through the eye. For most of recorded history light and sight have been one and the same. Ideas about the nature of light in Greek science were inseparable from those of the eye with which it was experienced. Accordingly, Greek theories of light incorporated the visual apparatus to varying degrees, thereby confounding light with sight. Two aspects of sight initially fuelled speculations about light: the experience of light following pressure or a blow to the eye, and the visibility of a reflected image in the eye. The idea of light being emitted from the eye was founded on the first of these, and the notion of an image being carried back to the eye was the source of the second. A third feature of sight, which distinguished it from the other senses, was that the experience could be terminated by closing the eyelids during daytime. Most theories struggled, with varying degrees of success, to account for these phenomena over a period of around two thousand years. In fact, the major advances in optics have involved differentiating physical from psychological phenomena. For the dioptrical properties of the eye it was achieved in 1604 by Johannes Kepler (1571-1630), who portrayed the manner in which images are formed on the retina; for colour it was Isaac Newton (1642-1727) who, in 1672, published the results of his prismatic experiments which indicated that the spectrum is a property of light rather than glass. Exactly a century

fig. 2: Johannes Baptista Thioly and Petrus Taillandier; Theses Opticae et Astronomicae, Lyon 1693, plate 1

after Kepler, Newton published his mature theory of light and colours in his *Opticks*. Light and sight were conflated in a variety of ways by Greek thinkers, and their ideas were transmitted and extended by Arabic writers like Ibn al-Haytham (c. 1040), to be reabsorbed into European thought from the thirteenth century onwards to form the medieval *Perspectivas* like that of Witelo or Vitellonis (c. 1230/35-1275/80); although it was written in the thirteenth century it was edited and printed by Frederic Risner in 1572 (fig. 1).

Optics

Sight aided optics and ophthalmology in the early stages of their developments, but it has not generally been accorded the same attention for the periods following the separation into physical, physiological, and psychological domains. For example, it has been said that Kepler's dioptrical analysis of the retinal image represented a "successful solution of the problem of vision". It certainly did provide a secure platform from which the analysis of vision could proceed, but from the psychological point of view, the statement is at best an oversimplification. Kepler formulated the problem that subsequent generations of students of vision have attempted to resolve: how do we perceive the world as three-dimensional on the basis of a two-dimensional retinal image? Indeed, I have referred to this as the 'legacy of Kepler' – reducing the problem to the analysis of single, static retinal images rather than considering the starting point as binocular and dynamic.

Physical optics came of age in the seventeenth century. In addition to his critique of Witelo's medieval optics in *Ad Vitellionem Paralipomena* in 1604, Kepler wrote a text on dioptrics in 1611. In the first of these he added many things to Witelo's perspective, both experimentally and theoretically. Amongst them was the formulation of the basic principle of photometry that the intensity of light diminishes with the square of the distance from the source. The classical arrangement for demonstrating this principle was illustrated by many seventeenth century writers and an example is shown in figure 2.

Students of optics added many new phenomena to test the theories of lights and colours that were advanced. For example, diffraction was demonstrated by Franciscus Maria Grimaldi (1613-1663) and on the basis of this he suggested that light might act like a liquid, flowing in waves. He added diffraction to the direct propagation of light, its reflection and refraction. In his book on light published two years after his death, Grimaldi (1665) wrote: "Light can be considered analogous to a liquid which can also spread out in waves, namely, when it passes round an object". Grimaldi demonstrated the phenomenon of diffraction (fig. 3, left) by partially blocking sunlight passing through two small apertures: bands of colour could be seen in the shadow area. Wave theory was supported and extended by Robert Hooke (1635-1703) and by Christiaan Huygens (1629-1695). Huygens proposed and illustrated the wavefronts that could be produced by points on luminous sources, and he made an analogy between light and sound; diffraction was analyzed in terms of the wavefronts originating at the aperture (fig. 3, right). Huygens wrote: "Now there is no doubt at all that light also comes from the luminous body to our eyes by some movement impressed on the matter which is between the two... If, in addition, light takes time for its passage... it will follow that this movement, impressed on the intervening matter, is successive; and conse-

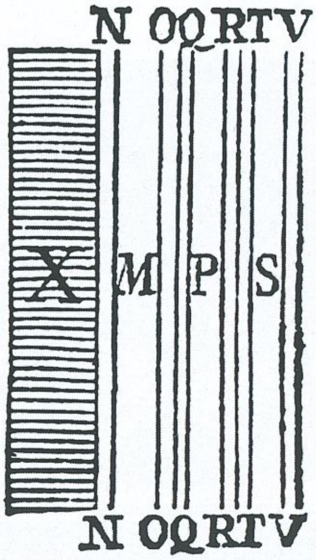


fig. 3 left: Diagram of diffraction, in: Franciscus Maria Grimaldi; Physico - Mathesis de Lumine, Coloribis, et Iride. Bologna, Bernia 1665

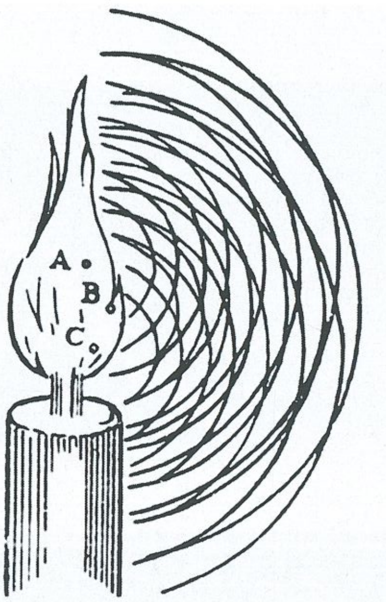


fig. 3 right: Representation of waves from a candle flame, in: Christiaan Huygens; Traité de la lumière. Leyden, van der Aa 1692

quently it spreads, as sound does, by spherical surfaces and waves: for I call them waves from their resemblance to those which are seen to be formed in water when a stone is thrown into it, and which present a successive spreading as circles... each little region of a luminous body, such as the sun, a candle, or a burning coal, generates its own waves of which that region is the centre. Thus in the flame of a candle, having distinguished the points A, B, C, concentric circles described about each of these points represent the waves which come from them. And one must imagine the same about every point of the surface and of the part within the flame".
Experimental and mathematical support for the wave theory of light was provided in the early nineteenth century and it essentially replaced Newton's corpuscular theory for the rest of the century.

