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Light and sight since antiquity

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"The phenomena of light and vision could not pass wholly unnoticed by those who gave the least attention to the works of nature, especially if they had any desire to know the cause of appearances, and the manner in which they are produced. But the first conjectures we meet with upon this subject, it must be owned, were not very promising."

(Priestley 1772, page 1)

Abstract. Light and sight were not distinguished from one another until the dioptrics and the anatomy of the eye had been adequately described in the seventeenth century. A survey of early theories of light is presented, together with descriptions of developing knowledge of ocular anatomy. Once the analogy between the eye and a camera had been made, the problem of accommodation was exposed, and corrections for errors of refraction could be given theoretical support. Theories of accommodation in the seventeenth and eighteenth centuries are briefly reviewed, as is the early history of eye glasses.

1 Introduction

One reason for Priestley's (1772) salutary start to his history of vision, light, and colours was that the distinction between light and sight was not seriously entertained until the optical properties of the eye had been described by Kepler (1604, 1611). At about the same time, the gross anatomy of the eye was appropriately depicted by Scheiner (1619) who also experimented with an artificial eye, thereby exposing the problem of accommodation. Early approaches to the study of light and its passage through the eye will be surveyed here. That is, the nature of light, the anatomy of the eye and visual pathways, and the process of accommodation will be treated in a chronological sequence. Most attention is paid to optics in antiquity, but forays as far as the eighteenth century will occasionally be made. Early descriptions of visual phenomena can be found in Wade (1996, 1998).

In antiquity, sight was essential to the study of optics, and disorders of sight influenced theories of vision. Ophthalmology has a longer recorded history than optics: several surviving papyri dating from the second millenium BC describe disorders and treatments of the eye. For example, the Ebers papyrus describes dimness of sight and strabismus (see Bryan 1930). A millenium later, there were specialists in diseases of the eye practicing in Egypt. An illustration of a cataract operation of the type that was probably performed almost two thousand years ago was redrawn by Thorwald (1962), and written records indicate that such operations had been conducted a thousand years earlier (see Magnus 1901). Greek medicine profitted greatly from these earlier endeavours, and added to them. Neither Egyptian nor Greek ophthalmology was free from the mystical and metaphysical, and observation was frequently subservient to philosophical doctrine.

Ideas about the nature of light itself 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 (Beare 1906). 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. 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 mediaeval *Perspectiva* (see Crombie 1952; Lindberg 1976; Sabra 1989). 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 Kepler, who portrayed the manner in which images are formed on the retina; for colour it was Newton, 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 after Kepler, Newton (1704) published his mature theory of light and colours in his *Opticks*.

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" (Lindberg 1976, page x). It certainly did provide a secure platform from which the analysis of vision could proceed but, from the psychological point of view, Lindberg's 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, Gibson (1966) took this to be a pseudoproblem, and others have referred to this 'legacy of Kepler' as having reduced the problem to the analysis of single, static retinal images rather than considering the starting point as binocular and dynamic (Wade 1990). The relationship between the inverted and reversed retinal image and perception was treated circumspectly by Kepler himself: "I leave it to the natural philosophers to discuss the way in which this image or picture is put together by the spiritual principles of vision" (Crombie 1964, page 147). Natural philosophers have not subsequently spoken with a single voice, but they have appreciated that physical optics is not the solution to vision. The policy I will adopt is to restrict consideration of the physical dimensions of light mainly to the period in which it was confounded with the psychological. The disputes between corpuscular and wave theorists will only be touched upon here; detailed appraisals can be found in Ronchi (1970) and Ziggelaar (1993).

2 Light

Most speculations about sight, advanced by Greek thinkers over many centuries, incorporated elemental philosophy—fire, earth, water, and air permeated perception. Touch was often taken as the most important sense, and the one to which others could be related; qualities associated with it, like hot, cold, moist, and dry, were thought to be common to all the senses, and were in turn linked to the four elements. Thus, vision was generally considered to involve some process of contact between the eye and objects (see Beare 1906; Lindberg 1978), and several means of achieving this contact were advanced.

These included various versions of emission or extramission theories, in which light originated in the eye and was projected from it. Reception or intromission theories, in which light travelled from objects to the eye, were also advanced, as were speculations incorporating aspects of both emission and reception. Emission theories could have been founded on the experience of light when pressure is applied to the eye (see Beare 1906; Grüsser and Hagner 1990), and they are consistent with the cessation of sight when the eyes are closed. Alcmaeon (c 500 BC) observed the first phenomenon and noted that "the eye obviously has fire within, for when one is struck [this fire] flashes out" (Stratton 1917, page 89). This speculation was extended by Empedocles (c 450 BC), who believed that the eye consisted of an internal fire sending out light like a lantern. He proposed that all the senses contained pores or passages into which something could fit. The passages of the eye were arranged alternately of fire and water, and white was perceived through "fiery pores" whereas black objects were perceived through the "watery" (see Stratton 1917; Siegel 1959). Dimness of sight derived from clogging the passages. Species and individual differences in day and night vision were attributed to the amount of fire in the eye, and the location from which it originated. Alcmaeon made a distinction between perception and thinking on the basis of species differences; he considered that all animals perceive in a similar way, but only humans have the capacity to understand. Empedocles, on the other hand, argued that the two processes are identical.

Theories based on light passing to the eye were proposed by Leucippus (c 430 BC) and supported by his pupil Democritus (c 400 BC) and others (see Ronchi 1970). They could account readily for the absence of sight with eye closure but not for the experience of light when pressure was applied to the eye. What was received by the eye was often more than light, but some image of the object itself. Leucippus, in advancing the equation of touch with all perception, suggested that images were carried from objects to make contact in the eye: "Now we do not actually see the objects coming nearer to us when we perceived them, therefore, they must send to our soul 'something' which represents them, some image, eidola, some kind of shadow or some material simulacrum which envelops bodies, quivers on the surface and can detach itself from them in order to bring to our soul the shape, the colours and all the other qualities of the bodies from which they emanate" (Ronchi 1970, page 7). Since all nature was composed of atoms in motion, according to Democritus, they were continually emitted from objects to compress the air and carry impressions to the eye (see Stratton 1917). The impression was like a copy of the object that could be received by the eye. Thus, the solution to many of the problems of perception that taxed subsequent students of sight was provided prior to any physiological process. The images carried with them the constant features of the objects, and for Democritus these included their three-dimensionality (see Siegel 1970). Democritus is best remembered for his atomic theory of matter which set in train a materialist philosophy that was to resurface with the scientific revolution of the seventeenth century, though its impact on Greek science was more limited.

This theory was amplified by Epicurus (c 300 BC) who also believed that the images retained the shape and colour of the objects themselves. The concept of some copy of objects, carried through the air to the eye, was to have widespread and long-lasting appeal, and it was referred to by many names. Indeed, by the end of the thirteenth century, Roger Bacon was able to list the terms image, species, idol, simulacrum, film, phantasm, form, intention, passion, and impression, that were used by authors of works on vision (Lindberg 1983b), to which could be added the effigies, figures, and membranes of Lucretius (c 56 BC, 1975). There was an obvious source of observational support for such a theory: the image of an object could be seen reflected from the eye of an observer. According to Epicurus, the copies were received by the eye, and so this theory was one of reception.

A combination of emission and reception was proposed by Plato (c 350 BC), although his theory of vision was always subservient to his philosophy of ideal forms (Plato 1896). The senses were not to be trusted because they provided evidence for particulars rather than universals. Plato suggested that light was emitted from both the eye and objects, and vision took place externally where these two streams united. According to Theophrastus: "His view, consequently, may be said to lie midway between the theories of those who say that vision falls upon [its object] and of those who hold that something is borne from visible objects to the [organ of sight]" (Stratton 1917, page 71). One of the difficulties with this theory was that light continued to be emitted from the open eye at night. Plato suggested that we cannot see at night because light is extinguished in darkness, just as heat and dryness are extinguished by cold and dampness. Aristotle was scornful of this speculation stating that neither heat nor dryness were attributes of light. For Plato, as for Aristotle, it was not light but colour that was the principal source of interest in vision. Plato distinguished between light and colour, considering that light had its ultimate source in the sun, but colour was a property of objects themselves.

Aristotle's (c 330 BC) theory is more in line with modern conceptions of light, and accounts of it can be found in his books on the soul and on the senses (see Beare 1906; J A Smith and W D Ross 1910; W D Ross 1913, 1927, 1931). His interests were in observation, and the phenomena he experienced directed the interpretations he proposed. Thus, he queried the emission theory of Empedocles by the simple expedient of testing a prediction that would follow from it: if light was emitted from the eye then vision should be possible at any time the eyes were open, including night time. The fact that the prediction was not supported led him to suggest an alternative theory of the nature of light. Similarly, he distinguished between vision and touch by noting that an object in physical contact with the eye could not be seen. His alternative interpretation was that vision is the result of some movement in the medium separating the eye from the objects perceived. Aristotle denied that the image visible in the eye of another observer was the source of vision: "The image is visible [in the eye] because the eye is smooth [like a mirror]. It exists, however, not in the eye but in the observer; for this phenomenon is only a reflection" (Siegel 1970, page 27). Ronchi (1970) remarked that Aristotle's criticisms of emission and contact theories were concise but his alternatives were not as clearly formulated.

Aristotle's theory was extended by his pupil Theophrastus (c 300 BC), from whom most of our information regarding the earlier theories of vision derives. Indeed, Stratton (1917)—who is perhaps better known for his experiments on adaptation to upright retinal images—went so far as to say that "we are indebted to Theophrastus for more than to all the other ancient authorities combined" (page 16) for a knowledge of Greek psychology before Plato. Not only did Theophrastus describe these theories, but he often criticised them roundly. For example, he attacked the idea proposed by Anaxagoras (c 450 BC) that "seeing is occasioned by the reflection in the eyes" (Stratton 1917, page 97) by noting that perceived size was not related to the size of the reflected image, and that "motion, distance, and size are visual objects and yet produce no image" (Stratton 1917, page 99). He accepted Aristotle's contention that vision acts via the transmission of light through some medium. Thus, light, generated by the sun, was reflected from objects but required a medium (air) through which to travel before it could be received by the eye. The emphasis on the medium, variously called the transparent or the diaphanous, reflected Aristotle's distinction between light as a substance, and light as a motion of the medium. Such motions could be instantaneous, and they could be perceived by many observers simultaneously. Aristotle's conception of light was not, however, widely adopted.

Of the Greek philosophers and mathematicians, Euclid (c 300 BC) assembled and analysed the phenomena of optics most lucidly; his *Optics* consists of seven definitions followed by a series of statements regarding visible consequences of them (see Burton 1945). Euclid followed Plato's lead and defined optics mathematically, thus equating light and sight. Euclid based his optics on the then well-known fact that light travels in straight lines, and pursued the consequences of this with commendable persistence. Vision was restricted to the cone of rays emanating from the eye and meeting the objects within it. The geometrical projections to these objects were lawful, and this lawfulness was applied to vision, too. Thus, Euclid provided not only an account of optical transmission through space, but also a geometrical theory of space perception itself. The perceived dimensions of objects corresponded precisely to the angles they subtended at the eye, and illumination of those objects had its source in the eye. The emissions from Euclid's eyes were referred to as visual rays, and their properties were conflated with a number of phenomenal features. The visual rays were discrete, and so small objects could fall between them, and remain unseen; that is, there is a limit to the dimensions of objects that can be detected, namely a threshold for visual acuity. Moreover, those objects seen by rays in the centre of the visual cone will be seen more clearly than those towards the edge; that is, direct (foveal) vision has better acuity than indirect (peripheral) vision. It followed, as Euclid stated, that nothing could be seen at once in its entirety, implying that the visual rays would move over an object (by moving the eyes) in order to see all its features. The theory was entirely concerned with spatial vision and neither mentioned nor could account for any aspects of sight that involved colour.

Within Greek science, colour was considered in terms of an analogy with the four elements, and of these fire and water were predominant. The numeration of four basic colours was clearly stated by Democritus and these were white, black, red, and green: "each of these colours is the purer the less the admixture of other figures. The other colours are derived from these by mixture" (Stratton 1917, page 135). Moreover, he adapted the concept of pores in the eye to account for colour vision: only when the geometrical shapes associated with particular colours corresponded to those of the pores would colour be experienced. Both Plato and Aristotle considered that colour was of paramount importance in perception, and that it could be dissociated from light. They knew that pigments could be extracted from certain substances, and they were well aware of the ways in which they could be mixed by artists. However, they stressed the importance of black and white: Plato treated them as opposites, and Aristotle considered that all colours could be made up from these two. Perhaps it was the observation that no colours appeared as light as white or as dark as black that led to this speculation (Wasserman 1978). Consequently, despite the equation of colours with the four elements, black and white tended to dominate the analyses of colour. A more detailed description of Greek theories of colour can be found in Beare (1906). The belief in the purity of white was retained by some (like Goethe) long after Newton's experiments on the prismatic spectrum (see Wade 1998).

