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OXFORD AND THE REVIVAL OF OPTICS IN THE THIRTEENTH CENTURY

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Abstract—Three Oxonian scholars, R. Grosseteste, R. Bacon and J. Peckham, are the initiators of the Revival of Optics in the thirteenth century. Their work is discussed.

Résumé—Au cours du treizième siècle trois savants d'Oxford—R. Grosseteste, R. Bacon et J. Peckham—ont fait renaître l'étude de l'Optique.

Zusammenfassung—Drei Gelehrte, die in Oxford lebten, haben im dreizehnten Jahrhundert das Studium der Optik zu neuem Leben erweckt. Es waren Robert Grosseteste, Roger Bacon und John Peckham.

INTRODUCTION

THREE Oxonians played a leading part in the Revival of Optics in the thirteenth century. The first was ROBERT GROSSETESTE. After him came ROGER BACON and JOHN PECKHAM.[1]

A fourth writer on Optics of the same century was Vitellio (Witelo, Vitello), who was of Thuringian and Polish origin. He never visited England, yet, as will be shown later, it seems possible that the writing of his long treatise does in fact bear a connection with Roger Bacon's *Perspectiva.*

The revival of Optics was part of a widespread movement which started with the so-called Carolingian Renaissance[2] and lasted, though not uninterruptedly, into the thirteenth century. In this century, a gradually increasing number of classical Greek and Arabic books on science reached Western Europe in Latin translations, exerting a vigorous influence.

The reason why the authors mentioned above took such a lively interest in Optics was that they were "Light Metaphysicians". In some very old religious and philosophical doctrines, Fire and Light had been regarded as the main essences of the Universe. Through Manichæism and Neo-Platonism, with its principle of emanation, this idea developed in the course of the early Middle Ages into a philosophical system which Clemens Bäumker called "Lichtmetaphysik". Light was not regarded merely as a symbol, used to indicate the Supreme Being, but as the Essence of the Universe.[3] Our four authors were strongly influenced by this doctrine.

Their writings also show the influence of another ancient way of thought, namely, "Formalism". Grosseteste and his friends in a sense may be described as being "modern", yet they still remained mediaeval clerics.

ALBERT EINSTEIN has written: "What we have come to learn so far entitles us to the certainty that in Nature the idea of a mathematical simplicity is realized" (or "actualized").[4] This statement evokes associations with the conceptions of many Greek and mediaeval philosophers.

Pythagoras (*fl.* 540–510 B.C.) and his followers held that Number was the Essence of the Universe, and some philosophers were convinced that numbers manifested themselves in celestial and terrestrial phenomena. For them geometry was of the utmost importance. Plato, in his *Timaeus*, ascribed to the four elements the shapes of four of the five regular geometrical solids. It is often difficult to understand whether these philosophers regarded numbers and regular solids as symbols of reality, or just the reverse.

With this formalism was linked a strong belief in teleology. The Creator's aim was to make the Universe as excellent as possible and this had to be achieved by the best and most simple means. PLATO, according to Plutarch, said: "God always geometrizes."[5]

Many mediaeval scholars were convinced that they could detect a simple mathematical foundation in natural phenomena.[6] They readily explained why rays of light are straight lines. Between two points can be drawn only one straight line, whereas the points can be joined by an infinite number of non-straight lines. Therefore the straight line was preferred on the strength of this "singleness". Again vision will suffer a minimal loss of vigour when it proceeds along straight paths.

It was also clear to these scholars why, in the case of specular reflection, the angles of incidence and reflection are equal. In this manner the reflected ray is the shortest possible.

An instructive example of this formalistic way of thinking is given by the ancient conceptions about the form and size of the visual field.

According to modern text-books of ophthalmology, the field (for each eye) is of irregular shape, and it extends on the temporal side to more than 90° and on the nasal side to about 55°.

The formalistic mediaeval scientists had the preconceived notion that the visual field must have a regular circumference. Heliodorus of Larissa, who believed that vision operated by means of rays issuing from the eyes, said that these rays must find their places within a regular figure, and that this was a cone of revolution having its apex in the eye and subtending an angle of exactly 90°. If this angle were not a right angle, said Heliodorus, it would of course be either obtuse or acute. Now innumerable acute and obtuse angles are possible, but there is only one right angle. Therefore, this was the angle preferred by Nature.[7] Moreover, a section normal to the axis of this regular cone is a circle. Here the intention of Nature is also obvious, for of all figures with equal circumference the circle encompasses the largest possible area.[8] Formalism also required coincidence of the apex of the cone with the centre of the eyeball.

The Ancients had a preference for constructions in accordance with preconceived ideas and in many cases did not practise anatomy. Their drawings of the visual organ look more like geometrical diagrams than human eyes.[9]

Similarly, considering the first of our three Oxonians, reasonings along such formalistic lines frequently occur in Grosseteste's writings. It is to Roger Bacon's credit, however, as we shall see, that he does not always approve of them. The belief that the World had been created by the best and simplest means was, nevertheless, still prevalent in the thirteenth century.

A. GREEK AND ARABIC THEORIES OF VISION

As the theories on Vision put forward by Greek and Arabic scientists and philosophers exercised a great influence on the thirteenth-century thinkers, a brief survey of these old doctrines is indicated.

1. *Greek Theories*

The many theories of Vision upheld by Greek philosophers can be divided into three groups:

(1) the centrifugal theories, based on Emission;
(2) the centripetal theories, based on Intussusception;
(3) Plato's *Synaugeia.*

(*a*) *Centrifugal theories.* The theory that Seeing is brought about by rays proceeding from the eyes is very ancient.