With the appreciation that light could be considered as a physical property, and that its reflections and refractions followed physical principles, its study became the province of physicists, whereas the examination of sight was pursued by physiologists and philosophers. The separation of the physics of light from the philosophy of sight was to reflect the ancient schism between materialists and idealists: light was an external, material phenomenon whereas sight was internal and subjective.

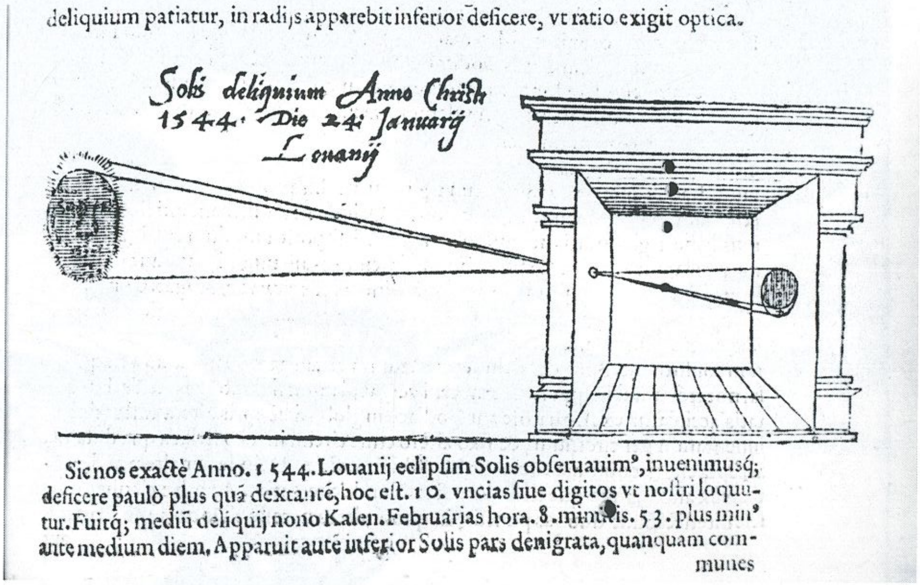
Dioptrics
When Kepler demonstrated that the structures of the eye refracted light to focus an image on the retina, he transformed the analysis of vision: the eye was considered to be an optical instrument and its analogy with a camera having a lens became widespread. The image so formed in eye and camera was inverted and reversed. The camera obscura had long been known and it was enlisted by artists to assist in the representation of scenes in accurate perspective and by scientists to investigate a wide range of optical phenomena. Scientists could study the eclipse of the sun (fig. 4 a) and artists could capture landscapes with a precision that was difficult to achieve otherwise (fig. 4 b).

The frontispiece to *Oculus hoc est: Fundamentum Opticum* by Christoph Scheiner (1571-1650) depicts a wide range of uses to which the camera obscura could be put (fig. 5, p. 698). The analogy between eye and camera was made graphically explicit by Scheiner in his book *Rosa Ursina*. Not only did he show natural and artificial eyes, he indicated how optical corrections could be made to overcome defects of long- and short-sightedness. Scheiner was able to demonstrate the image forming properties of the eye by placing an excised ox's eye in the aperture of a *camera obscura* and noting how an image could be seen on the exposed rear surface of the retina. His demonstration was considered so valuable that it was repeated and illustrated seven years later by René Descartes (1596-1650), who even replaced the retina with an eggshell in some experiments. Descartes' depiction of the cosmic observer inspecting the image formed on the retina is one of the most significant illustrations in visual science. Athanasius Kircher (1602-1680) kept abreast of many advances in science during the seventeenth century, and he was quick to capitalise on the insights of others. He not only produced his own diagram of image formation (fig. 6 a, p. 699), but in the second edition he also illustrated an early form of the magic lantern (fig. 6 b, p. 697), invented by Christiaan Huygens (1629-1695). Both illustrations were published in his *Ars Magna Lucis et Umbrae*.

The analogy between eye and camera clarified the nature of the focused image on the retina but it introduced another problem: how does the eye focus on images at different distances? The solution to this problem, which took over two hundred years, could not commence without an adequate knowledge of the anatomy of the eye.

Anatomy of the eye
The gross structure of the eye presented a problem for anatomists, particularly before the dioptric properties of the eye had been established. Consequently, the optic nerve was often depicted as leaving the eye on the optic axis. This was the case for medieval scholars like John Peckham (ca 1230-1292) in his *Perspectiva Communis* (fig. 7). The crystalline lens was considered to be the receptive organ, and so the central location of the optic nerve was not thought to introduce any difficulties for vision. Even the beautiful, multilayered figure in Bartisch's *Ophthalmoduleia* made the same error. The figure enables the reader to strip away the coats of the eye to reveal the structures beneath. It is a tour de force of printing but it was not, alas, matched by the accuracy of the anatomy.

Kepler's dioptrics shifted the focus from the lens to the retina, and within a few years the first correct illustration of the mammalian eye was provided by Scheiner. The lens and its curvatures are appropriately represented and the optic nerve leaves the eye nasally. This figure has frequently been reprinted, and it is often claimed that it represents a human eye, even though Scheiner stated that he did not have the opportunity of dissecting one: "The observation of most animals' eyes tells us all these things; indeed these processes happen in the eyes of cows, sheep, goats, and pigs, on which I have



deliquium patiatur, in radijs apparebit inferiorẽ deficere, vt ratio exigit optica.