Greek theories of light were transmitted through the Roman period mostly by Graeco-Roman writers, although the transmission was modulated by a growing desire to integrate optical theories with the practicalities of observation. Lucretius (c 56 BC, 1975) made many references to vision in his poem *De Rerum Natura*; he believed that light (lumen) was emitted from the sun, and when it struck objects it carried images (eidola) of them to the perceiver. Lucretius appreciated that images in themselves would not be useful to perception unless they carried with them some index of the distance the objects were away from the observer, so that its dimensions could be determined. The mechanism that he proposed for this—of the image brushing aside the intervening air—was exceedingly vague, but he was addressing a general problem that exists in all accounts of spatial vision (see Ronchi 1970). Lucretius followed in the line of the Epicureans, but the relative merits of such reception theories were still in conflict with emission theories, as supported by Hero of Alexandria in the first century AD. He divided the science of vision into three parts: optics, dioptrics, and catoptrics (see Cohen and Drabkin 1958). He considered that the velocity of light was infinite, because of the immediate visibility of heavenly bodies upon opening the eyes.

Major advances in the study of optics were made by Ptolemy in the second century. His *Optics* are usually associated with those of Euclid (see Delambre 1812; Lejeune 1948, 1956, 1989; Crombie 1967), but his emphasis on the primacy of colour and on the advantages of observation placed him in closer alignment with Aristotle: for both light served the function of rendering the colour of objects visible. We know relatively little about Ptolemy's theory of light, because the first book of his *Optics* has not survived, but it can be partially reconstructed. What is clear is that his approach was more experimental than those of his predecessors, and that he introduced measurements of both reflected and refracted light. Ptolemy extended Euclid's geometrical optics by incorporating facts of both physical optics and visual perception, and by studying them experimentally (see A M Smith 1996). In particular, he appreciated that light rays should be thought of as continuous rather than discrete in the way Euclid had stated. He proposed that colour was an integral component of light, and he conducted experiments on colour mixing using a rotating colour wheel (see Wade 1996). He argued that visual size cannot be equated with visual angle, and introduced the concept that perceived size was derived from visual angle and distance; that is, he addressed the issue of perceptual constancy (H E Ross and Plug 1998; Wade and Swanston 1996). He was in agreement with Euclid about the variations in visual acuity throughout the visual pyramid (rather than cone). The two pyramids of vision (one for each eye) needed to be integrated and he conducted experiments with a board in order to study this binocular combination (see Crone 1992; Howard and Wade 1996; A M Smith 1996). Ptolemy also realised that illusions occur in vision: "For there are some errors that are caused in all the senses and others that are confined to things seen, of which some are visual and others are in the mind" (Lejeune 1956, page 56). He was one of the first writers to provide a detailed account of illusions. Indeed, he devoted over one third of Book II of his *Optics* to errors of sight; they were classified, and then considered under the headings of colour, position, size, shape, and movement. In short, Ptolemy initiated a reconciliation between physical and psychological analyses of vision which was amplified by Ibn al-Haytham (see Sabra 1989).

Galen was a near contemporary of Ptolemy; both were active in Alexandria and Galen was likely to have been aware of and to have benefitted from a knowledge of Ptolemy's optical investigations (Siegel 1970). Galen addressed matters of sight in the context of anatomy and speculative physiology, though he made many astute observations, particularly in the context of binocular vision. He also ventured, with some misgivings, into the arena of optics. In his book *On the Usefulness of the Parts of the Body* (May 1968) he expressed regret for introducing optical concepts in a medical text, since they were at that time deeply unfashionable. His theory of vision was physiological, and it was based on the pneumatic concepts advocated by Empedocles: pneuma, or visual spirits, passed along the hollow tubes of the optic nerves to interact with returning images of external objects in the crystalline lens: "The lens is the primary organ of vision. It is one of the constituents of the eye and is composed of uniform parts. It is altered by something pertaining to the colors of the outside object which the animal perceives" (Siegel 1970, page 58). Here we find another enduring notion: that the 'seat of vision' resides in the lens of the eye. Indeed, Galen himself supported this proposal by virtue of the blindness that results from cataracts and the sight that is restored when they are surgically removed. By adopting an anatomical and physiological analysis of vision, Galen was confronted with the existence of two eyes and the observation by them of a single visual world. He was able to draw from Ptolemy's analysis of certain aspects of binocular single vision (see Howard and Wade 1996), and to suggest his own physiological theory for its occurrence. The pneuma were unified from a single site in the anatomical process—the optic chiasma—where the two optic nerves were thought to be united.

Little was added to optical theory in the late Roman period, and the Greek texts were retained and copied initially in Byzantium and later in Persia and North Africa (see Crombie 1952; Ronchi 1970; Lindberg 1976, 1983a; Schmitz 1981, 1982). Translations of Greek works into Arabic reached their peak in the ninth and tenth centuries, and they in turn were translated into Latin from the twelfth century (see O'Leary 1949; Lindberg 1992). Because of strictures against dissection, Galen's anatomy and physiology of the eye were generally accepted by Islamic scholars, but they did extend knowledge of optics. Al-Kindi (c 860) summarised the principal theories of optics proposed by Greek philosophers. Vision could follow from intromission, as the atomists like Democritus had argued, by extramission after the manner of Euclid's theory, by some form of Platonic interaction, or via some medium. Al-Kindi rejected three of the four possibilities, adopting a Euclidean extramission theory. His rejection of the others was largely a negation of any form of intromission in the process of vision (see Lindberg 1976). The difficulty with theories incorporating intromission was conceived in terms of the contrast between optical projection to a point (the eye) and perceptual constancy: the former underwent many variations that were not evident in the latter. This apparent conflict between perspective and perception was to influence mediaeval scholars, too.

Both Avicenna (c 1020) and Ibn al-Haytham (c 1040) accepted that the crystalline lens was the receptive organ for vision, although Ibn al-Haytham did hint at times that the retina was involved, too. Ibn al-Haytham was a mathematician who hailed from Basra and later worked in Cairo. It is said that he rashly predicted that he could regulate the flow of the Nile; he first saw the Nile on being invited to match his promise, and realised the folly of his assertion, which he then retracted. Salvation from the wrath of the Caliph was sought by simulating insanity, and finally finding refuge in a Cairo mosque, where he taught and wrote for the rest of his life. He was very familiar with the writings of Euclid and Ptolemy, as he supplemented his income by making translations of them (Sabra 1989). However, he adopted a theory of light similar to that of Aristotle, in which the medium was of prime importance. Ibn al-Haytham's book on optics had virtually no impact on his contemporaries, but it was rediscovered almost two centuries later, and translated into Latin in the thirteenth century. His name was latinized in a variety of ways (of which Alhazen was the most common) and his book on optics was translated as either *Perspectiva* or *De Aspectibus*. It was this book which awakened Western scholars like Roger Bacon (c 1270, Burke 1928), Vitellonis (or Witelo, c 1275, A M Smith 1983), and John Pecham (c 1280, Lindberg 1970) to the physics of light, its mathematical treatment, and its application to vision. Later still, in 1572, Alhazen's *Opticae Thesaurus* was published, together with Witelo's *Perspectiva*, in a single volume, edited by Freidrich Risner. It was in Kepler's (1604) reaction to the latter, that among the things omitted by Witelo was the optical analysis of the retinal image. The mediaeval *Perspectiva* was principally about direct vision, that is visual optics rather than catoptrics or dioptrics. They shared a common assumption that vision should be analysed in terms of a pyramid with its base on external objects and its apex located on the surface of or in the eye. This perspective pyramid carried with it the problems posed by Al-Kindi, namely the conflict between optical projection and visual perception. One consequence of this was to treat perception with great suspicion, while accepting the validity of perspective projections. Thus, through much of the late mediaeval period considerably more attention was directed to physical than to psychological dimensions of optics (Ronchi 1970; Meyering 1989).

Grosseteste (c 1250) is not considered to have had access to Alhazen's *De Aspectibus*, and his analysis of light and vision was Platonic, with light emitted from the eye interacting with that reflected from objects (see Grüsser and Hagner 1990). In the fifth century, Plato's distinction between the material, sensual body and the rational soul had been incorporated into Christian theology by St Augustine, and it even permeated the nature of light: spiritual light was the internal illuminant of ideal forms, and physical light was considered to be analogous to this (Crombie 1953). The ideal forms were rarely encountered in perspective projections; they were present in the mind and could be illuminated by divine light. Hence we find the emergence of distinctions between different forms of lights—lux and lumen—which were maintained from the time of Albertus Magnus (c 1250, see Dewan 1980) to Reisch (1503). Lumen was external light, as from the sun or fire, whereas lux was perceived light.

The impact of absorbing the optics of Ptolemy (which had been translated into Latin in the twelfth century) and of Ibn al-Haytham is clear in the contrast between Grosseteste and Roger Bacon. For Bacon pyramids of light strike the eye, but the physiological dimension remained Galenic. The crystalline lens was still taken to be the 'seat of vision' and 'species' remained a part of the process. Binocular combination was achieved at the optic chiasma: "We are to understand, moreover, that from the common nerve an imaginary straight line is directed between the two eyes and the object seen, meeting the axes of the eyes in the same part of the object seen, and this is the common axis" (Burke 1928, page 511). Objects peripheral to the common axis was not seen as distinctly.

The science of optics remained relatively unchanged in the late mediaeval period. In the sixteenth century both Maurolico and Porta continued the tradition of the early mediaeval perspectivists, and also described the refraction of light through lenses. Porta likened the camera obscura to the eye in the second edition of his popular treatise *Magiae Naturalis* (1589), and he wrote a more serious book on vision, *De Refractione*, four years later. The work of Maurolico contains strands that were to be amplified by Kepler (1604), although his work was unlikely to have been available to the latter (see Ronchi 1970). It was written in manuscript form between about 1520 and 1555 but it was not published until 1611, after Kepler's (1604) critique of Witelo's *Perspectiva*. Witelo's work was widely circulated towards the end of the sixteenth century: as noted above, it had been edited and published by Risner in 1572, together with Alhazen's *Opticae Thesaurus*, and it was these analyses of optics that stimulated Kepler's interests.

The confusions about the nature of light at the end of the sixteenth century were crystallised by Laurentius (1599/1938). He compared and contrasted the emission and reception theories of Plato and Aristotle. Among the nine "Reasons to proue that we see, by sending foorth something" were: "Wherefore should the eye grow weake with looking, but because there commeth out of it too much light, and that all the spirits vanish and fade away? Whence commeth it that such as would see a very little thing a far off, do claspe their eyes, & halfe close their eyelids? Is it not that so they may vnite the beames, and joyne together the spirits, to the end that afterwards they may cast them out more forcibly and directly?" (pages 38–39). While Plato suggested that there was fire or light in the eye, Aristotle's eye was filled with water, and Laurentius found the demonstrable support for the latter to be ample proof of Aristotle's theory. Nonetheless, he did provide "Reasons prouing that we see by taking in something"; in the main these were repetitions of Aristotle's observations about the passivity of sensation generally, responses to intense lights, and dimness of sight in old age.

Physical optics came of age in the seventeenth century (see Mach 1926; Sabra 1967; Ronchi 1970). In addition to his *Ad Vitellionem Paralipomena* of 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 Rubens in the frontispiece to Book V of Aguilonius (1613). The light from candles passes through two circular apertures on to a screen; a septum ensures that each aperture receives light from one source only. In Rubens's engraving the light from a single candle at one distance is equal to that from two at about twice the distance. It is probable that Aguilonius was neither aware of nor subscribed to Kepler's inverse-square formulation (see Ziggelaar 1983), but he did provide the experimental basis on which photometry would be built in the next century by Bouguer (1729, 1760) and Lambert (1760). Kepler devoted considerable attention to refraction in *Dioptrice*, but he did not determine the general sine law. Willebrord Snell (c 1581 – 1626), in an unpublished manuscript written around 1621, described the relationship between angles of incidence and refraction, upon which the subsequent technical advances in optical instrument manufacture were based. He did not use sines in his formulation, but the dimensions that he described are equivalent (Vollgraff 1936).

Snell's law, as it became known, was elaborated by Descartes (1637/1902, 1965) in his *Dioptrique*, and he treated the analysis of the rainbow in his discourses on meteorology (see Boyer 1987). His experimental approach to displaying the prismatic spectrum was somewhat different to that adopted later by Newton (1704); sunlight fell normally on one face of the prism, and was refracted at the second face, upon which the aperture was placed; he noted that the distinctness of the spectrum was dependent on the size of the aperture. His mechanistic interpretation of visible colours was in harmony with his concept of light generally: colours corresponded to different rates of rotation of bodies in the medium.