The oldest book extant on geometrical optics is EUCLID's *Optics*,[10] written about 300 B.C. It consists of some sixty theorems preceded by twelve assumptions (or definitions). The following is a translation[11] of some of the assumptions:

(1) Let it be assumed that lines drawn directly from the eye pass through a space of great extent;[12]
(2) and that the form of the space included within our vision is a cone, with its apex in the eye and its base at the limits of our vision;
(3) and that those things upon which the vision falls are seen, and that those things upon which the vision does not fall are not seen.

Euclid does not explain in what manner these rays do bring about Vision. He must have chosen this theory because it lends itself to geometrical operations. Euclid connected, in pairs, object points with image points, as it is done in modern constructions. His theorems deal with the sizes of visual angles under different conditions.

It is not clear how the Ancients conceived the manner in which visual apperception arose by means of these rays issuing from the eyes. HIPPARCHUS (160–125 B.C.) is alleged to have said that the rays touched the objects seen like feeling hands.[13] ARCHYTAS of Tarent (*ca.* 430–365 B.C.), a follower of Pythagoras, supposed that seeing was accomplished by *radii . . . oculis profecti sine ullo foris amminiculo. . . .*[14]

The theory of Emission was based on the following facts:

(1) The eyes show a reflected image of the visible objects.
(2) A man who rapidly moves his eyes sees light (phosphenes) even in complete darkness.
(3) Pressure on the eyeball also causes such phosphenes.
(4) Some men (e.g. the Emperor Tiberius, according to SUETONIUS)[15] and many animals can see in dark surroundings.
(5) The eyes of animals often shine and seem to emit light, etc.

The belief that the eye can emit light was very tenacious. In *Henkes Zeitschrift für gerichtliche Medizin* (1833, 4 Quart., p. 266) a legal case is mentioned. A man who was attacked in utter darkness maintained that he had recognized his assailant by means of the light which was produced by a blow with a fist on his eye. Medizinalrath Seiler stated before the judge that this could have been so.

The origin of modern optics goes back to this work of Euclid's.

The most interesting book on Optics written by a scientist of the classical period is PTOLEMY's *Optics* (*ca.* A.D. 150).[16] It is known only through a very poor Latin translation.[17] The first and the last part of it are lost. Thus it is not possible to determine exactly the extent of Ptolemy's knowledge of this branch of science. Consequently it is possible that certain passages in Alhazen and in our thirteenth-century authors, which appear original to us, were in fact borrowed from Ptolemy.

Frontispiece of JOHN PECKHAM's *Perspectiva communis* (1504): GAURICUS (Editor), Venice.

[*facing p.* 315]

Ptolemy, like Euclid, accepted the theory of Emission. It is not clear what part Light plays in his doctrine. He was one of the few scientists of the Antiquity who performed purposeful and accurate physical experiments.[18] His observations about double images in binocular vision are excellent.

Most interesting is the manner in which he measured angles of refraction. These experiments of Ptolemy had a great influence on the Oxonians of the thirteenth century, and his results were not surpassed until the seventeenth century. He knew that the path of the rays in refraction is reversible. Table 1 shows the results of Ptolemy's experiments on refraction.

TABLE 1. TRANSITION OF LIGHT FROM AIR INTO WATER

Angle of incidence	Angle of refraction according to Ptolemy	Angle of refraction computed for $n = 1{\cdot}3$
0°	0°	0
10°	8°	7° 29′
20°	15° 30′	14° 51′
30°	22° 30′	22° 1′
40°	29°	28° 49′
50°	35°	35° 3′
60°	40° 30′	40° 30′
70°	45° 30′	44° 48′
80°	50°	47° 36′

The position of a virtual image produced by refraction was determined by reasoning *per analogiam*. In the case of reflection by a plane mirror, the eye E (Fig. 1a) sees the reflected image of the object V at the point of intersection of the ray EC with the perpendicular VB which falls from V upon the surface of the mirror.[19] Ptolemy knew, furthermore, that a ray of normal incidence is not refracted, and, in determining the position of the virtual image produced by refraction, he also made use of this perpendicular (Fig. 1b). The eye O, which

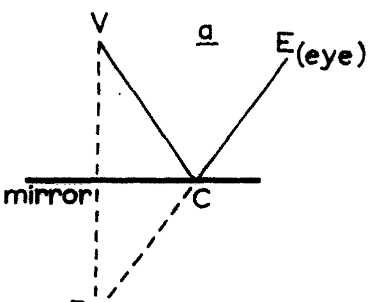

FIG. 1(a)

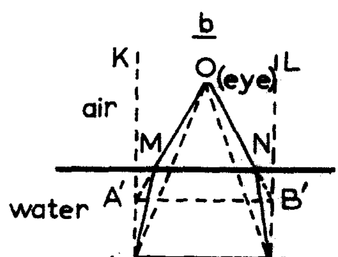

FIG. 1(b)

is in air, looks at the object AB, which is below the water-level. The rays OM and ON are refracted at the surface of the water at the points M and N, reaching the extremities of the object along the paths MA and NB. According to Ptolemy the virtual images of the extremities A and B are determined by protracting the rays OM and ON until they meet the perpendiculars AK and LB. So the virtual image is A′B′. It is magnified because the eye perceives it under the visual angle A′OB′ which is larger than the angle AOB under which the object would be seen if it were also surrounded by air.[20] Alhazen, Grosseteste, Bacon and Peckham also used this construction. It was ISAAC BARROW (1674) who showed that it is incorrect.[21]

As a psychologist, Ptolemy is, in a sense, a precursor of John Locke, George Berkeley, Hermann von Helmholtz and many other scientists. In his theory the factor "association" takes a preponderant part. When we receive fresh visual impressions we connect them with impressions previously received. We recognize objects as belonging to certain classes which we know by experience. The connection takes place subconsciously by means of syllogisms which are formed so quickly that we are not aware of them.[22] This is essentially the same as HELMHOLTZ's concept of *Unbewusste Schlüsse* (subconscious syllogisms).[23]

It is obvious that such conclusions will sometimes be drawn from defective premises and be false. Here lies the origin of optical illusions. These do not result from defects of the visual organ, but from defective reasoning. Alhazen, Grosseteste, Bacon, Peckham and Vitellio adopted this psychological doctrine.