Sic nos exactè Anno. 1544. Louanij eclipſim Solis obſeruauimꝰ, inuenimusq; deficere paulò plus quã dextantẽ, hoc eſt. 10. vncias ſiue digitos vt noſtri loquuntur. Fuitq; mediũ deliquij nono Kalen. Februarias hora. 8. minutis. 53. plus minꝰ ante medium diem. Apparuit autẽ inferior Solis pars denigrata, quanquam communes

fig. 4 a: Petrus Apian und Gemma Frisius; Cosmographia, Antwerpen 1584
First published illustration of a dark room as camera obscura for studying the eclipse of the sun on 24th January 1544 in Louvain, p. 312

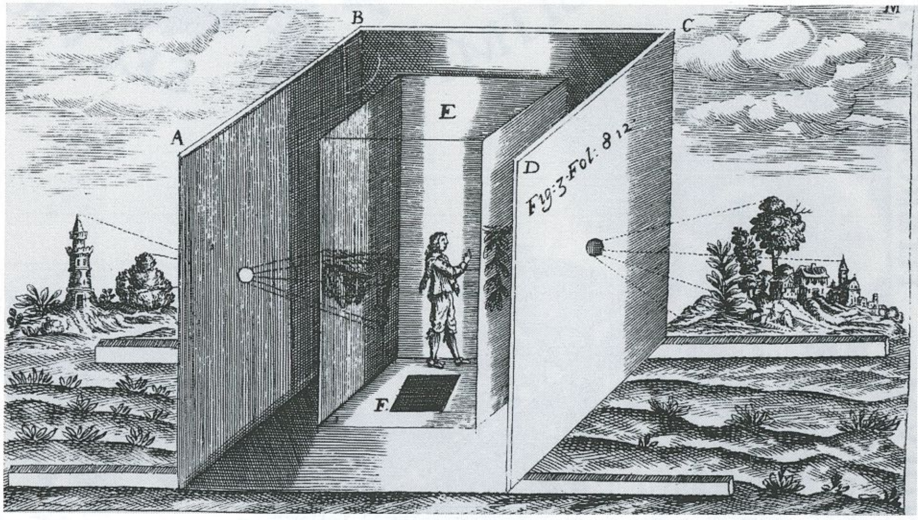


fig. 4 b: Athanasius Kircher, Ars Magna Lucis et Umbrae, Rom 1646
First illustration of a portable camera obscura, which could be carried like a sedan chair. The artist climbed into the camera from below, p. 807, plate 28

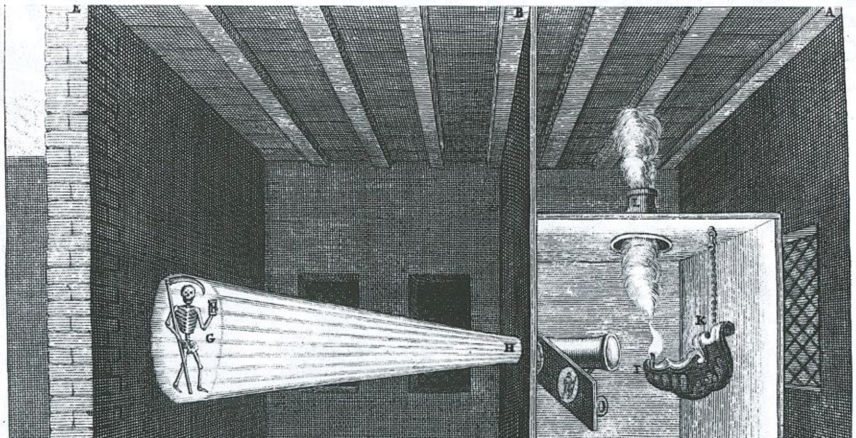
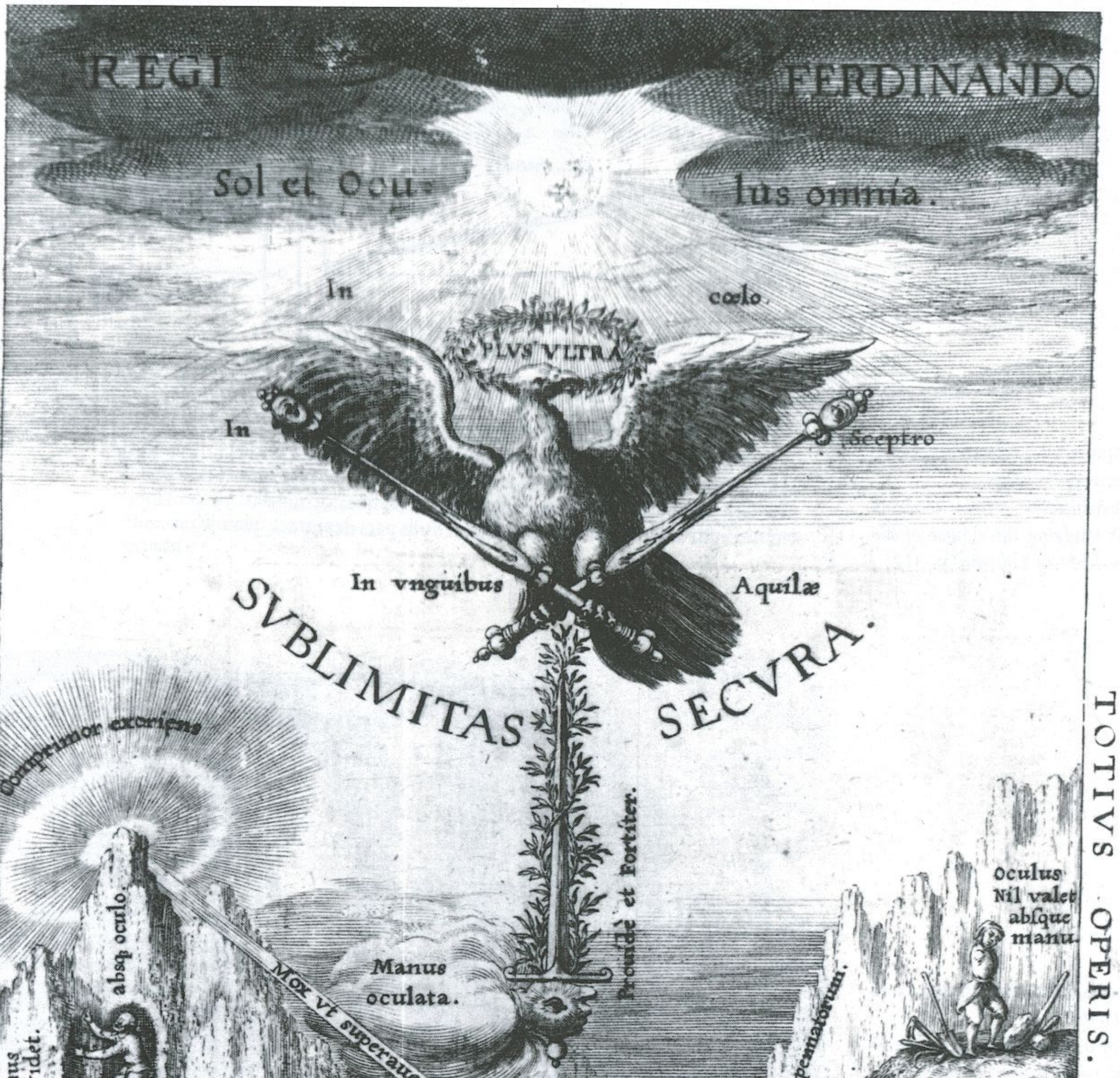