Had Huygens not been aware of Snell's manuscript and made reference to it in his *Dioptrique* (1653), the relation between sines of the angles of incidence and refraction might have been called Descartes's law (see Montucla 1758). In his *Traité de la Lumière* (1690, 1912) Huygens made analogies between mechanical events like projectiles bouncing from surfaces, and applied these to reflections and refractions of light. Light, according to Descartes, acted like a mechanical force which is transmitted through transparent media. His theory of light attracted much criticism in his day because of the inconsistencies it embraced. On the one hand he argued that light was propagated instantly, and on the other that it varied its velocity according to the density of the medium through which it travelled.

The phenomenon of diffraction was demonstrated by Grimaldi (1665), who suggested that light might act like a liquid, flowing in waves. Wave theory was supported and extended by Huygens: he 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 analysed in terms of the wavefronts originating at the aperture. In contrast, Newton proposed that light consisted of small corpuscles which collided with one another (see Shapiro 1980). Thereafter, the theoretical contrast was between Huygens's wave theory and Newton's corpuscular theory of light (see Sabra 1967; Ronchi 1970; Cantor 1977).

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.

3 Sight

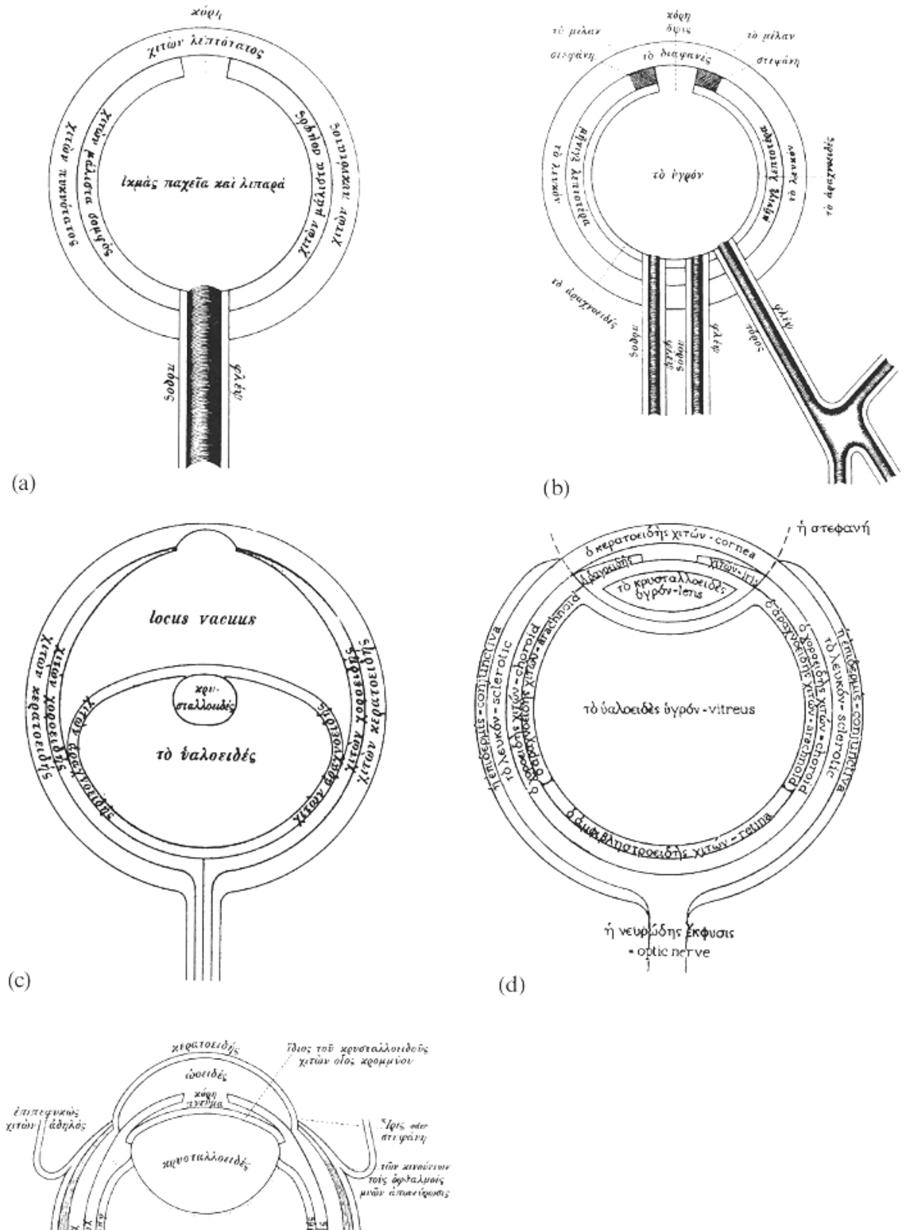
Well over two thousand years ago there were medical practitioners in Babylon, Mesopotamia, and Egypt, some of whom were eye specialists; they must have had a working knowledge of ocular anatomy in order to carry out the operations they are known to have performed. However, the records that have survived (for example in the Ebers papyrus) relate mainly to the fees they charged and the penalties they suffered for faulty operations rather than the conditions they cured (see Hirschberg 1899; Shastid 1917; Duke-Elder 1961). Their skills and understanding would have been passed on to Greek physicians, who both developed and recorded them. Many Greek texts, through their translations, have been transmitted to us, but any illustrations that they might have included have not survived. This void has been filled by Magnus (1901), who has redrawn diagrams of the eye to reflect the written accounts of ocular anatomy in the Greek period. Sudhoff's (1907) counsel of caution should be repeated when interpreting these reconstructions: in producing these illustrations Magnus would have found it difficult to exclude his knowledge of both anatomy and perspective, so the reconstructions would have appeared very strange to the authors to whom they are attributed. In this regard, it is instructive to compare Galen's eye (figure 1e, after Magnus) with the fragment of a manuscript drawing that is reproduced in May's (1968) translation of Galen. The latter is a much cruder representation that does not bear a great deal of similarity to the reconstruction by Magnus, but both would have been derived from text alone. Moreover, not all those to whom diagrams of the eye are attributed would have based their knowledge on dissections of animal or human eyes: perhaps only Aristotle and Galen would have recorded their own observations.

Sight will be considered here first in terms of the anatomical structure of the eye and its comparison with a camera. One consequence of the latter was a concentration on the problem of accommodation. Helmholtz (1873) summarised the situation thus: "The mechanism by which this is accomplished ... was one of the greatest riddles of the physiology of the eye since the time of Kepler.... No problem in optics has given rise to so many contradictory theories as this" (page 205). Corrections for errors of refraction have a longer history still, and this will be touched upon briefly before describing some of the early views about the retina and the paths taken by the optic nerves to the brain.

3.1 *The eye*

The initial Greek speculations about the anatomy of the eye, like those advanced by Empedocles, were founded in philosophy: the four elements of fire, earth, water, and air, led to the proposition that there must be four coats to the eye. The optic nerve was described by Alcmaeon in the sixth century BC, and it was thought of as a hollow tube, enabling humours to pass from the brain to the eye. About a century later Democritus provided a more detailed description of the eye (figure 1a). It was a simple spherical structure consisting of two coats enclosing a humour that could pass along the hollow optic nerve, after the manner proposed by Alcmaeon. Light could pass through the aperture (pupil) and no lens was represented within the eye. The optic nerve left the eye in the line of the optic axis.

The dominance of philosophy over observation was partially reversed for the school of Æsculapius that emerged in the fifth century BC, of which Hippocrates (c 460 – 370 BC) was a member. Naturalistic observation partially replaced superstition, but the examination of anatomical organs was prohibited at that time (see Garrison 1914; Osler 1921; Singer 1925; Choulant 1945). The moral strictures of the day did not countenance dissection of dead bodies, although this was soon to change with the Platonic dissociation of the body from the soul. It is known that Aristotle did dissect the eyes of animals, and he is believed to have written at least one book (now lost) on the eye (see Diogenes Laertius 1959). Drawing on the evidence from dissection marked the dawning of more exact knowledge of the structure of the eye. Aristotle's diagram (figure 1b) shows three coats enclosing the humour, supplied by three ducts "From the eye there go three ducts to the brain: the largest and the medium-sized to



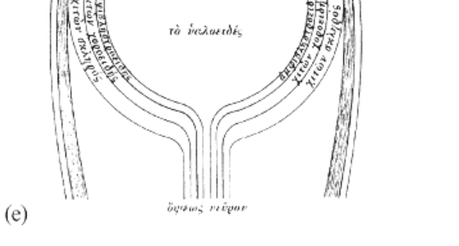


Figure 1. Magnus's (1901) reconstructions of drawings of the eye after written descriptions by: (a) Democritus (c 460 – 370 BC); (b) Aristotle (c 384 – 322 BC); (c) Celsus (c 25 BC – 29 AD); (d) Rufus of Ephesus (fl 100) with English names added by Singer (1921); (e) Galen (c 130 – 200).

the cerebellum, the least to the brain itself; and the least is the one situated nearest to the nostrils. The two largest ones, then, run side by side and do not meet; the medium-sized ones meet—and this is particularly visible in fishes—for they lie nearer than the large ones to the brain; the smallest pair are the most widely separate from one another, and do not meet" (J A Smith and W D Ross 1910, page 495a). The lens was probably not included because its appearance was assumed to be an artifact of dissecting a dead eye.

In the first century AD, the Roman writer Celsus (c 25 BC – 29 AD) drew together the Greek knowledge of medicine. The drawing of the eye attributed to him (figure 1c) did represent the lens although it was located in the centre of the eye. The anterior chamber was described as an empty space and it was separated from the posterior by a membrane, to which the lens was attached: "This is enclosed by a small membrane, which proceeds from the internal part of the eye. Under these is a drop of humor, resembling the white of an egg, from which proceeds the faculty of vision. By the Greeks it is called chrystalloides" (Shastid 1917, page 8581). As was noted above, the notion that the lens was the seat of vision, which was amplified by Galen, was to survive for many centuries.

The lens was more accurately located in Magnus's drawing (figure 1d) based on the writings of Rufus of Ephesus (c 100), and the vitreous humour lay between it and the retina. The vitreous was completely enclosed and the optic nerve was not continuous with it, unlike in Galen's diagram (figure 1e). In the latter the anterior and posterior curvatures of the lens were distinguished, and two of the extraocular muscles were shown. Rufus wrote of the lens that "at first this had no special name, but later it was named *lentil-like* on account of its form, and *crystalline* on account of the character of its humour" (Singer 1921, page 389).

One of the greatest of the Greek anatomists was Galen of Pergamum (c 130 – 200). He practiced medicine in Alexandria and Rome as well as in Pergamum. Galen based his anatomy on dissections of animals, particularly monkeys, but most of his ocular anatomy was derived from dissecting the eyes of freshly slaughtered oxen (Siegel 1970). He drew extensively on the anatomical writings of Herophilus (c 300 BC), which are now lost, and on the physiological speculations of Erasistratus (c 290 BC), both of whom based them on dissections of human and animal bodies (see Singer 1925). The restrictions that were subsequently placed on dissections resulted in a reliance on Greek (and particularly Galen's) works on anatomy, and they were recounted dogmatically until the time of Vesalius over one thousand years later. The journey from Galen to Vesalius was tortuous, not least for those who required surgery. The disinterest in science and medicine after the sacking of Rome in the fifth century left Europe in the 'Dark Ages', but Greek anatomical wisdom was retained by Islamic scholars, who translated many books into Arabic and eventually transmitted them to late mediaeval students (O'Leary 1949).

Galen's medical works were translated into Arabic by Hunain ibn Is-hâq (c 807 – 877). The earliest surviving diagrams of the eye are to be found in Islamic manuscripts (see Meyerhof 1928; Polyak 1942, 1957), of which that by Hunain ibn Is-hâq (figure 2a) is probably the oldest. It is essentially a functional diagram, since it adopts different viewpoints for different parts of the eye. This could be the reason why the pupil and the lens are shown in circular form, and the lens is situated in the middle of the eye. The extraocular muscles were also illustrated (figures 2c and 2d). Hunain ibn Is-hâq's illustration was copied several times in the centuries that followed. Thus, Arabic accounts of the eye drew on Galen for inspiration, but their illustrations reflect a greater concern with geometry than anatomy. This is also the case for the diagrams corresponding to Ibn al-Haytham's text. The Arabic manuscript represents two eyes, and incorporates the meeting of the optic nerves at the optic chiasma (see Polyak 1942). Ibn al-Haytham added greatly to the understanding of binocular vision, which was probably the reason for representing two eyes. The illustration of the eye that was printed in Risner's translation of Alhazen and Witelo published in 1572 is essentially similar to that of Vesalius, and shows a single eye.