(*b*) *Centripetal theories*. The theory of intussusception was first put forward by such materialist philosophers as Democritus (d. 361 B.C.) and Epicurus (342–270 B.C.). The Latin poet Lucretius (95–52/51 B.C.) describes it thus: "I say, therefore, that semblances and thin shapes of things are thrown off from their outer surface, which are to be called, as it were, their films or bark, because the image bears a look and shape like the body of that from which it is shed to go on its way."[24]

The following arguments were put forward to support the theory of Immission or Intussusception:

(1) A bright light causes an after-image.

(2) A bright light makes a dim light invisible.

(3) The perceived colour of an object is dependent on the colour of the light which illuminates that object.

(4) Light causes contraction of the pupil (this fact, however, was known only to a few scientists).

Avicenna said that, if the theory of Emission were true, a man with weak eyes (emitting only dim light) would see more clearly when another man with good eyes looked at the same object and that two men would have a higher visual acuity when they both looked at the same time at the same object.

Aristotle (384–322 B.C.) also was an adherent of the theory of intussusception but his conception of the visual process is less materialistic and more difficult to understand. Roger Bacon developed this theory. It is described by the Stagirite himself in the following manner:[25] "The thing seen is . . . colour, and this lies on the surface of the object in itself. Every colour can produce movement in the 'transparent' in a state of activity. Therefore nothing is visible without light. . . . We must explain what light is. Transparency evidently exists. By transparency I mean that which is seen, but not directly seen without qualification, but as it were owing to a colour from somewhere else. The transparent character is shared by air, water and many solid objects. . . . Now *light is the activity of this transparency qua transparent. Potentially*, wherever it is present, *darkness* is also present. *Light* is then in a sense the *colour of the transparency*, whenever it becomes *actually transparent, owing to fire* or any such agency as the upper firmament . . . darkness is a removal of an active condition from the transparency, so that obviously light is the presence of such an active transparency. . . . The colourless is receptive of colour. . . . The *essential nature of colour is its capacity to produce movement*[26] . . . *the actuality of the transparency is light*[27] . . . colour moves the transparency, e.g. the air, and the *sense organ* is moved by this provided that it is continuous."[28]

It seems that Aristotle supposed that in the transparent or "diaphanous" medium surrounding an object, the qualities of that object were present in a slumbering condition from which they were awakened when the diaphanous medium was illuminated by the presence of fire. Then the potential qualities became actual qualities. The process of actualization was propagated from the objects towards the eye, which, being transparent itself, could also manifest the qualities of the visible object. This doctrine did not lend itself as well to geometrico–optical operations as EUCLID's theory.[29]

(*c*) *Plato's* Synaugeia. PLATO's (429/28–347 B.C.) theory, *Synaugeia*,[30] may be regarded as a kind of compromise between the two foregoing ones. *Synaugeia* means coalescence of rays. The following is a translation[31] of parts of Plato's own formulation of his doctrine: "Of the organs first they (the creative powers) wrought *light-bearing eyes*. . . . That part of fire which has the property of not burning, but of yielding an innocuous light, they contrived to fashion into a *substance homogeneous with the light of day*. For the fire within us, being twin with this, they caused to flow through the eyes in its pure form smooth and dense . . . and to filter forth only such fire. . . . Whenever there is daylight around the visual current (the light which flows out of the eyes), this current, issuing from the eyes and meeting with its like, and becoming compacted into union with the latter (i.e. with the homogeneous external daylight), coalesces with it into one homogeneous whole in the line of vision, i.e. in the direction in which the current issuing from within meets front to front with, and presses against, any of the external objects with which it comes into collision."

This theory does not, any more than Aristotle's, lend itself to geometrico–optical treatment.

Goethe sometimes reminds us of this ancient theory: *Wär nicht das Auge sonnenhaft, die Sonne könnt' es nie erblicken. . . .*

Roger Bacon and John Peckham also believed in external and internal rays. They probably knew Plato's ideas on the visual process.

2. *Optics and the Arabs*

During the early Middle Ages the study of science, and therewith of optics, was neglected in Europe. Athens, an important cultural centre, had been the seat of a school where Neo-Platonists still took an interest in physics. But in A.D. 529 the Emperor Justinian disbanded this heathen school and the teachers sought refuge in Asia. During the following centuries Byzantine scholars were more interested in law, history, theology and politics, than in the natural sciences.

The teachers of the disbanded school continued their studies in Persia, Syria and Asia Minor, where many books by ancient Greek philosophers were translated into Asiatic languages. The Arabs, who had conquered the Near East, took a pleasure in science. Many Greek books were translated into their language. Later Sicily and Spain also became centres of culture. The Arabs were not satisfied with making translations. There arose a generation of men who tried to write original works.

About the year A.D. 1000, in Sicily, and even more so in Spain (at Toledo), many books were translated from Arabic into Latin. In the course of time a gradually increasing number of these Latin books reached France and England. Scholars in these countries were thus for the first time enabled to get acquainted, although indirectly, with the doctrines of many Greek classical writers. The books aroused enormous enthusiasm and exerted a strong stimulus on the minds of Western scientists.[32]

At first, few of these books were of a high quality. Translating, first from Greek into Arabic, and then from Arabic into Latin, gave rise to many misinterpretations. The very defectiveness of these translations, however, created the urge to obtain better versions.