fig. 6 b: First printed illustration of a magic lantern projection, in: Athanasius Kircher, Ars Magna Lucis et Umbrae, Amsterdam 1671, p. 769


REGI
FERDINANDO
Sol et Ocu-
lus omnia.
In
cœlo.
PLVS VLTRA
In
Sceptro
In vnguibus
Aquilæ
SVBLIMITAS
SECVRA.
COMPENDIVM HIEROGLYPHICVM
TOTIVS OPERIS.
Comprimor exoriens
absq. oculo.
Manus Nil videt.
Quo obscurior, hoc illustrior.
Mox vt superauero rupes.
Manus oculata.
Prudenter et Fortiter.
Oculus Nil valet absque manu.
Frustra ante oculos pennatorum.
Post
euer.
llonem
rigor
Attollor in imo.
Post angustias dilator.
Non in
teger
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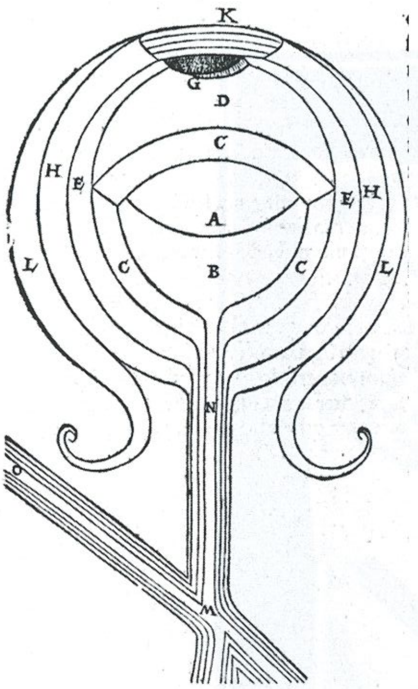
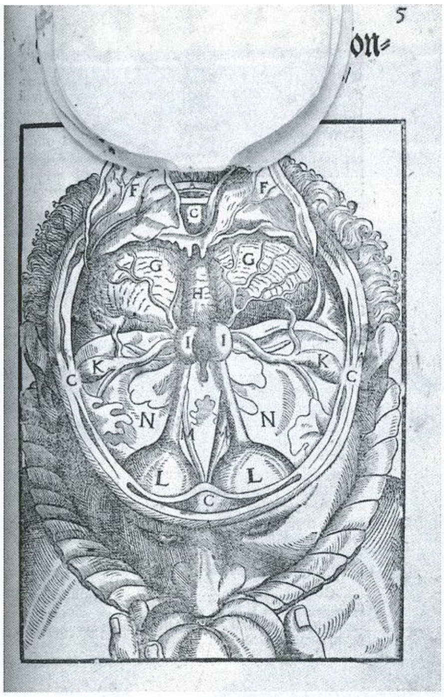
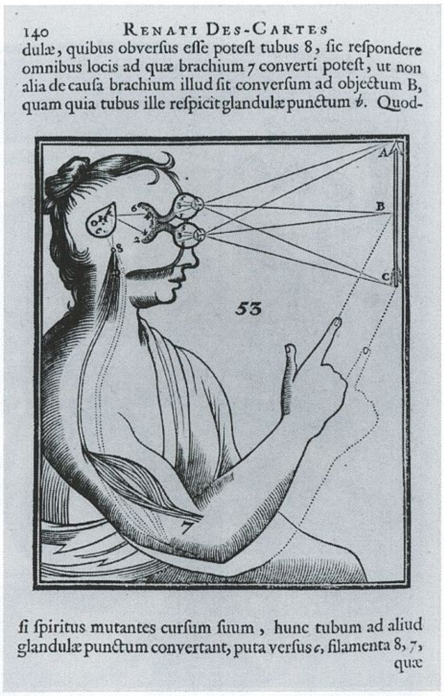
trat.
HVMILITAS
GLORIO
SA
CAVDAM OCVLVS, SED HABET RERVM SAPIENTIA FINES

fig. 5






140 Renati Des-Cartes

dulæ, quibus obverſus eſſe poteſt tubus 8, ſic reſpondere omnibus locis ad quæ brachium 7 converti poteſt, ut non alia de cauſa brachium illud ſit converſum ad objectum B, quam quia tubus ille reſpicit glandulæ punctum *b*. Quod-