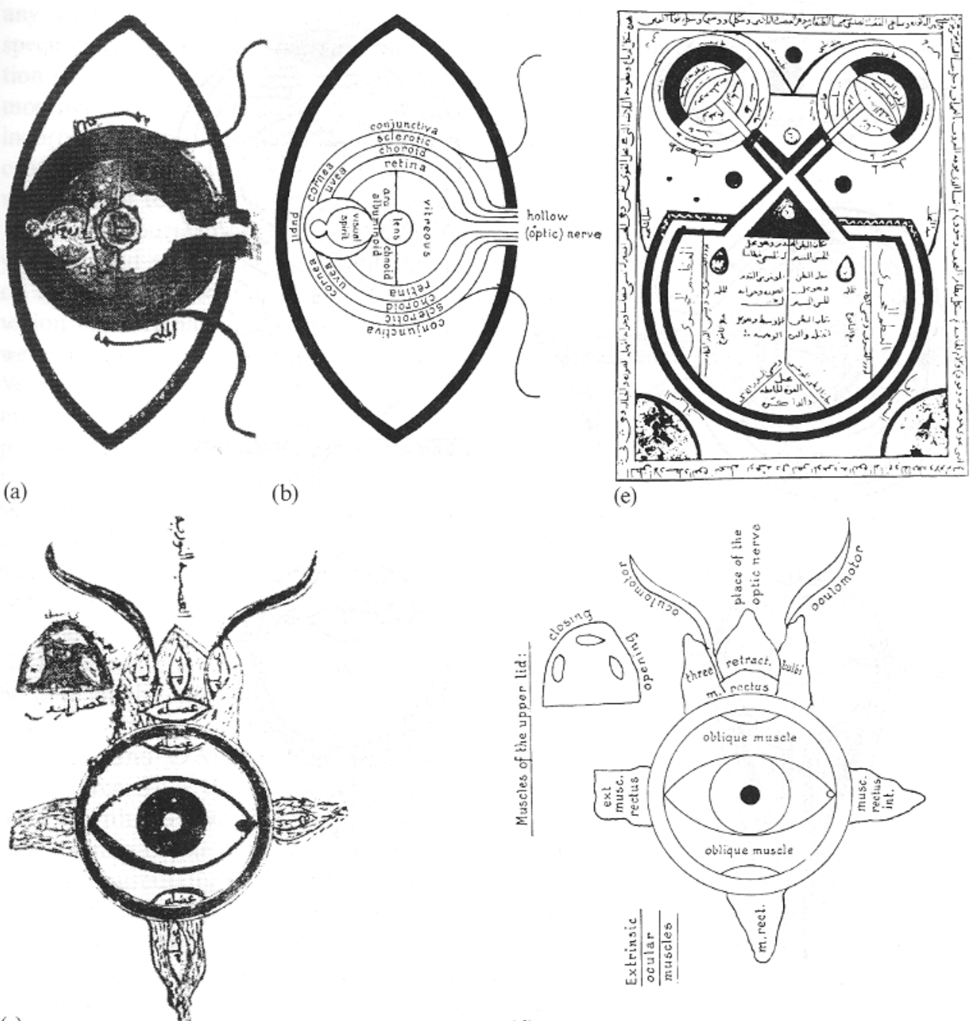
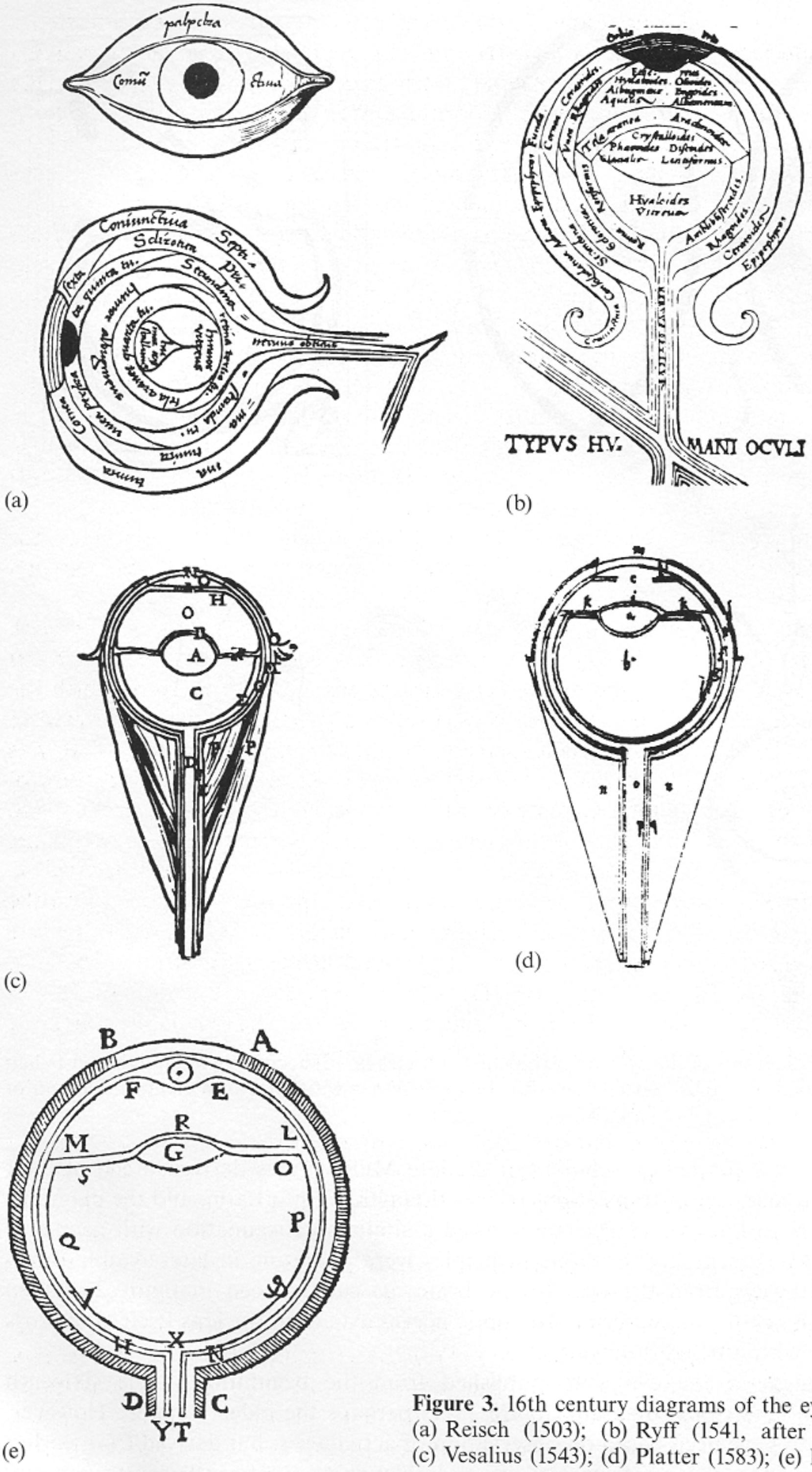


Figure 2. Arabic diagrams of the eye and extraocular muscles (a – d) according to Hunain ibn Is-hâq (c 808 – 873) labeled in English (after Meyerhof 1928), together with (e) a 16th century diagram of the visual pathways (after Choulant 1945).

As was the case for optics, scholars in the late Middle Ages derived much of their knowledge from manuscript translations of Ibn al-Haytham into Latin, and the diagrams of the eyes by both Bacon and Pecham showed a similar preoccupation with geometry (see Polyak 1942). Essentially the same principles were operating in later Arabic drawings of the pathways from the eyes to the brain, as can be seen in figure 2e, taken from a sixteenth century manuscript. The optic nerves extend to the lens itself, and cross at the chiasma with a delightful symmetry.

Printed figures of the eye were published from the beginning of the sixteenth century, and Reisch's (1503) diagram (figure 3a) is perhaps the oldest version. However, this is unlikely to have been based on observation of actual eyes, but derived from earlier manuscript drawings; it does bear a close resemblance to a fifteenth century manuscript drawing based on concentric circles (see Sudhoff 1907; Choulant 1945). Reisch wrote his encyclopaedia as a guide for the Carthusian monks in his order. The section including the diagram of the eye is but a small part of the work, and does not suggest



(a) (b) (c) (d) (e)

Figure 3. 16th century diagrams of the eye according to: (a) Reisch (1503); (b) Ryff (1541, after Sudhoff 1907); (c) Vesalius (1543); (d) Platter (1583); (e) Porta (1593).

any active pursuit of ocular anatomy. A similar diagram (figure 3b) was printed in a specifically anatomical book by Ryff (1541), with an improvement in the representation of the crystalline: it took on a lenticular rather than a spherical shape. This slight modification does suggest that the benefits of direct observation were beginning to be incorporated into anatomical drawings. Ryff's diagram was frequently copied in the century that followed (Choulant 1945). Very shortly thereafter, the genius of Vesalius was brought to bear on the topic, and the modern era of anatomy was founded.

In the fourteenth century the sanctions prohibiting dissection of human bodies were relaxed and knowledge concerning anatomy in general slowly began to be based on more secure ground, although the descriptions were not always accurate and observation often remained a slave to Galenic dogma. The dissecting skills of the anatomist were critical, and the major advances came with practitioners like Leonardo da Vinci and Vesalius. Leonardo's detailed drawings of dissections made little contemporary impact in the early sixteenth century because they remained both in manuscript form and in private hands (MacCurdy 1938). Unlike his anatomical drawings of the musculature, those of the eye displayed a conflation of dissection and dogma: his rather crude sketches reflected a reliance on Galen, even though he did prepare the excised eye for dissection (by boiling it in the white of an egg). His drawings of the eye showed the lens as spherical and central in the eye, and the optic nerves passed to the cerebral ventricles (see McMurrich 1930; Gross 1995).

The renaissance of anatomy is associated with Vesalius, who published his book *De Humani Corporis Fabrica* in 1543. It is taken to be a synthesis of science and art because of the high quality of the anatomical illustrations. The blocks from which the woodcuts were printed survived into the twentieth century, and they were reprinted in Saunders and O'Malley (1950). Vesalius presented an account of anatomy that was almost free from the legacy of Galen. While Vesalius could examine the structure of the eye with his own rather than Galen's eyes, he did not pay too much attention to it. His diagram of the eye (figure 3c) did not match the detail or accuracy of those for the skeletal musculature and internal organs: a symmetrical lens was still located in the centre of the eye and the optic nerve was situated on the optic axis. He listed the various structures, but did not pursue their function in any detail. Thus, there was the crystalline lens (A) and ciliary processes (K), the aqueous and vitreous humours (O and C), the retina (E), the optic nerve (D), and the extraocular muscles (P). Platter (1583) moved the lens towards the pupil and recorded the differences between the curvatures of its front and back surfaces (figure 3d), otherwise the structures were essentially similar to those described by Vesalius, as was the case for Porta's (1593) diagram (figure 3e).

Fabricius ab Aquapendente (1600) placed the lens appropriately, and defined the optical centres of several surfaces of the eye (figure 4a). The optic nerve left the eye centrally in these diagrams, but there is a hint of its lateral shift in the diagram (figure 4b) from Aguilonius (1613). A few years later Scheiner (1619), another Jesuit scholar, gave the first accurate diagram of the eye (figure 4c); 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 (eg Polyak 1957; Finger 1994), 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 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

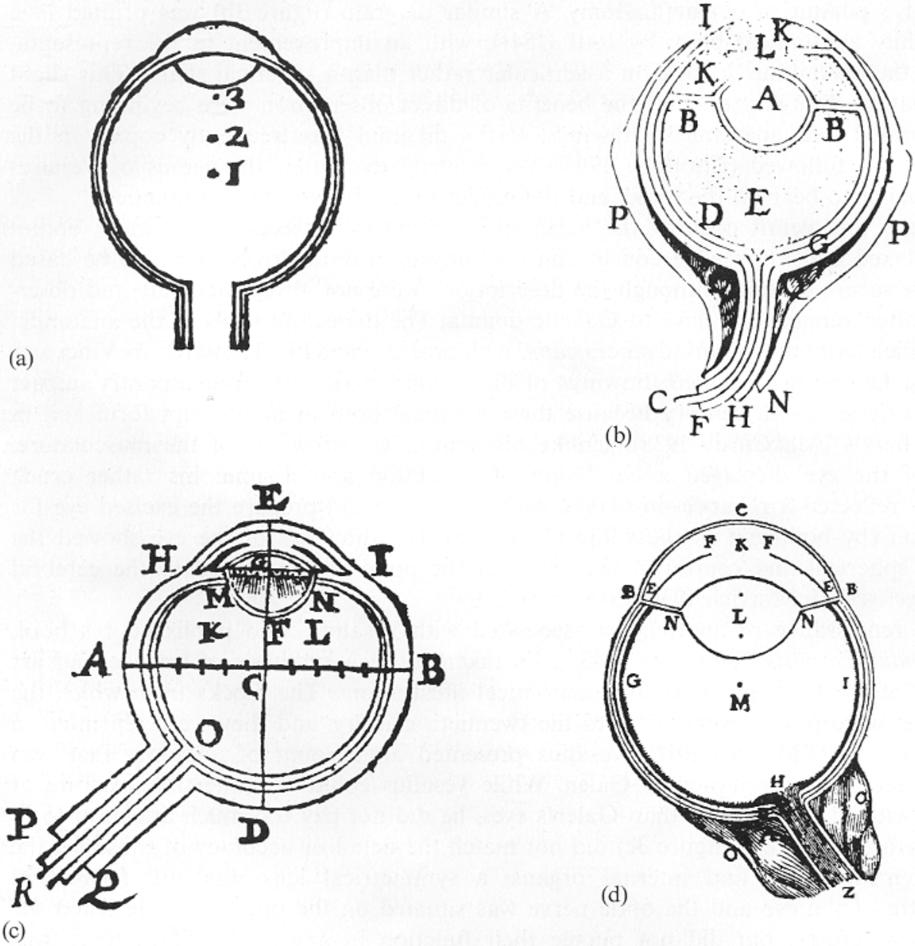


Figure 4. 17th century diagrams of the eye according to: (a) Fabricius ab Aquapendente (1600); (b) Aguilonius (1613); (c) Scheiner (1619); (d) Descartes (1637/1902).