Euclid, Aristotle (hitherto known only by his book on logic) and Ptolemy became the principal sources from which the scientists in the thirteenth century drew their inspiration. As the Arabs had shown a great interest in Optics and in Ophthalmology, some Arabic authors, especially Alhazen, became very influential in the Western development of Optics. Three other authors are often mentioned, namely PSEUDO-EUCLID, TIDEUS and ALKINDI,[33] but, although they were often quoted by European authors, their works in fact were of no great value. The Arab Alhazen, on the other hand, is a very important scientist who takes a prominent place in the history of Optics,[34] as shown by the following fact. In 1604 the famous astronomer Johannes Kepler published the first modern book on Optics. He gave it the title *Ad Vitellionem Paralipomena.* Now Vitellio, who lived in the thirteenth century, was only a commentator of Alhazen who lived about 1000. This shows that in Kepler's opinion there had been so little progress in the science of Optics, that it seemed to him that his task was merely to add to Vitellio's, and thus to Alhazen's, doctrine.

Alhazen was a man of very wide knowledge.[35] His real name was Abū Muhammed B. Al-Hasen Ibn Al-Haiṯam Al Bāsri. He was a native of Basra (B.C. 962) and he died in Cairo in 1038.

He was a great admirer of Aristotle's. He knew Euclid's *Elements* (but not his *Optics*), Ptolemy's *Optics*, and the works of the physician Galen. He was an eclectic. His treatise on Optics was translated into Latin in the twelfth century by Gerard of Cremona. The first printed edition appeared in 1572. Alhazen had the choice between the centripetal and the centrifugal theory. As a follower of Aristotle he preferred the first[36] and he tried to amalgamate this doctrine with Ptolemy's geometrico–optical theory. From Galen he adopted the idea that the crystalline lens of the eye was the seat of vision.

He taught that sources of light, and objects which reflect or refract rays of light, send forth in all directions pencils of rays which bring along with them "species" or "formae" of the visible objects, as well as colours. His theory was that each separate point of the anterior surface of the crystalline lens, when it is stimulated by a ray, produces perception of a separate point of the visible object. There is thus a distinct connection in pairs between object points and image points.[37] Each perception of a point is accompanied by a distinct sense of direction. This sense of direction of the points of the anterior surface of the lens depends on an innate faculty. Here Alhazen met with a first difficulty, which is illustrated by Fig. 2.

According to Alhazen, stimulation of a point on the anterior surface of the lens gives rise to a perception of a point of light placed along a distinct direction with respect to the eye. Now consider three point-sources of light, *R* red, *B* blue and *Y* yellow, in front of the eye. Every point, *a*, *b*, *c*, *d*, *e*, *f*, *g*, of the anterior surface of the lens receives rays of these three colours. Point *d* receives red, blue and yellow rays, and thus should cause a sensation of a *mixed* colour coming from the direction *dB*. A similar conclusion applies to the case of all the other points. Therefore the result should be the perception of a *homogeneous* visual field of mixed colour, a field devoid of gradients. Such a uniform, empty, field would of

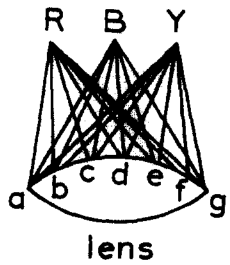

FIG. 2

course be quite useless. It could be compared with that which the Dutch poet Herman Gorter called "a dome of *blind* light" (*een koepel van blind licht*). Hegel already had said: . . . *im reinen Lichte sieht man nichts, . . . erst an der Grenze fängt die Realität an* (*Encycl. d. philosoph. Wissenschaften*, 1817).

Alhazen avoided this obstacle by introducing an abstraction. He assumed that only those rays which are normally incident upon the surface of the lens give rise to a perception of light. To support this hypothesis he mentions the fact that an arrow hitting a target does produce the maximum effect when its direction is normal to the surface of the target. By introducing this hypothesis Alhazen could deal with the subject in accordance with Ptolemy. For whether the direction of the rays was centrifugal or centripetal made no difference to demonstrations on paper. One was dealing only with straight lines, and the correspondence between object points and image points was restored.

On the assumption that only rays normally incident on the lens were effective, it was also necessary to assume that the rays penetrated the cornea along directions normal to its surface, and normal also to the anterior surface of the crystalline lens.