ſi ſpiritus mutantes curſum ſuum, hunc tubum ad aliud glandulæ punctum convertant, puta verſus *c*, filamenta 8, 7, quæ

done many experiments in the presence of other people; logical reasoning leads me to suppose a similar process for the human eyes as well, because in every man's eye there is a hole, through which the optical nerve comes out, placed in the same position as in animals; indeed the cavities of each eye are placed in the skull along the sides of the bone which shapes the nasal projection, although in the case of man we have to rely on reasoning more than on observation, because I have never had the opportunity to test a human eye." Scheiner's analysis was rapidly absorbed by both anatomists and philosophers like Descartes in his *Dioptrique*.

fig. 5 (p. 698): Christoph Scheiner; Oculus hoc est: Fundamentum Opticum. Innsbruck 12. Juni 1619, Frontispiece (various camerae obscurae)

fig. 7 (left): Die Erforschung des Auges, in: John Peckham, Perspectiva Communis, Nürnberg 1542, propositio XXX, din verso

fig. 8 (centre): Diagram of the visual pathways, in: Georg Bartisch; Augendienst. Dresden 1583, p. 5

fig. 9 (right): Das Auge als Camera obscura. in: Renatus Descartes; Tractatus de Homine et Formatione Foetus. Amsterdam 1677, p. 140

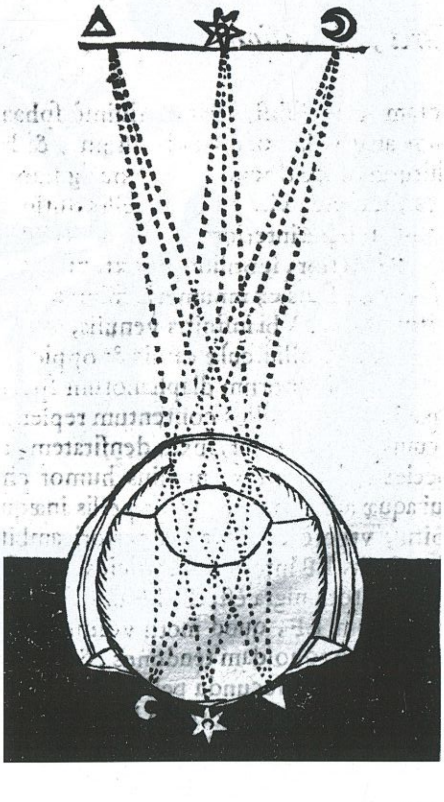
fig. 6 a (below): The image formation in the eye, in: Athanasius Kircher; Ars Magna Lucis et Umbrae. Rom 1646, p. 162

Visual pathways

Ignorance of the anatomy of the eye was amplified with respect to the pathways from the eyes to the brain. The optic nerves were considered to be hollow tubes along which the visual spirit could flow to ventricles in the brain. Three ventricles were innumerated in Galenic anatomy, and Albertus Magnus (ca. 1198-1280) incorporated them into late medieval philosophy as representing the sites of perception, reasoning, and memory. The prevalence of this notion is evident in the diagram of the visual pathways given by Leonardo da Vinci (1452-1519). In some other of his drawings the optic nerves lead directly into the first of the three ventricles without even meeting at the optic chiasm. Dissections of bodies often cast little light on the structure of the brain because it was likely to be in a decomposed state by the time the anatomist examined it; the brain was frequently the last structure to be dissected and so such errors were difficult to eradicate. Bartisch's multi-layered figure of the brain repeated this belief, as is shown in figure 8.

Vesalius depicted the optic nerves as projecting to the same side of the brain as the eye from which they came. This was to be repeated, as is clear from Descartes' figure of the pathways, taken from his *Tractatus de Homine* (fig. 9). The fibres from the two eyes were united in the pineal body under this scheme. Newton also carried out dissection of the visual pathways, and his depiction was considerably more accurate than previous ones had been. The optic nerve fibres from the temporal hemiretinas projected to the same side of the brain and those from the nasal hemiretinas crossed over at the chiasm. It took over a century before this was firmly established anatomically.

The diagrams of the eye tended to concentrate on its optical functions rather than those of accessory structures like the eye muscles. Scheuchzer sought to provide all these aspects of ocular anatomy in his depiction (fig. 10). Although the book was published in 1733, the lessons of Scheiner had not been learned: Fig. IV of the eye still



PSAL. XCIV. v. 9.
Deus ὀφθαλμοτέχνης.

Pſal. XCIV. v. 9.
Das Auge ein Wercke Gottes.

fig. 10

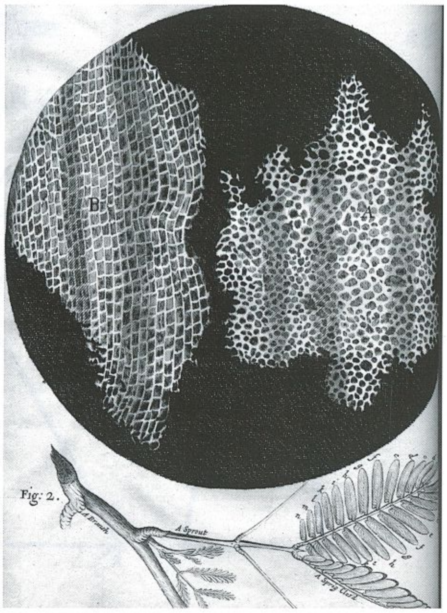
fig. 10 (p. 700): Diagrams of the eye and its structures, in: Johannes J. Scheuchzer, Physica Sacra, Augsburg, Ulm 1733, Vol. 3, plate 561