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" (1619, page 18). Scheiner's analysis was rapidly absorbed both by anatomists and by philosophers, as is evident in figure 4d taken from Descartes's (1637) *Dioptrique*.

3.2 *Artificial eyes*

Scheiner drew parallels between artificial and natural image formation in his book *Oculus* (1619), and he described how an artificial eye could be constructed. Some years later, Scheiner (1630) presented a pictorial analysis of optical image formation in the camera and the eye—with both inverted and upright images due to the addition of convex and concave lenses. He noted that an upright retinal image resulted in inverted vision. Furthermore, Scheiner described how an image could be seen on the exposed surface of an excised animal's eye—an experiment he "had often performed". The most familiar illustration of image formation in an excised eye is that from Descartes's *Dioptrique* (1637), in which the cosmic observer ponders on the spatial arrangement of the inverted and reversed retinal image. Descartes was able to provide a more precise analysis of image formation because he could apply Snell's law to the refractions taking place. The analysis was essentially repeated in his *Treatise of Man* (Hall 1972), but slightly different diagrams were printed in *De Homine* (1662) and in *Traité de l'Homme* (1664).

The general principles of image formation have a much longer history. Shadow casting was known to scientists in China as early as the fifth century BC, and the practical optics of the camera obscura, or dark chamber, were described by Chinese scientists in the ninth century (Needham 1954; Hammond 1981). Little in the way of a theory of image formation is considered to have derived from these experimental enquiries. Ibn al-Haytham described an inverted image in a dark chamber, and pinhole experiments were conducted by late mediaeval students of optics (Waterhouse 1902; Lindberg 1983a; Sabra 1989). However, the equation of such optical image-forming devices with the eye appeared much later. Leonardo da Vinci (c 1500) conducted experiments with a camera obscura, and drew an analogy between its operation and that of the eye (see Keele 1955; Strong 1979; Eastwood 1989). In this regard, as in many others, his ideas were neither published nor widely known until long after his death. Another artist, Barbaro (1569), recommended the assistance that the camera obscura could offer to the painter, particularly when a convex lens was placed in an enlarged aperture (see Mayor 1946). A powerful convex lens was recommended, and the sharpest image could be located by moving a sheet of paper towards or away from the aperture. He also realised that the sharpness of the image could be further enhanced by reducing the size of the aperture through which the light entered the dark room.

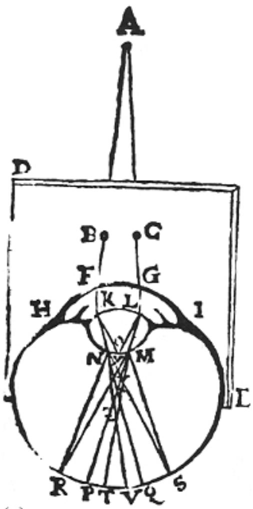
Despite these earlier accounts, it is Porta who has most frequently been accorded the distinction of equating the optics of a camera with those of the eye. This is not because he was the first to reach that conclusion, but because his description in the second edition of *Magiae Naturalis* (1589) was the most widely read and widely cited. In their histories of optics Montucla (1758), Priestley (1772), and Wilde (1838) all credited Porta with inventing the camera obscura. The *Magiae Naturalis* was an amalgam of mysticism, folklore, and science; it was reprinted in many editions and translated into several languages. Porta concluded that forming an image on a surface was an adequate account of "how vision is made", but he still considered that the image in the eye was formed on the rear surface of the lens. A few years earlier, Felix Platter (1583) had suggested that the retina was the sensitive organ of vision, and a few years later, Kepler (1604) gave the correct description of image formation on the retina. Kepler achieved this analysis without an adequate appreciation of the laws of refraction; Snell's sine law was not made known until a few decades later, and Kepler had based his analysis on an approximation to the law. Laurentius (1599/1938) also likened the eye to a camera: "Finally, the eye is like vnto the looking glasse, and this receiueth all such shapes as are brought vnto it, without sending any thing of it owne vnto the object. They differ onely in this, that the looking glasse hath no power to recommend his formes and shapes vnto their judge, as the eye doth vnto the common sense by the nerue opticke" (pages 41 – 42).

It is clear from Scheiner's analysis that the equation of eye and camera raised issues of focusing (or accommodation) within the optical system. These were given more detailed consideration by Rohault (1671), who constructed a large artificial eye, and conducted a series of experiments with it: "The opake Coats, or Tunicks, were all made of thick Paper, except the *Retina*, which was made of a very white thin Piece of Vellum; in the Room of the *Tunica cornea*, I put a transparent Glass, and instead of the Chrystalline Humour, was a Piece of Chrystal of the Figure of a Lens, but more flat than this Humour; for since there was nothing in this Machine but Air, in the Places of the aqueous and vitreous Humours, a little less Convexity was sufficient to produce the Refractions required: And because it was very difficult to flatten or lengthen this artificial Eye, in the manner the natural Eye is done by the Muscles, I placed the Vellum in such a manner, that it could be moved backward and forward, at pleasure" (1723, pages 243 – 244). Rohault reached a series of conclusions based upon experiments with this artificial eye, determining the separations between the vellum and the lens that would form distinct images of objects at different distances. The limitations of an optical system with a lens of fixed curvature were plain to see: objects at only one distance can be adequately focused, otherwise the artificial retina needed to be moved closer to or farther from the lens.

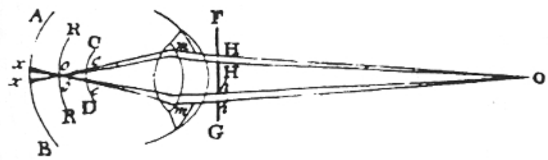
3.3 *Accommodation*

The analogy between eye and camera, together with an appreciation that the retina was the receptive organ, introduced a new set of problems in the study of vision. If the camera can only focus on objects at a particular distance, how is the eye able to focus upon objects over a wide range of distances? This is the problem of accommodation, the term that Porterfield (1738) coined: "our Eyes change their Conformation, and accommodate themselves to the various Distances of Objects" (page 126). Boring (1942) claimed that the term 'accommodation' was not introduced until a century later. From the time of Kepler to the middle of the nineteenth century accommodation was one of the most intensively studied and controversial topics in vision, as is indicated by the earlier quotation from Helmholtz. Not surprisingly, since the equation of the eye with a camera had proved so popular, the solutions were often derived from characteristics of cameras. A camera with a small aperture has a much greater depth of focus than one with a larger aperture; moving the camera lens towards or away from the screen onto which images are projected will vary the distance at which objects are sharply focused; conversely, moving the screen itself will have the same effect. Each of these physical speculations was advanced, together with others that were physiological. Kepler (1611) favoured the view that the lens moved forward and backward in the eye. Scheiner (1619) supported this proposal largely on the basis of observations with a camera, but he did also mention that the lens could vary in shape. However, Scheiner's greatest contribution to this area was his experiment with closely spaced pinholes: when their separation was less than the diameter of the pupil, objects seen through them were multiplied at all but one distance of the card from the eye: "Make a number of perforations with a small needle in a piece of pasteboard, not more distant from one another than the diameter of the pupil of the eye ... if it is held close to one eye, while the other is shut, as many images of a distant object will be seen as there are holes in the pasteboard..., at a certain distance, objects do not appear multiplied when they are viewed in this manner" (page 38). Scheiner described and illustrated the consequences of viewing points of light and also the spire on a tower through closely spaced apertures, although later in his book he did present a diagram of what has become called 'Scheiner's experiment', as is shown in figure 5a.

Porterfield (1738) provided a similar, though more detailed, diagram of the experiment (figure 5b) and gave the correct interpretation of it: "Now it is certain, that if the Rays of Light that come from each Point of the Object are exactly united in a corresponding Point of the *Retina*, the Object will always appear single, though it be viewed though several small Holes, for the luminous Cones, OHH, O*hh* which have for their Apex or Top a Point of the Object, O, and for their Basis the little Holes in the Card, HH, *hh*, will also have all their opposite Tops *o*, *o* in one and the same point *o*, of the *Retina*, RR, which must needs make the Object appear single: But if the Eye have not that Conformation, which is necessary to unite these Rays in a Point in the *Retina*, each of these Cones will be cut by the *Retina*, either before or after their Reunion; and therefore each Point of the Object shall, by its Rays, touch the *Retina* in as many Places as there are Holes in the Card, and consequently the Object will appear multiplied, according to the Number of Holes" (pages 140 – 141). Porterfield improved on Scheiner's experiment by using as a stimulus "a small luminous Point in a dark Place", and on this basis made the first optometer. Porterfield extended his experiments to refute La Hire's (1685) contention that the eye did not need to accommodate



(a)



(b)

Figure 5. The Scheiner experiment: (a) as illustrated in Scheiner (1619); (b) its interpretation by Porterfield (1738).

to objects at different distances, because of the contraction of the pupil when observing near objects and because it could function well by ignoring blurred images.

Despite the analogies of accommodation with focusing in a camera, Descartes's (1664) earlier physiological speculations were to prove particularly astute. The lens itself was considered to change its curvature, becoming more convex for focusing on near objects, and less convex for more distant ones (see figure 6): "The change of shape that occurs in the crystalline humor permits objects at different distances to paint their images distinctly on the back of the eye ... if, for example the humor *LN* [the lens] is of such a shape that it causes all the rays from point *R* to strike the nerve precisely at point *S*, the same humor without being changed will be able to make the rays from point *T* (which is closer) or those from point *X* (which is farther away) come there too. But it will make the ray *TL* go toward *H*, and *TN* toward *G*; and *XL* contrarily, toward *G*, and *XN* toward *H*, and so with the others. Whence in order to represent point *X* distinctly, it is necessary that the whole shape of this humor *LN* be changed and that it become slightly flatter, like that marked *I*; and to represent point *T* it is necessary that it becomes slightly more arched like that marked *F*" (Hall 1972, page 56). He even suggested that accommodation provides a source of distance information for objects that are close to the eye.

To these speculative mechanisms could be added another, that the cornea increased its curvature in order to focus on near objects. This was advanced by Desaguliers (1719), who proposed that the lens was fixed in curvature, and pressure on the humours of the eye forced it forwards, thus increasing the corneal curvature. Another possibility that was entertained concerned the elongation of the eye as a consequence of the action of the extraocular muscles. Associated to such elongation would have been an increase in corneal curvature. As indicated above, the most systematic experiments on accommodation, prior to those of Thomas Young, were conducted by Porterfield (1738). He devised an optometer for determining the near and far points of vision, and he was able to discount both of the speculations above by recourse to sight following removal of the crystalline lenses; he examined such an aphakic individual who was unable to accommodate at all without the aid of a convex lens, and the power of the lens required to be modified for objects at different distances. Porterfield concluded that, since elongation of the eye was still possible for such a person, the crystalline lens must be involved in accommodation, although he remained unsure of the manner in which it functioned.