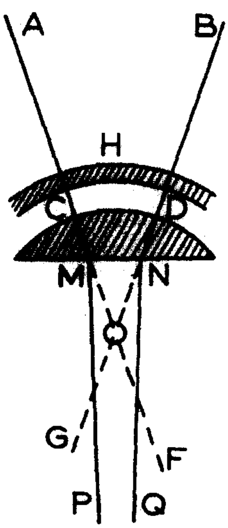

FIG. 3

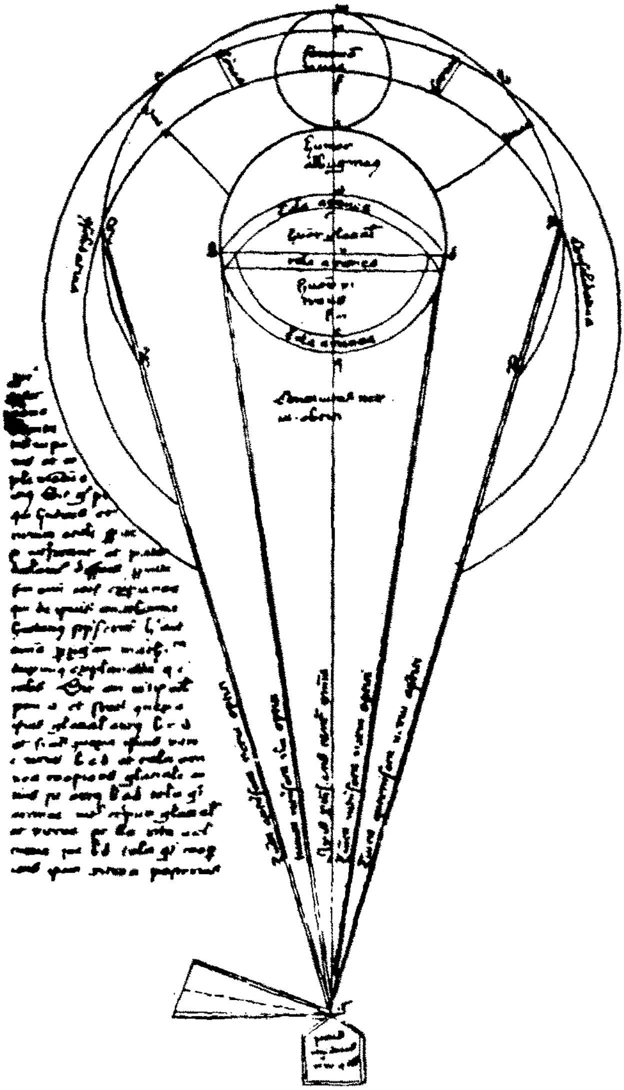

FIG. 4. Anatomy of the human eye, according to VITELLIO (Ms. Bibl. Nat. Paris).

According to Alhazen an object produces impressions on the lenses of *both* eyes, so that it was apparently to be expected that *double* vision would always occur. In order to avoid this further difficulty the author introduced yet another hypothesis.

Alhazen said that vision was not completed at the anterior surface of the lens. From Galen he borrowed the idea that the optic nerves were hollow (*nervi concavi*) (Fig. 3). The normally incident rays pass through the anterior surface of the lens and penetrate into the interior of the eye. Being normal to a spherical surface, they should meet in the common centre of curvature of the cornea and the anterior surface of the lens, at O. If such were the case they would continue their course in the directions of OF and OG, and so the ray

AO, which at first was on the left side, would come to the right side; the opposite would be the case with the ray *BO*. Alhazen could not accept this crossing of rays. For, before KEPLER (1604), no scientist could bring himself to believe in an inverted retinal image. Therefore Alhazen had to change the paths of these rays. He says that they were refracted at the posterior surface of the lens, at the points *M* and *N*, so that they became less convergent. In this manner they were able to enter the hollow optic nerves and reach the point where the two optic nerves meet, the *chiasma nervorum opticorum*. Here the images produced by both eyes eventually coincided, and this explained why vision was not double.[38] This made it necessary for Alhazen to introduce the hypothesis that the lens was less dense than the vitreous body behind the lens.

The chiasma was regarded as the seat of the *Sensus Communis*. In Fig. 4 the pentagon below shows the seat of the Sensus Communis. The eyeball with the optic nerve suggests the idea of a funnel. The figure is very formalistic. All the centres of curvature are on the axis of the eye.

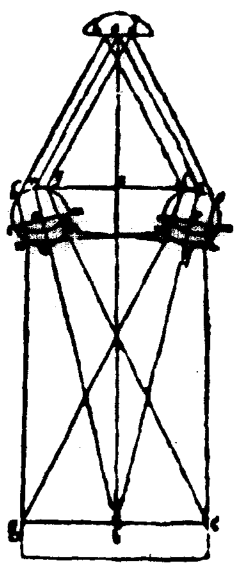

FIG. 5. Binocular vision, according to VITELLIO's *Perspectiva* (1572). RISNER (Editor), Basle (Univ. Libr. Leyde) 676 A 13.

Fig. 5 indicates how the images of three object points, produced in the two eyes, should coincide in the chiasma.

All this may seem rather naïve and it is full of errors. Yet, by reintroducing the centripetal theory of vision, Alhazen showed the right path to future generations of students of optics.

The psychological part of Alhazen's book conforms with Ptolemy's ideas. Alhazen's theory also makes use of subconscious syllogisms. He was a very good observer. Many passages in his work might have been written in the nineteenth century. He repeated Ptolemy's experiments on refraction and made the discovery that incident and refracted rays proceed in the same plane as the normal.[39] Like his predecessors he failed to detect a regular relationship between the angle of incidence and the angle of refraction. His method was very accurate. It is a pity that he did not give the numerical results of his experiments.[40]

Alhazen used Ptolemy's (erroneous) construction for the virtual images formed by refraction. His study of refraction was not limited to plane surfaces. He is, as far as we know, the first scientist who mentions refraction by curved surfaces. It is possible, however, that Ptolemy dealt with this subject in the last part of his book, which is lost.

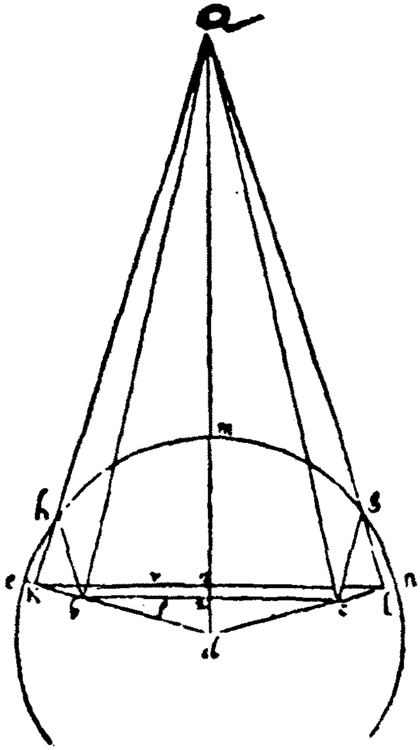

FIG. 6. Magnification of an image by means of a glass sphere. VITELLIO (1572), *Perspectiva*, RISNER (Editor).