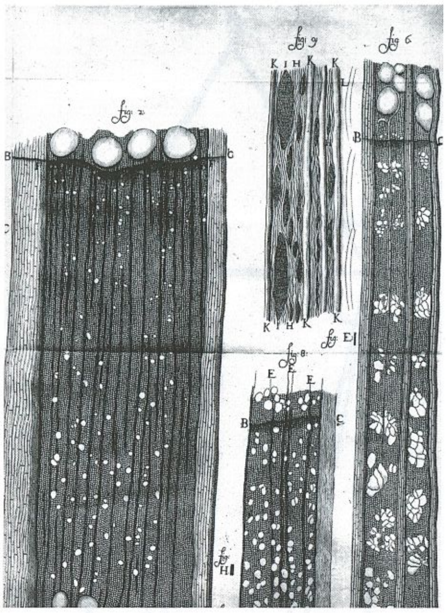
fig. 11 (left): Representation of cells in cork, in: Robert Hooke; Micrographia: or some Physiological Descriptions of Minute Bodies made by Magnifying Glasses. London 1665, p. 114/115

fig 12 (right): Representation of cells in wood, in: Antoni van Leeuwenhoek: Ondekte Onsigtbaarheeden, Leyden, 12. Januar 1680

fig. 13 (below left): Oculaire binocle, in: Cherubin d'Orléans; La Vision Parfaite, Paris 1677, p. 102

fig. 14 (below right): microscope with two oculars, in: Johannes Zahn, Oculus Artificialis Teledioptricus, Nürnberg 1702, p. 706





had the optic nerve leaving the eye on the optic axis, rather than nasally, as Scheiner had established.

Microanatomy

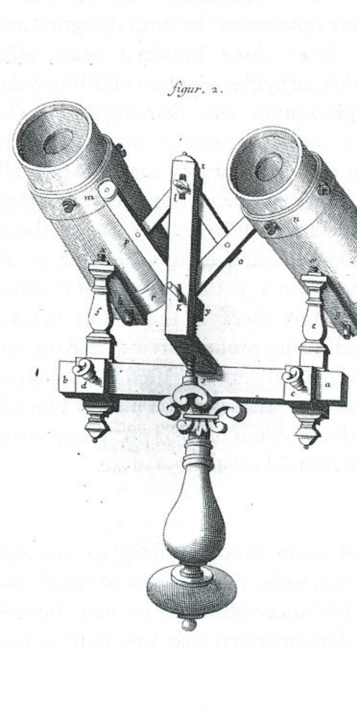
Scheiner could only examine the anatomy of the eye with his own eye, but shortly afterwards it was possible to see structures that were invisible to the naked eye. Microscopes opened a new world to anatomists as telescopes had done for astronomers. Hooke inadvertently gave the name to the building blocks of the body-cells. The structure of cork, visible via the microscope (fig. 11), resembled monastic cells, and they were so named by Hooke. Almost two centuries later the cell doctrine was formulated. Antonius van Leeuwenhoek (1632-1723) directed his simple magnifier to the optic nerve, and stated that the nerves were solid rather than hollow (fig. 12). Microanatomy was not advanced greatly in the eighteenth century, and the use of the microscope was often disparaged. Nonetheless, when achromatic microscopes were introduced in the nineteenth century there was a veritable explosion of research.

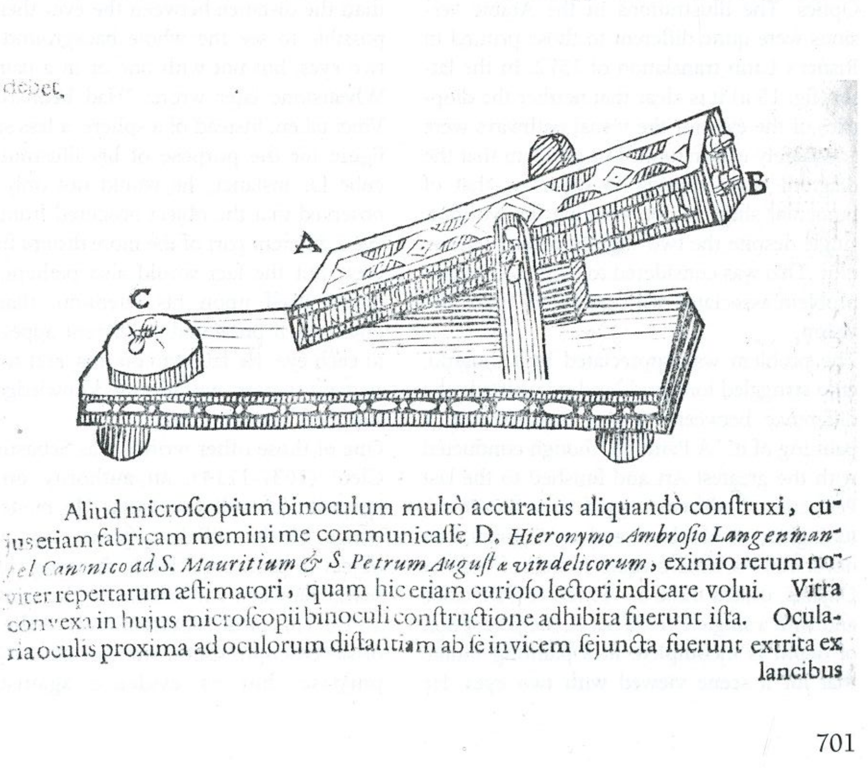
Binocular microscopes

The microscopes of Hooke and Leeuwenhoek were made for the use of one eye. Binocular microscopes were produced soon after, but they added little to the discoveries that were made with the instrument. Le Père Cherubin d'Orléans (1613-1697) produced a range of beautiful binocular instruments – both telescopes and microscopes – which were illustrated in his books. A binocular microscope is shown in figure 13. Cherubin d'Orléans made the instruments because he believed that binocular vision was more perfect than monocular, although he provided little evidence to support the belief. His fine engravings contrast with the cruder woodcuts printed in Zahn's book (fig. 14), but they do have a certain vitality to them. These instruments were, in fact, pseudoscopic rather than stereoscopic, so that any depth seen with them would have been the reverse of that in the specimens observed. The first stereoscopic binocular microscope was not made until the mid nineteenth century, by Charles Wheatstone (1802-1875).