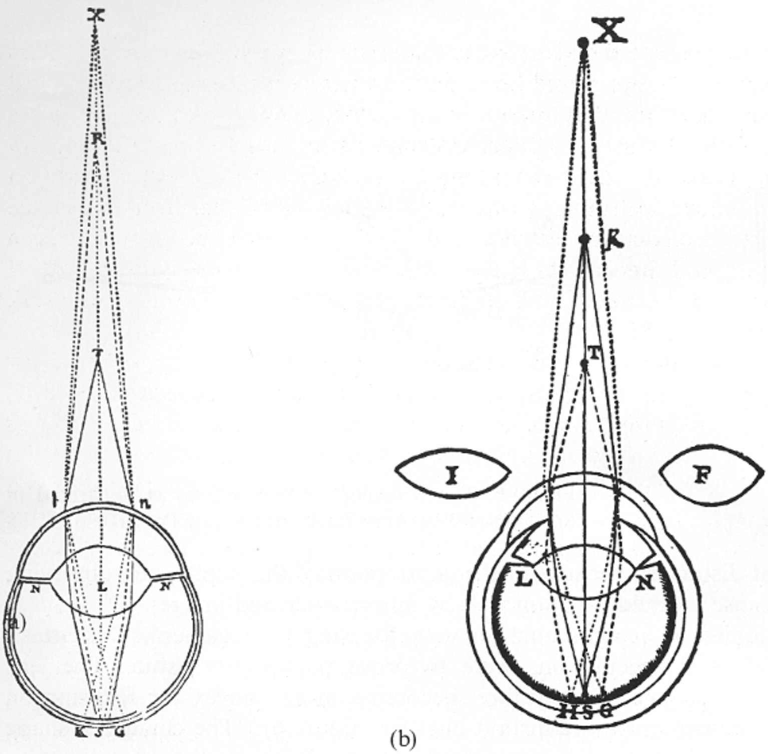


Figure 6. Diagrams of accommodation from: (a) Descartes (1662); (b) Descartes (1664/1909).

The involvement of the ciliary process was acknowledged, but its location and attachment to the lens led him to the conclusion that its action moved the lens forward and backward in the eye itself.

As Priestley (1772) remarked: "That the eye does, by some conformation, adapt itself to the view of objects at different distances, seems to have been indisputably proved by Dr. Porterfield; but among those who suppose a conformation of the eye for this purpose, independent of a variation in the aperture, it is by no means agreed in what it consists" (page 646). Thus, writers on the eye and vision selected one or more of these hypotheses as their candidates for accommodation until the late eighteenth century, when Young reported his experimental enquiries. His logical and physiological conclusions were initially presented in a paper to the Royal Society of London in 1793, upon which was founded his election as a Fellow. There followed a remarkable series of experiments that was published in 1801, supporting changes in lens curvature. Such support was not derived from direct evidence, but rather from the rejection of all alternative hypotheses. Changes in corneal curvature were excluded in two ways: the images of candle flames reflected from the cornea did not change with variations in accommodation, and immersion of the eye in water did not abolish accommodation. Elongation of the eye was rendered untenable because accommodation was still possible when considerable external pressure was applied to the eye.

The association of accommodation of the eye to convergence of the eyes was made by many writers, and it was discussed principally in the context of depth or distance perception. In the seventeenth century, both Aguilonius and Descartes discussed them as cues to distance, and they formed a cornerstone of Berkeley's theory of muscular involvement in distance perception (see Baird 1903; Boring 1942). However, their close physiological connection was emphasised by both Porterfield (1738, 1759) and Wells (1792).

3.4 *Eye glasses*
Telescopes and microscopes use the same basic materials as eye glasses—ground glass lenses—in order to explore the upper and lower limits of nature inaccessible to the naked eye. It is not surprising, therefore, that interest in the history of eye corrections for errors of refraction derives from the use of optical instruments as aids to scientific enquiry (Singer 1921; Crombie 1967). Yet there was a long period before the connection between eye glasses and other optical instruments was made. Ronchi (1968) has argued that the delay was due to a basic mediaeval distrust of the senses, though this view has been questioned by Lindberg and Steneck (1972). Historical accounts of the development of eye glasses themselves can be found in Hill (1915), Needham and Gwei-Djen (1967), Rosen (1956), and Schmitz (1982, 1995).

Glass has been manufactured for over three thousand years, and its optical property of magnification is unlikely to have gone unnoticed. For example, Seneca (c 63, 1971) gave an account of the magnification of letters seen through a lens or burning glass (a water-filled glass ball), and solid reading glasses were placed on text to magnify it (see Schmitz 1995). Furthermore, individual differences in vision were remarked upon by Aristotle and Pliny (c 77, 1940). Aristotle commented on weakness of vision in the shortsighted and the aged, and he speculated that they might have different foundations: the former inspected objects at close distances whereas the latter viewed them from afar. He also noted that shortsighted people reduce the aperture of the pupil in order to see more clearly. However, the sections on shortsightedness are to be found in *Problemata* (J A Smith and W D Ross 1910), which is often cited as pseudo-Aristotle; it was derived from a genuine work of that title, since lost, and it was probably a compilation from several sources. There are many repetitions and contradictions in Book XXXI, which is concerned with problems connected with the eyes. Suspect as the interpretation might be, the observations are acute. Pliny extended these observations: "Moreover some people have long sight but others can only see things brought close to them. The sight of many depends on the brilliance of the sun, and they cannot see clearly on a cloudy day or after sunset; others have dimmer sight in the day time but are exceptionally keen-sighted at night" (c 77/1940, page 521).

Optical corrections for presbyopia are considered to have been adopted from the late thirteenth century, perhaps initially by Roger Bacon, and thereafter avidly exploited by many (see Singer 1921). As Schmitz remarked: "Bacon is certainly not the 'discoverer' of reading glasses, but he is the one who recognized the significance of visual aids, carried out improvements on them, sought a scientific explanation for their operation, and addressed the problem of optical corrections theoretically" (1995, page 27). Bacon described how a convex lens resulted in letters of text appearing both clearer and enlarged. He appreciated that letters of any small size, and even grains of sand, could be seen by the aged eye if the magnification was sufficient: "If any one examine letters or other minute objects through the medium of crystal or glass or other transparent substance, if it be shaped like the lesser segment of a sphere, with the convex side towards the eye, and the eye being in the air, he will see the letter far better, and they will seem larger to him .... *For this reason such an instrument is useful to old persons and to those with weak eyes, for they can see any letter, however small, if magnified enough*" (Singer 1921, pages 395–396). Rosen (1956) cites an anonymous reference to Alessandro Spina, a Dominican monk, which indicates that there was an element of the magical or the mercenary in the production of eye glasses at the beginning of the fourteenth century. The inscription on a Florentine burial slab states: "Here lies Salvino degli Armati, son of Armato, of Florence, inventor of eyeglasses. May God forgive his sins. A.D. 1317" (Rosen 1956, page 184). Eye glasses were soon depicted in paintings, the earliest of which is probably by Tommaso da Moderna in 1352 (Rosen 1956; Schmitz 1982, 1995).

Leonardo considered that convex lenses assisted vision by reducing convergence; that is, the lenses were thought of as prisms rather than magnifiers. Porta (1593), on the other hand, interpreted their benefits to the aged in terms of reduced control over pupil diameter. Maurolico (1611, 1940) came much closer to realising the correct relationship; while still maintaining that the crystalline lens was the receptive organ, he described changes in its shape and associated these with myopia and presbyopia. Moreover, he advocated the use of concave lenses for the shortsighted, in contrast to convex lenses for aged eyes. As was noted above, Maurolico's book, though written in the middle of the sixteenth century, was not published until 1611, and so was unlikely to have been read by Kepler, when he was addressing similar problems.

Thus, although the assistance of convex lenses in presbyopia was readily appreciated in the thirteenth century, the integration of lenticular optics with vision, and their relation to accommodation was to wait another three centuries. Two factors retarded such integration: ignorance of the dioptrics of the eye and of its anatomy. These were more clearly understood early in the seventeenth century and corrections for both shortsightedness and longsightedness became routine, notwithstanding the doubts that remained concerning their causes. Kepler (1604) considered that errors of refraction were a consequence of experience: those whose work involved detailed observation of near objects became incapable of seeing distant objects, and vice versa. Descartes's (1637) analysis was much more mechanistic and pragmatic. He attributed shortsightedness and longsightedness to the shape of the eyeball itself, and sought to determine the appropriate optical correction by, essentially, employing different lenses to define the near and far points of distinct vision. Despite his assertion that the lenses selected should be the easiest to make, those shown in the accompanying diagram (figure 7a) would not comply to that requirement. It is noteworthy that in his *Dioptrique*, from which the figure is taken, detailed directions for grinding lenses are given.

Thereafter, the corrections for myopia and presbyopia were amplified and illustrated by many writers on optics and the eye. Molyneux (1692) added that the assistance of convex lenses in presbyopia was not simply a consequence of magnification: in old age even large print could not be read without the aid of spectacles. The optical corrections for these conditions were readily apparent, but the causes remained obscure.

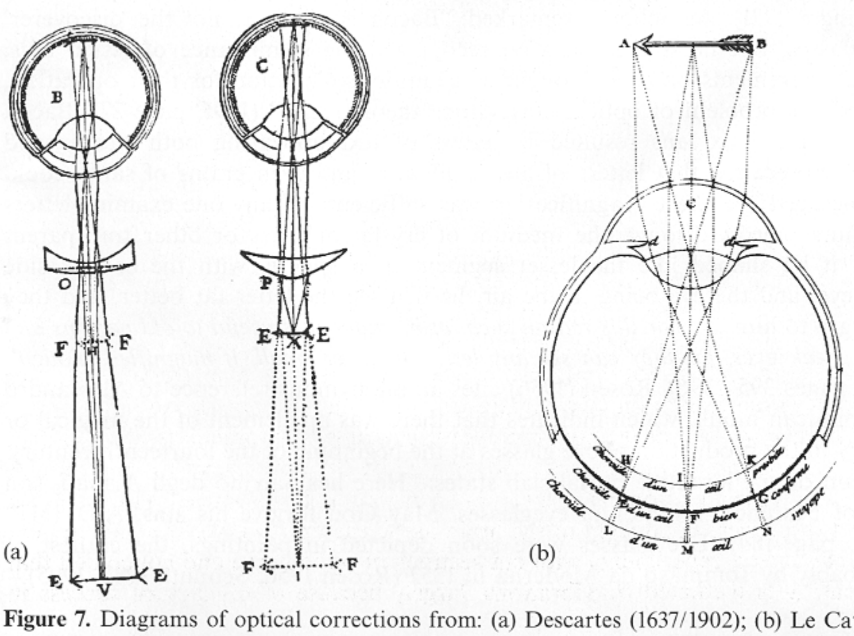


Figure 7. Diagrams of optical corrections from: (a) Descartes (1637/1902); (b) Le Cat (1744).

In order to reconcile the obvious correction with the possible cause many hypotheses were entertained. Newton (1704) proposed that the cornea shrunk and the lens grew flatter in old age. Thus, convex lenses corrected the defect, resulting in distinct vision for nearer objects. Myopes, who required concave lenses in their youth, were able to see distant objects more distinctly in old age; this demonstrated an appreciation of the developmental interaction between myopia and presbyopia. Le Cat (1744) pursued the Cartesian analysis with greater diligence, providing in a single illustration (figure 7b) the focal planes for normal, myopic, and presbyopic eyes.

The pragmatism of the New World was evident in Franklin's (1785/1970) introduction of bifocal glasses: since reading was normally accomplished with downward gaze, and scanning the scenery with an upward gaze, the two halves of the spectacles could be so constructed to accommodate both functions: "I imagine it will be found pretty generally true, that the same Convexity of Glass, through which a Man sees clearest and best at the Distance proper for Reading, is not the best for greater Distances. I therefore had formerly two Pair of Spectacles, which I shifted occasionally, as in travelling I sometimes read, and often wanted to regard the Prospects. Finding this Change troublesome, and not always sufficiently ready, I had the Glasses cut, and half of each kind associated in the same Circle, thus. By this means, as I wear my Spectacles constantly, I have only to move my Eyes up or down, as I want to see distinctly far or near, the proper Glasses being always ready" (1785/1970, pages 337–338).

3.5 *Retina*

The retina was considered by Galen to be an outgrowth of the brain; it had a net-like structure, and it provided nourishment for the vitreous which nourished the lens—the "principal instrument of vision". In this way the pneuma, or visual spirits, could communicate between the brain and the lens: the pneuma were considered to travel along the optic nerves and interact with images of external objects carried in the air to the lens. The visual spirits returned along the optic nerves to the cerebral ventricles where they interacted with the animal spirits. The retina was thus relegated to a nutritional role in this theory of vision. The difficulty with reconciling such a theory with the transmission of light through the transparent lens is evident in a statement by Averroes (c 1180), in which the possibility of the retina being the 'perceptive faculty' is entertained: "The innermost coats of the eye [ie the retina] must necessarily receive the light from the humors of the eye, just as the humors receive the light from the air. However, inasmuch as the perceptive faculty resides in the region of this coat of the eye, in the part which is connected with the cranium and not in the part facing the air, these coats, that is to say, the curtains of the eye, therefore protect the faculty of the sense by virtue of the fact that they are situated in the middle between the faculty and the air" (1961, page 9).

Platter (1583) was explicit in specifying the retina as the receptive organ: "The principal organ of vision, namely the optic nerve, expands through the whole hemisphere of the retina as soon as it enters the eye. This receives and discriminates the form and colour of external objects which together with the light enter the eye through the opening of the pupil and are projected on it by the lens" (Koelbing 1967, page 72). This view was amplified by Kepler (1604), but how vision occurred was still a mystery, as Kepler acknowledged, and the formation of an image on the retina was not the solution.