Fig. 6 shows the construction of the virtual image produced by one curved surface.[41] The rays *bh* and *cg*, issuing from the extremities of the object *bc*, reach eye *a* after being refracted at *h* and *g*. The lines *ha* and *ga* are protracted. They intersect the normals on the spherical surface (*de* and *dn*) at *k* and *l*. The line *kl* is the virtual image of *bc*.

The virtual image produced by two refractions—in the case of a glass sphere—is also mentioned (Fig. 7). The eye-point is *A* and the object is *bc*. Two rays, *bi* and *bj*, issuing from *b* reach the eye along the paths *bieA* and *bjfA*. Two rays, *ch* and *ck*, coming from *c*, reach the eye along the paths *chdA* and *ckgA*. Rays proceeding from intermediate points of the object *bc* leave the sphere between the points *d* and *e* and between *f* and *g*. The virtual image is situated where the rays *Ad*, *Ae*, *Af* and *Ag* intersect the normals *Od*, *Oe*, *Of* and *Og*. The result is a corona or armilla.[42]

It seems that Alhazen did not perform experiments with lenses or, if he did, his lenses were so imperfect that they did not produce clear images.

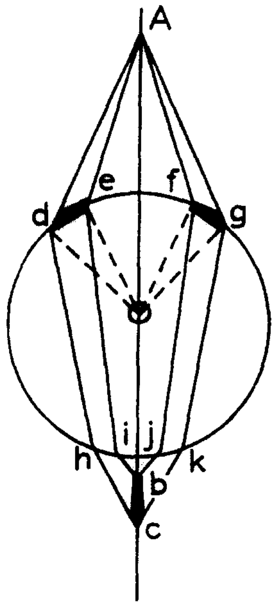

FIG. 7

B. GROSSETESTE

The new Latin translations of Greek and Arabic texts became known in England, where Robert Grosseteste became interested in optics.

Grosseteste was born in Suffolk about 1175. He studied at Oxford and probably at Paris. After his return to Oxford he became Rector Scholarum, Chancellor and, in 1224, Rector of the Franciscan habit; he was a secular priest. At Oxford he laid the foundation of his knowledge of Aristotle. He was a good Greek scholar and probably wrote a commentary on Aristotle's *Physics*. In 1225 he was elected Bishop of Lincoln. He at once set himself to reform all the abuses which his predecessors had left behind them. He had a very difficult life and was involved in many quarrels. He died in 1253. Probably no one exerted a greater influence upon English thought and literature during the two centuries following his time than Robert Grosseteste. His personal influence during his lifetime was scarcely smaller.[43] He was a great man.[44]

Grosseteste was a Light metaphysician[45] and entered the field of optics by the road of mathematics. The geometry which he required was very elementary, yet it would have been too difficult for scholars of the tenth and eleventh centuries. It was about the year 1000 that Gerbert of Aurillac (Pope Sylvester II, 999–1003) had introduced from the Spanish March the abacus and the new Indian method of computation. Gradually mathematical knowledge spread more and more. Geometry was reintroduced by Adelard of Bath's translation of Euclid's *Elements*. Such a revival of mathematics was needed to enable the study of optics to start.[46]

Roger Bacon says that *apud Latinos* lectures on optics were never held at Paris or anywhere else, except at Oxford. It seems probable that here Grosseteste was the lecturer, for he was at Oxford and he is the only scholar whose writings on optics have been preserved.[47]

Among his many treatises the following deal with optics:

(a) *De luce seu de inchoatione formarum;*[48]
(b) *De lineis, angulis et figuris;*[49]
(c) *De iride seu de iride et speculo;*[50]
(d) *De colore;*[51]
(e) *De motu corporali et luce.*[52]

According to Grosseteste light is the dominant factor in the World[53] and its most important property is self-multiplication.[54] Light also creates Space.[55]

In his speculations on optics, Grosseteste makes use of the centripetal as well as of the centrifugal theory.

The emanation of light proceeds along straight lines. This is a manifestation of Nature, which always follows the shortest possible ways.[56] The straight line *habet aequalitatem sine angulo: sed melius est aequale quam inaequale.*

That normally incident rays of light produce maximal effect is obvious, because the right angle ranks higher than an acute or obtuse angle.

Speaking about reflected rays, the author says that normally incident rays lose more of their energy than obliquely incident rays, because the alteration of direction (the difference between the incident and the reflected directions) is maximum when the rays are perpendicular.

Reflection on smooth surfaces is stronger than on rough surfaces because in the latter case the species are scattered.[57]

At a surface separating two different media rays can be refracted in two manners:[58]

(a) rays passing from a more subtle into a denser medium are refracted toward the normal erected on the point of incidence;
(b) rays passing from a denser into a more subtle medium are refracted from the normal.

A refracted ray is stronger than a reflected ray because it suffers less deviation.

A ray refracted towards the normal is stronger than a ray which is refracted from the normal.[59] These statements are based upon theoretical considerations and not on experiments and are often inexact.