Binocular vision

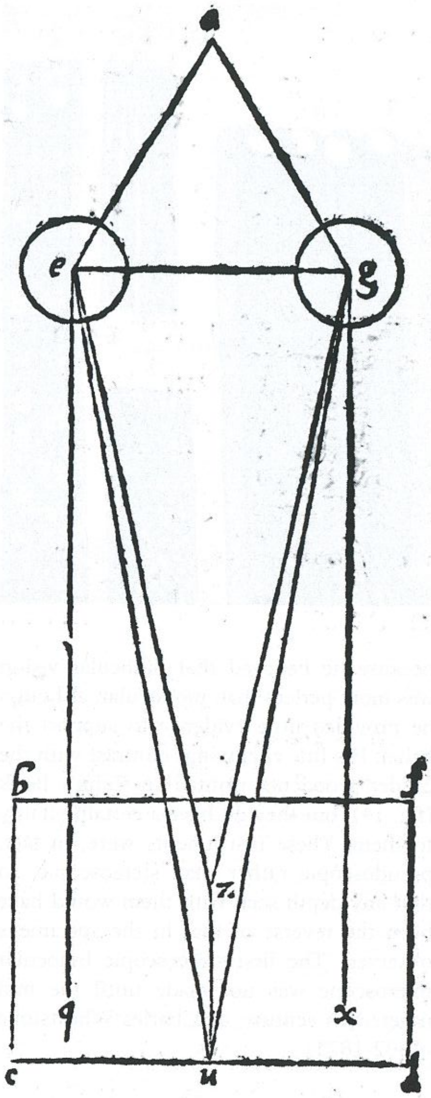
It is remarkable that few insights into the nature of binocular vision were derived from these binocular instruments. However, greater minds had applied themselves to the same





debet,

Aliud microſcopium binoculum multò accuratius aliquandò conſtruxi, cujus etiam fabricam memini me communicaſſe D. *Hieronymo Ambroſio Langenmantel Canonico ad S. Mauritium & S. Petrum Auguſtæ vindelicorum*, eximio rerum noviter repertarum æſtimatori, quam hic etiam curioſo lectori indicare volui. Vitra convexa in hujus microſcopii binoculi conſtructione adhibita fuerunt iſta. Ocularia oculis proxima ad oculorum diſtantiam ab ſe invicem ſejuncta fuerunt extrita ex lancibus



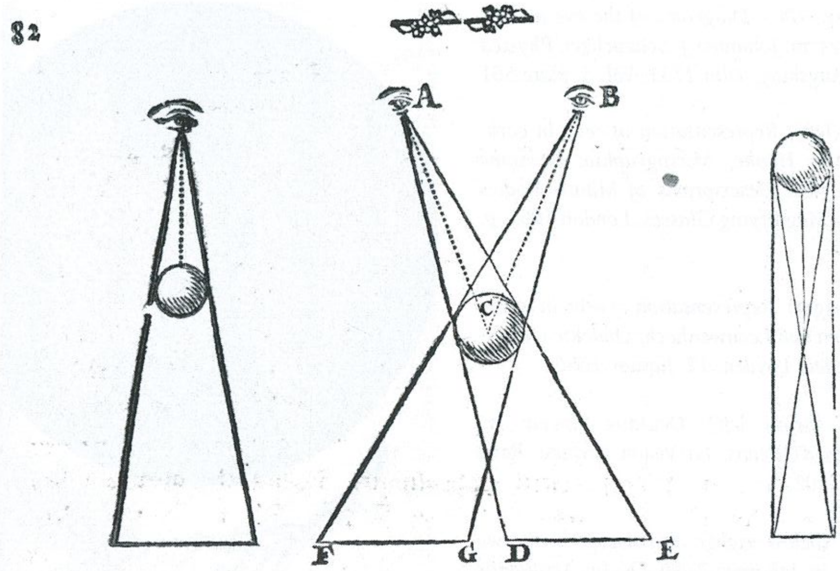


Fig. 15 a (left): Axis Pyramidum Opticarum, in: Abu 'Ali Al Alhazen: Opticae Thesaurus, c. 1000 (translated by Vitello, Basel 1572, p. 76)

Fig. 15 b (right): Die Sehstrahlen, in: Leonardo da Vinci; Praktisches Werk von der Mahlerey, (transl.) Nürnberg 1786, p. 82

Fig. 15 c (p. 703, left): Illustration of the different projections of an object to each eye, in: Sébastien LeClerc, Discours touchant le point de vue, dans lequel il est prouvé que les choses qu'on voit distinctement ne sont vue d'un oeil, Paris 1679

fig. 16 (p. 703, right): Visualisierung von Klangschwingungen, in: Ernst Florens Friedrich Chladni; Entdeckungen über die Theorie des Klanges. Leipzig 1787, plate 1

fig. 17 (p. 703, below): Large listening or transmission trumpets in architecture, in: Athanasius Kircher, Phonurgia Nova. Kempten 1673, p. 162

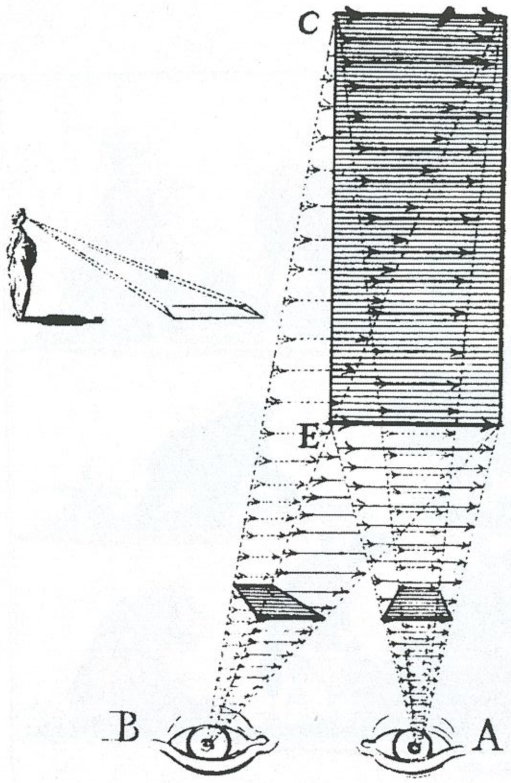
problem with a similar lack of success. Alhazen had represented the ways in which the two eyes can be combined in his book on Optics. The illustrations in the Arabic versions were quite different to those printed in Risner's Latin translation of 1572. In the latter (fig. 15 a) it is clear that neither the dioptrics of the eye nor the visual pathways were adequately understood. The problem that the diagram is attempting to depict is that of binocular single vision – seeing the world as single despite the two slightly different views of it. This was considered to be the dominant problem associated with studies of binocular vision.