Not surprisingly, the old ideas about species were retained by some, like Willis (1664), to account for vision, even if the species were carried by the optic nerve to the brain. A truly mechanistic interpretation was given by Newton: light produced vibrations in the retina, and these were conducted to the brain along the optic nerve. It would appear that Newton conducted experiments with cut sections of optic nerve and concluded that vision like hearing is mediated by vibrations, largely because of his lack of success in isolating the animal spirits: "tho' I tied a piece of the optic nerve at one end, and warmed it in the middle, to see if any airy substance by that means would disclose itself in bubbles at the other end, I could not spy the least bubble; a little moisture only, and the marrow itself squeezed out.... And that vision is thus made, is very conformable to the sense of hearing, which is made by like vibrations" (Harris 1775, page 100).

A somewhat similar mechanical analogy was entertained by Leeuwenhoek (1675), who examined the structure of the retina with his simple microscope. He reported seeing many small "globuls", which could have been rods, cones, or optic nerve fibres. He likened a glass of water to the optic nerve which contained the globules or filaments, when the surface of the water is touched, the pressure is transmitted to the base, as the filaments might transmit to the brain. It was over a century and a half later before the microanatomy of the retina was revealed in greater detail (see Polyak 1957). Zinn (1755) did provide an illustration of the microscopic appearance of the net-like patterning over the retina, but the early microscopes could not resolve the detail of its cellular structure. This was to await the application of compound achromatic microscopes available in the early nineteenth century.

Porterfield (1759) contended that the retina was a necessary but not sufficient component of visual perception. In this regard, he was able to draw upon the experience of his own phantom limb, since he was often aware of feelings in the amputated part of his leg. These he attributed to the continued activities of the severed nerves in his stump, which would have transmitted signals to the brain.

3.6 *Visual pathways*

Ignorance of the anatomy of the eye in antiquity was amplified with respect to the pathways from the eyes to the brain. Indeed, the involvement of the brain itself in perception and cognition was often denied in early Greek science. On the basis of his dissections of animals, Alcmaeon did advance the opinion that these functions were located in the brain, but his view was not widely held (Singer 1925). Hippocrates also located the pleasures, sensations, and thoughts in the brain, but the most widely held belief made the heart the locus of sentience, and this was supported by the authority of Aristotle. He had observed that stimulation of the exposed brain did not result in any sensation, and that invertebrates did not have a brain. In addition, he believed that the brain was devoid of blood, which was considered to be an essential component of sensation (see Beare 1906; Gross 1998). The heart, on the other hand, was thought to have connections with the sense organs and it was the source of heat in the body. Earlier, Empedocles had advanced the opinion that the heart was the source of the anima or soul, the spirits of which were circulated around the body by the blood.

As was noted above, Alcmaeon proposed that the optic nerves were hollow tubes, and this tradition was continued by Aristotle, as is evident from the diagram of the eye attributed to him (see figure 1b). Magnus (1901) represented Aristotle's pathways as comprising three ducts which were considered to pass from the eye to the brain; the largest and medium-sized ducts proceeded to the cerebellum, and the smallest to the cerebrum. Contrary to Aristotle, Galen believed that the origin of the visual pathways was located in the anterior ventricle of the brain, where the animal spirits could interact with the visual spirits, borne by the optic nerves. The optic nerves themselves came together at the optic chiasma, but each of the nerves remained on its own side: "If one did not prepare this specimen carefully, one might easily believe that the [optic nerves] really cross each other and run one above the other. That, however, is not the true state of affairs. But as soon as they have touched each other inside the skull they unite their central canals; they then separate immediately, as if to show simply and solely that they only came in contact in order to unite their canals" (Siegel 1970, pages 60–62). Hunain ibn Is-hâq restated the Galenic doctrine that the hollow optic nerves unite at the chiasma (see Meyerhof 1928), and it was so depicted by Ibn al-Haytham (see Sabra 1989), and maintained in later Arabic representations (see figure 2e).

The anterior ventricle to which Galen referred was likely to have been the thalamus. Three ventricles were enumerated in Galenic anatomy, and Albertus Magnus incorporated them into late mediaeval philosophy as representing the sites of perception, reasoning, and memory (Dewan 1980). The prevalence of this notion is evident in Leonardo's diagram of the visual pathways (figure 8a): in some other drawings the optic nerves lead directly into the first of the three ventricles without even meeting at the optic chiasma (see McMurrich 1930; Keele 1955; Gross 1995). The illustration shown here does depict the optic nerves meeting at the chiasma before projecting to the ventricle. The more detailed dissections by Vesalius (1543), Varoli (1591), and Laurentius (1613) resulted in illustrations of the base of the brain that charted the course of the optic nerves to the chiasma and beyond, but they were restricted to the gross anatomy (see figures 8b – 8d).

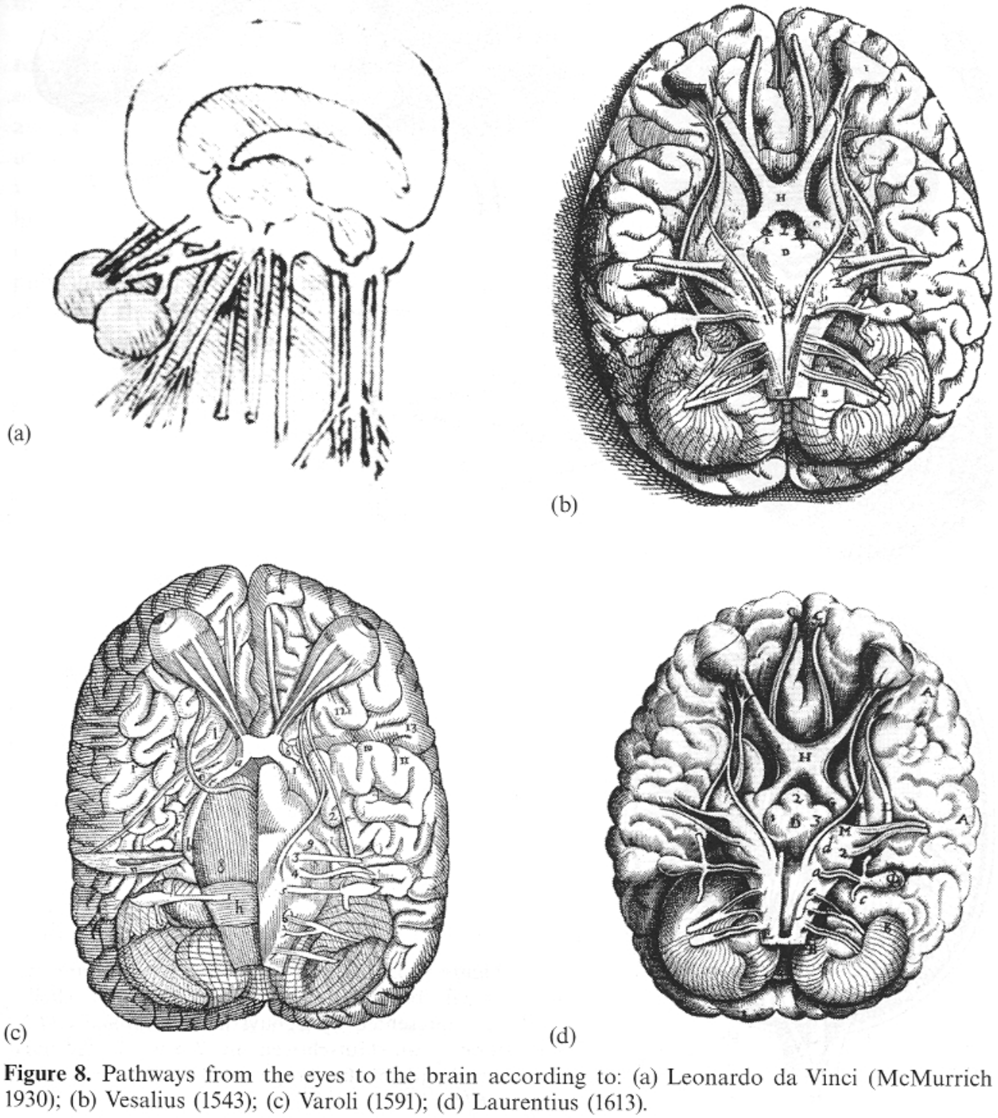
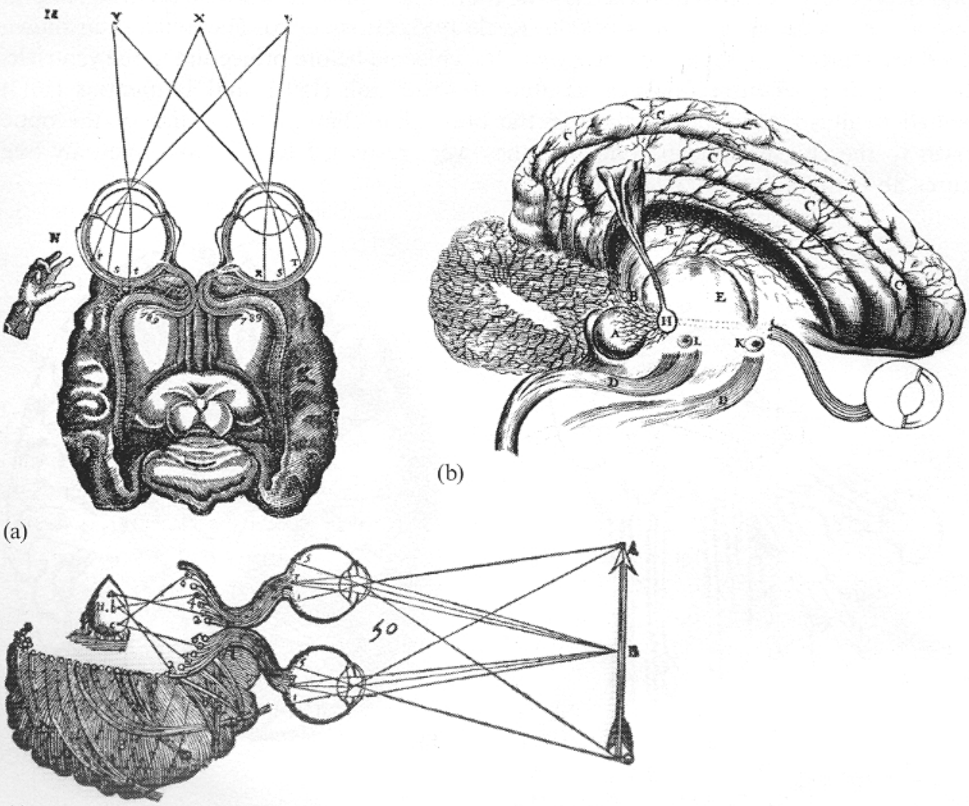
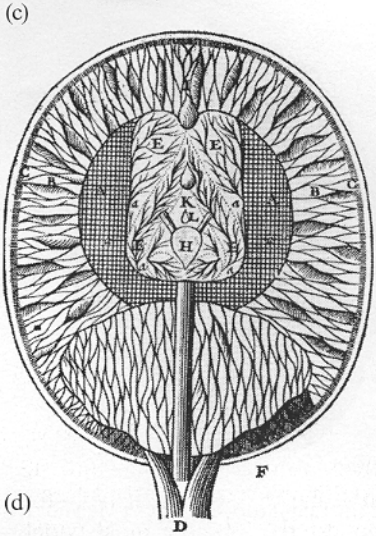


Figure 8. Pathways from the eyes to the brain according to: (a) Leonardo da Vinci (McMurrich 1930); (b) Vesalius (1543); (c) Varoli (1591); (d) Laurentius (1613).

The separate and ipsilateral projection of the optic nerves was to be repeated by Vesalius, and it was integrated into Descartes's analysis of vision (figure 9). The diagrams in Descartes's *Dioptrique* (1637, figure 9a) and in his *Traité de l'Homme* (1664, figure 9c) retain the ipsilateral projection of the optic nerves to the brain, but those from each eye are combined in the pineal body in the latter. The illustration from the *Traité* has been reproduced many times, particularly in the context of historical analyses of binocular vision (Polyak 1957; van Hoorn 1972; Held 1976; Wade 1987; Crone 1992; Howard and Rogers 1995). However, it is instructive to compare it with the monocular



(a) (b) (c)



(d)

Figure 9. Descartes's diagrams of the brain and visual pathways: (a) from *Dioptrique* (1637); (b) represented by Schuyl in *De Homine* (1662); (c) by van Gutschoven in *Traité de l'Homme* (1664); (d) by La Forge in *Tractatus de Homine* (1677).

representation made for *De Homine* (1662, figure 9b): both engravings were derived from essentially the same text, which does not mention stimulation of two eyes. A number of similar illustrations from *De Homine* all depict one eye only, whereas their corresponding figures from the *Traité* display two. It would seem that the illustration has played a greater role in historical interpretations than the text from which it was derived, and the credit should be placed with the artist as well as Descartes. It is particularly significant in this case, because neither of the series of diagrams was produced by the author of the text (see Hall 1972). *Dioptrique* was published during Descartes's life, but the *Treatise* first appeared over a decade after his death, and two separate versions of it were printed. The first, in 1662, was translated into Latin (*De Homine*) and illustrated by Schuyl, who is said to have worked from a defective manuscript copy of the French. The French version (*Traité de l'Homme*) appeared in 1664; the text was given to two illustrators (van Gutschoven and La Forge), who each made a complete set of drawings independently of the other; van Gutschoven's were the ones most generally printed, though some of La Forge's were included, too. The whole set of La Forge's illustrations can be found in the Latin edition of 1677, and the equivalent diagram of the brain is shown in figure 9d.