In *De iride seu de iride et speculo* the word *Perspectiva* is used as a synonym of Optics. *Perspectiva*[60] is subdivided into three parts:

(1) The science of straight rays (*De visu*).
(2) The science of reflected rays (*De speculis*).
(3) The science of refracted rays.

Grosseteste says that this third subdivision had not yet been an object of study in England,[61] but that Aristotle had already written about this difficult topic. Ptolemy and Alhazen he does not mention.

He says that *philosophi naturales* are adherents of the doctrine of Intussusception, whereas mathematicians make use of the centrifugal theory.

Although Aristotle speaks of vision as a centripetal process, there are some passages in his work which, in Grosseteste's opinion, indicate that he also believed in emission. Grosseteste quotes these passages, which are not very convincing, but which enabled him to deal with reflection and refraction according to the centrifugal theory.[62] Why he preferred this theory is easy to understand. It enabled him to use straight lines and connect object points with single image points.

It seems that Grosseteste did not know Alhazen's and Ptolemy's books or, if he saw them, that he did not study them carefully. Otherwise it might be expected that he would have solved the problem of refraction in a different manner.

His conception in this respect is very formalistic. He was convinced *a priori* that between an angle of incidence and the correspondent angle of refraction there must exist a simple and regular relationship. He reasoned by analogy. In the case of reflection, the angle of incidence and reflection are equal. In refraction this equality cannot exist, otherwise there would be no refraction. The next simple proportion to 1 : 1 is 2 : 1. Therefore: the refracted ray's direction *bf* is the bisectrix of the angle *cbd* between the normal *ed* at the point of incidence and the prolongation of the original direction of the incident ray (Fig. 8).[63]

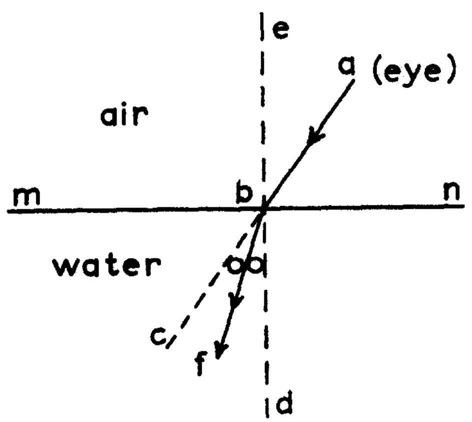

FIG. 8

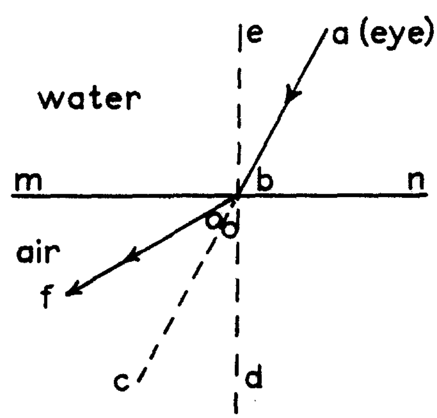

FIG. 9

In this case the eye is situated in the more subtle medium (air). When the eye is surrounded by the denser medium (water) (Fig. 9) the protracted direction *bc* is the bisectrix of the angle *fbd*.[64]

The construction of the virtual image of an object, when the refracting surface is plane, is done in the manner indicated by Ptolemy. The question arises whether Grosseteste had *indirect* knowledge of Ptolemy's assertions. He writes: *Res autem, quae videtur per medium plurium perspicuorum, non apparet esse ut ipsa est secundum veritatem, sed apparet esse in concursu radii egredientis ab oculo in continuum et directum protractum et lineae ductae a re visa cadentis in superficiem secundi propinquiorem oculo ad angulos aequales* [*normally*] *undique* (cf. Fig. 1b). Refraction by curved surfaces is not mentioned. Therefore it seems that Grosseteste did not know Alhazen's *Optics*.

His theory of the rainbow is not original.[65] Rays of light produced by the sun are refracted by the drops of a *hollow* cloud and give rise to the phenomenon.[66] Whereas here he speaks of refraction, however, earlier authors spoke of reflection.

De colore is a very short treatise. Colour is Light incorporated into the *perspicuum* (diaphanous medium).[67] A great deal of bright light in a pure perspicuum is *whiteness*; a dim light in impure surroundings is *blackness*. Between white and black there are fourteen colours.

In Grosseteste's *De iride* there are two remarkable passages: "For this part of *Perspectiva* [on refraction] shows us by what means we may make very remote objects appear to be quite near, and large objects, which are near the eyes, appear very small, and remote small objects appear as big as we like, so that it is possible for us to read very small characters at an incredible distance or to count grains of sand, or blades of grass or any other very small things."

". . . and it is clear to them in what manner they can shape perspicuous bodies, so that those perspicuous objects receive the rays, issuing from the eye, under a visual angle in the eye, as large as they like, and constrict the rays as much as they like on the visible objects, big or small, far away or near; and in this manner all visible objects may appear in any place and any size *ad libitum*; and it is clear how they can make very large objects appear very small, and, contrariwise, very small and remote objects as if they were big and very well discernible by sight."[68]

It is often said that Roger Bacon was the first scientist who hinted at the possibility of using lenses in spectacles and telescopes, but in this respect the preceding passages show that Grosseteste has the priority.

Did Grosseteste perform experiments with lenses? His inaccurate ideas on the proportion between the angles of incidence and of refraction do not give the impression that he was a great investigator.