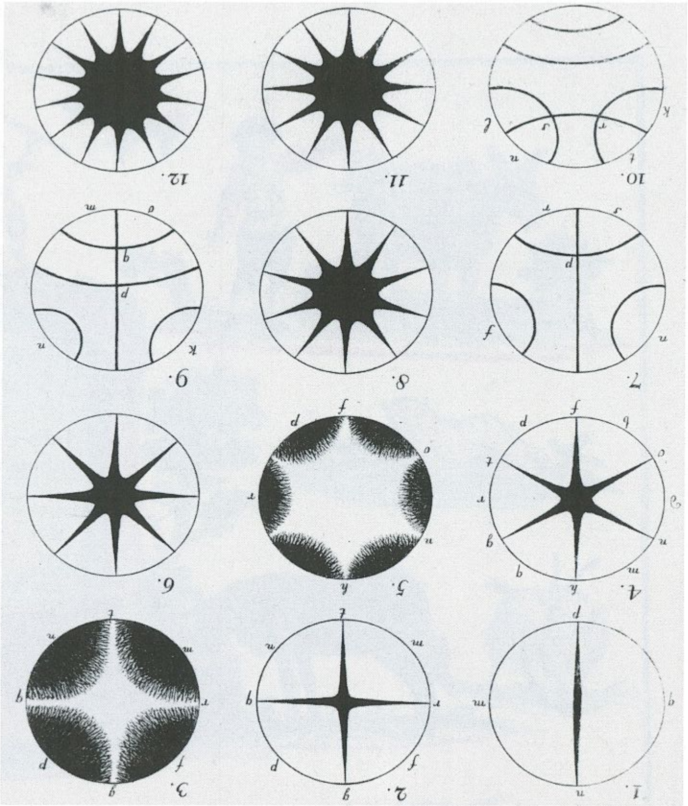
The problem was appreciated by Leonardo, who struggled long and hard to reconcile the difference between viewing a scene and a painting of it: "A Painting, though conducted with the greatest Art and finished to the last Perfection, both with regard to its Contours, its Lights, its Shadows and its Colours, can never show a *Relievo* equal to that of Natural Objects, unless these be viewed at a Distance and with a single Eye". That is, the perception of depth is incomplete in a painting unlike that for a scene viewed with two eyes. He made many diagrams of viewing a sphere with two eyes, one of which is shown in figure 15 b. If the diameter of the sphere is less than the distance between the eyes then it is possible to see the whole background with two eyes, but not with one or in a painting. Wheatstone later wrote: "Had Leonardo da Vinci taken, instead of a sphere, a less simple figure for the purpose of his illustration, a cube for instance, he would not only have observed that the object obscured from each eye a different part of the more distant field of view, but the fact would also perhaps have forced itself upon his attention, that this object itself presented a different appearance to each eye. He failed to do this, and no subsequent writer within my knowledge has supplied the omission".

One of those other writers was Sébastien Le Clerc (1637-1714), an authority on perspective, as well as vision. He made drawings of the different projections of an object to each eye, clearly showing the disparity between the images to the eyes (fig. 15 c). This clear representation of the basis of stereoscopic vision was not used for this purpose, but as evidence against the Cartesian concept of binocular fusion of similar images. It remained for Wheatstone to demonstrate that slightly different images to each eye can yield depth rather than double vision. This he confirmed with the stereoscope, the instrument he both designed and named. Over three hundred years after Leonardo's struggles, the basis for binocular depth perception was demonstrated. The situation was eloquently summarised in Wheatstone's obituary by Signor Volpicelli of the Accademia dei Lincei: "Our countryman, Leonardo da Vinci, in 1500, or thereabouts, conceived and was the first to affirm, that from a picture it was not possible to obtain the effect of relief. But Wheatstone, reflecting profoundly in 1838, on the physiology of vision, invented the catoptric stereoscope, with which he philosophically solved the problem of the optical and virtual production of relief".

Sound

It might seem more difficult to visualise sound than sight, but one area in which this has proved successful is in acoustic figures. Hooke demonstrated that fine flour spread





over a surface will form distinctive patterns when the surface is set into vibration. He also produced similar effects by sounding a bell. However, the scientist who examined these acoustic figures in most detail was Ernst Chladni (1756-1827). The procedure was described later in the following way "Scattering fine sand over the plate, I damp the middle point of one of its edges by touching it with my finger nail, and draw a bow across the edge of the plate, near one of the corners. The sand is tossed away from certain parts of the surface, and collects along two *nodal lines* which divide the large square into four smaller ones." The figures produced could be simple or complex, depending on how and where the plate was damped. Chladni illustrated the figures in a series of books (fig. 16), and they became known as Chladni figures.

Both Hooke and Newton described ear trumpets as aids to hearing, and Hooke speculated that it should be possible to hear the internal movements of the body by means of a suitable instrument. It took many years before such specific auditory instruments were devised in the context of medicine. In the nineteenth century, Laennec invented a simple tube that could amplify sounds from the chest when placed between ear and chest; it became called a stethoscope. However, elaborate ear trumpets were shown by Kircher in his book on sound. Not only did he illustrate different forms of ear trumpet, but he also applied the same principle on a larger scale to transmitting sounds between different parts of a building (fig. 17).

The visualisation of acoustic figures stimulated research in vision as well as sound and it resulted in the discovery of several novel visual phenomena! Thus, visualisation provides more than a means of communicating scientific ideas, it can even generate new illusions.

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