Descartes did stress the correspondence between points on the object, those on the retina, and their projection to the brain, but it is unlikely that he was addressing the issue of corresponding points in the two retinae. His analysis of binocular vision was by the ancient analogy with a blind man holding two sticks, and it was not physiological. The union that was depicted in the pineal body reflected an attempt to match singleness of vision with a single anatomical structure. Thus Descartes's speculative physiology defined his visual anatomy. His achievement was in presenting an account of the visual pathways in terms of their topographical organisation. In the same year that the *Traité* was published Willis (1664) established that the optic nerves projected to the optic thalami, although the distinction between the thalami and the striate cortex had not been made at that time (see Neuberger 1981; Finger 1994).

Descartes's analysis of vision was based on his conception of light: when light strikes the eye it applies force to points on the retina which are transmitted along the optic nerve to the brain. Rohault (1671), on the other hand, was specifically concerned with binocular projections, delineating sympathetic (or corresponding) points on each eye (figure 10a). Although he retained the independence of the two optic nerves, the fibres from corresponding points were united in an undefined part of the brain, denoted by X. Rohault used evidence from brain injury and disease to localise sensation in the brain rather than the nerves: "And because we have no Sensation likewise, when any Object makes an Impression upon a Nerve, if its Communication with the Brain be hindred, or if the Brain it self be affected with any particular Distemper; therefore it is reasonable to think, that the Nerves are not the immediate *Organs* of the Soul, but they are so formed by Nature, as to transmit the Impression which they receive, to the Place in the Brain where the Origin of them is, and where probably the immediate Organ of the Soul's Sensation is" (1723, page 245).

The concept of the hollow optic nerves, which had survived since Alcmaeon, was gradually being replaced. Rohault described transmission along the nerves and Briggs (1682) represented the optic nerves as composed of fibres. Not only did he produce a delightful illustration of the visual pathways (figure 10b), retaining the independence of the optic nerves, but he also had them terminating in the thalami. Moreover, he stimulated Newton's interest in the visual pathways, and in the ways in which messages from the two eyes could be combined. Briggs proposed a mechanistic principle involving tension applied to the individual nerve fibres "like *unisons* in a *Lute*" (page 172); only when the tension was equal in the two sets of fibres did single vision occur. He sent his paper to Newton and their correspondence indicates the latter's reserve concerning it

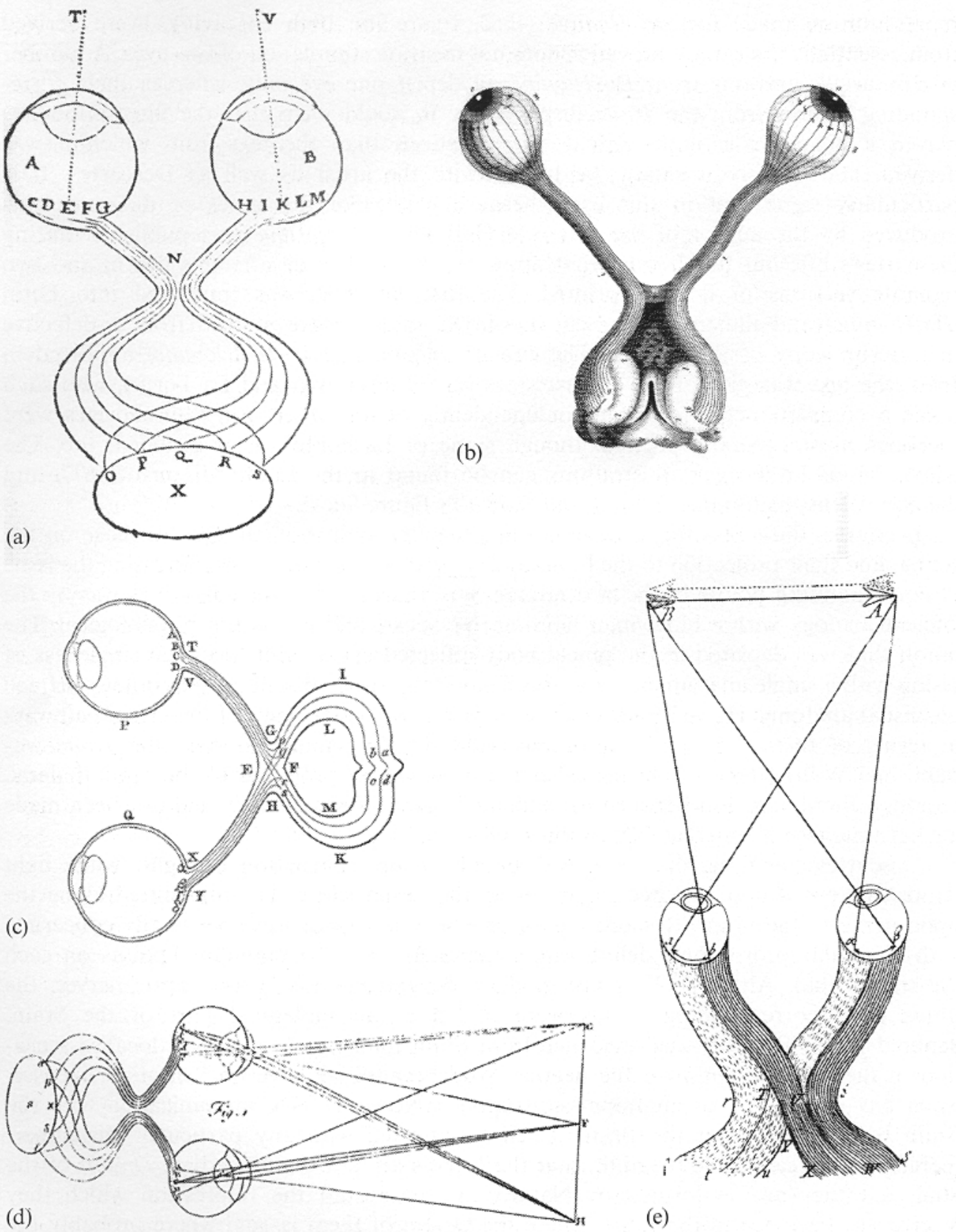


Figure 10. Visual pathways according to (a) Rohault (1671); (b) Briggs (1682); (c) Newton, as represented in Brewster (1855); (d) Porterfield (1737); (e) Taylor (1738).

(see Brewster 1855; Turnbull 1960). In order to rise above the level of opinion, in around 1682 Newton conducted the experiment referred to above, made the first representation of partial decussation at the optic chiasma (figure 10c), and proposed a theory of binocular single vision based upon it: "Now I conceive that every point in the retina of one eye, hath its corresponding point in the other; from which two very slender pipes filled with the most limpid liquor, do without either interruption, or any unevenness or irregularities in their process, go along the optic nerves to the juncture EFGH, where they meet either betwixt G, F or F, H, and there unite into one pipe as big as both of them; and so continue in one, passing either betwixt I, L or M, K, into the brain, where they are terminated perhaps at the next meeting of the nerves betwixt the cerebrum and cerebellum, in the same order that their extremities were situated in the retina's. And so there are a vast multitude of these slender pipes which flow from the brain, the one half through the right side nerve I L, till they come at juncture G F, where they are divided into two branches, the one passing by G and T to the right side of the right eye A B, the other half shooting through the space E F, and so passing by X to the right side of the left eye $\alpha\beta$. And in like manner the other half shooting through the left side nerve M K, divide themselves at F H, and their branches passing by E V to the right eye, and by H Y to the left, compose that half of the retina in both eyes, which is towards the left side C D and $\gamma\delta$" (Harris 1775, pages 109–110).

The subtlety of Newton's analysis was not, however, widely disseminated. He did make passing reference to it in Query XV of his *Opticks* (1704), but it was not accompanied by a diagram: "Are not the Species of Objects seen with both Eyes united where the optick Nerves meet before they come into the Brain, the Fibres on the right side of both Nerves uniting there, and after union going thence into the Brain in the Nerve which is on the right side of the Head, and the Fibres on the left side of both Nerves uniting in the same place, and after union going into the Brain in the Nerve which is on the left side of the Head, and these two Nerves meeting in the Brain in such a manner that their Fibres make but one entire Species or Picture, half of which on the right side of the Sensorium comes from the right side of both Eyes through the right side of both optick Nerves to the place where the Nerves meet, and from thence on the right side of the Head into the Brain, and the other half on the left side of the Sensorium comes in like manner from the left side of both Eyes. For the optick Nerves of such Animals as look the same way with both Eyes (as of Men, Dogs, Sheep, Oxen, &c.) meet before they come into the Brain, but the optick Nerves of such Animals as do not look the same way with both Eyes (as of Fishes and of the Chameleon) do not meet, if I am rightly informed" (pages 136–137). In presenting this as a query, rather than the report of an experiment (as in the unpublished manuscript) its speculative nature would have been reinforced. The manuscript passed into the possession of William Jones in the eighteenth century, and was later purchased by the Earl of Macclesfield (see Westfall 1980). Prior to its purchase Harris saw the manuscript, and published a copy of it in his *Treatise of Optics* (1775). Harris's *Treatise* started life as a book on microscopes in 1742; his work as assay master to the Mint probably prevented its completion. He died in 1764, and his friends collected the manuscript and arranged for its publication 11 years later. The engraving shown here was redrawn by Harris and also by Brewster (1855), but a copy of Newton's drawing can be found in Grüsser and Landis (1991) and Crone (1992).

Despite the authority of Newton's analysis, it was not immediately accepted. Perhaps this was in part due to the brief nature of the published version in the *Opticks*, in contrast to the longer, unpublished manuscript account. Porterfield (1737) was well aware of Newton's description of partial decussation, and reprinted Query XV in full. While concluding that "This is indeed the most beautiful and ingenious Explication of the Manner how an Object appears single from the Coalition of the Optick Nerves that ever appeared" (page 197), he rejected it largely on the authority of anatomists like Vesalius. His diagram (figure 10d), which was essentially like Rohault's, showed ipsilateral projection to the brain, and it was reprinted unchanged in his *Treatise* of 1759.

Newton was almost correct in his analysis: partial decussation was appropriate, but he represented the nerves themselves as uniting at the chiasma. That is, optic nerve fibres from corresponding points on each eye formed single fibres in the optic tract. This detail was rectified by Taylor (1738) in an accurate representation of the partial crossing over and independence of the nerve fibres (figure 10e): fibres in the optic nerve diverged after the optic chiasma, with those from the left halves of each retina projecting to the left part of the brain, and vice versa. Taylor (1750) reprinted this figure in a translation of the earlier French book on ophthalmology into German; it is this later diagram that has often been cited as the first correct representation of the optic pathways (eg Polyak 1957; Finger 1994).

Taylor had represented the partial decussation at the optic chiasma, but this was based more on speculation than dissection. Despite the existence of Taylor's diagram, the precise paths pursued by the two optic nerves to the brain were the object of much debate, which was not finally resolved until the early nineteenth century. Wollaston (1824) was able to marshall evidence from his own hemianopia as well as from anatomy to support partial decussation. The detailed anatomy of the crossings was clearly described later in the century by von Gudden (1870) and by Munk (1879), but few speculated on the more central pathways of vision. This was to become a topic of considerable interest, largely as a consequence of Ferrier's (1876) studies of electrical stimulation and ablation of the occipital cortex.

4 Conclusion

With a better understanding of the physical nature of light, its refraction through the eye, and the structure of the eye itself the stage was set for the modern era of vision research. One concept proved particularly difficult to dislodge—the motion of spirits through the nerves and brain. The spirits were retained even after the optic nerves were shown to be solid, because there was no adequate alternative to replace them. Newton had presented a mechanistic theory of vision based on vibrations, but there was little to distinguish this from an appeal to the soul, since neither could be measured. The existence of electrical activity in neuromuscular preparations, the isolation of nerve cells, and their combination in a neuron doctrine awaited experimental studies in the late eighteenth and nineteenth centuries.

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