Was he a visionary who foresaw the future development of optics? It is possible, though it cannot be proved, that he gained some knowledge from books written by other authors.[69]

Spectacles are first mentioned about the year 1300. Did Grosseteste and Bacon by their visionary utterances stimulate some contemporary to a more accurate study of the properties of lenses, which led to the invention of spectacles?[70] *Non liquet.*

To scientists of today Grosseteste's doctrine may seem naïve, devoid of solid foundation, and possessed of few original ideas. Nevertheless, as a scholar, his attitude differed very much from that of most of his colleagues. In the first half of the thirteenth century he was one of the few men who were really interested in Nature, in mathematics, in optics. At the same time he was a man of wide interests, versed in literature and philosophy.

Grosseteste lived in a century when scholars were convinced that every problem could be solved by metaphysical deduction and when—just as in the first half of the nineteenth century, at the time when the schools of Fichte and Schelling were flourishing—scientific observation of natural phenomena was considered to be a pastime of an inferior and useless kind.

It would be impossible to expect that Grosseteste would at once have become a scientist in the modern sense of the word. But a man of the thirteenth century who preached a doctrine differing to some extent from those of his contemporaries may claim a certain measure of originality. Grosseteste was the first in a very long series of scientists who gradually raised optics to its present level. It was not given to him to take many steps in the goodly land. His writings on optics occupy only a relatively small space (about twenty pages) in his voluminous work.

C. ROGER BACON

As the number of Greek and Arabic books translated into Latin increased, the representatives of the generation following Grosseteste had more and more books of this kind at their disposal. Thus Roger Bacon could become acquainted with the works of Euclid, Ptolemy, Alkindi, Alhazen, Constantinus Africanus, Theodosius and Aristotle. In Bridge's edition of Bacon's works[71] 212 pages are taken up by his *Perspectiva* and his *De multiplicatione specierum.*

Roger Bacon,[72] the "doctor admirabilis", was born between 1210 and 1215. He studied first at Oxford. His knowledge of Greek and Hebrew later made him independent of bad Latin translations. About 1240 he went to Paris, where he took his doctor's degree. There he made the acquaintance of Adam de Marisco, a man who kept himself far away from the prevailing metaphysical controversies and who, in private, pursued experimental research. It seems that Adam de Marisco exerted a great influence on Bacon.[73]

At Paris, it is likely that Bacon heard about two of his countrymen, Alexander Neckham and Alfred of Sareshel, who had previously lectured there on Aristotle's *Physics*. Between 1245 and 1250 Bacon took the Franciscan habit. He lectured at Oxford between 1250 and 1257.

In 1255 Bonaventura (John Fidanza), an exalted mystic, was elected General of the Franciscans. He disliked suggestions about Church reform put forward by Bacon. Bacon was sent to Paris, where he was put under restraint and for ten years was kept under close confinement without being able to communicate with his friends. In 1268 he was back in Oxford.[74]

Pope Clement IV, who had met Bacon during his visit to England, sent him a letter[75] enjoining him to forward to him secretly and privately any writing he could prepare, notwithstanding all injunctions to the contrary from his superiors. In 1266 and 1267 Bacon wrote his *Opus Majus*, *Opus Minus* and *Opus Tertium* and sent these by a trusted messenger to the Pope. The fate of these manuscripts is not known. Clement, who seems to have evinced a friendly disposition towards Bacon, died on 29 November 1268. Three years elapsed before his successor, Gregorius X (1271–1276), was elected.

In 1277 Jerome d'Ascoli, who had succeeded Bonaventura, convened a chapter of the Franciscans in Paris. Here Bacon was condemned *propter novitates suspectas*, and he spent fourteen years in prison.[76] Soon after being released he died, in 1292 or 1294. "Greek, mathematics, and experimental science were overwhelmed in the paralyzing mists of Scotian dialectic" (BRIDGES).[77] In the two following centuries there was almost no progress in the domain of optics. The revival had been of short duration. In the thirteenth century mediaeval philosophy was flourishing and scholars turned away from descriptive observation and analysis of empirical facts, applying themselves to metaphysical deduction and to the classifying of ideas.[78]

Alhazen's *Perspectiva* was Bacon's guide in his writings, which to a large extent constitute a commentary on the book of the Arab. Bacon adopted the idea that only normally incident rays are effective and he also accepted Alhazen's psychological doctrine.

Bacon's description of the anatomy of the visual organ is based on Galen, Avicenna, Constantinus Africanus and Alhazen.[79] He too believed that the crystalline lens was the seat of vision and that the act of seeing was completed in the chiasma of the optic nerves.

Whereas Alhazen wrote about convex lenses only, Bacon mentioned also the optical properties of curved surfaces having their *concavity turned towards the eye*. Here he distinguished four different situations (*canones*). This classification (Fig. 10), which was also adopted by John Peckham, is as follows:

(a) The object is in the denser medium:

(1) The eye R is somewhere between the concave surface and the centre of curvature F.

(2) The centre of curvature is between the concave surface and the eye.

(b) The object is in the more subtle medium:

(1) The eye is between the concave surface and the centre of curvature.

(2) The centre of curvature is between the eye and the concave surface.

The virtual image is determined by means of Ptolemy's and Alhazen's construction.

Propoſitio XI.

Concauitate diaphani denſioris ad oculum verſa, accidit conuerſo illi, quod contingit conuerſa ad oculum conuexitate.

Quando enim oculus eſt in ſubtiliori medio, & concauitas obuerſa oculo, ac oculus intra cētrum & rem viſam, imago quidem propinquior videbitur, ſed minor. Idem fit cæteris paribus, quando centrum inter oculum & rem viſam collocetur. Oculo verò exiſtente in denſiore medio, concauitate tenuioris ad oculum conuerſa, ſiue oculus ſit inter rem viſam, & centrum, ſeu centrum inter oculum & rem viſam, apparebit imago remotior & maior: quæ omnia in ſequentibus patent figuris.

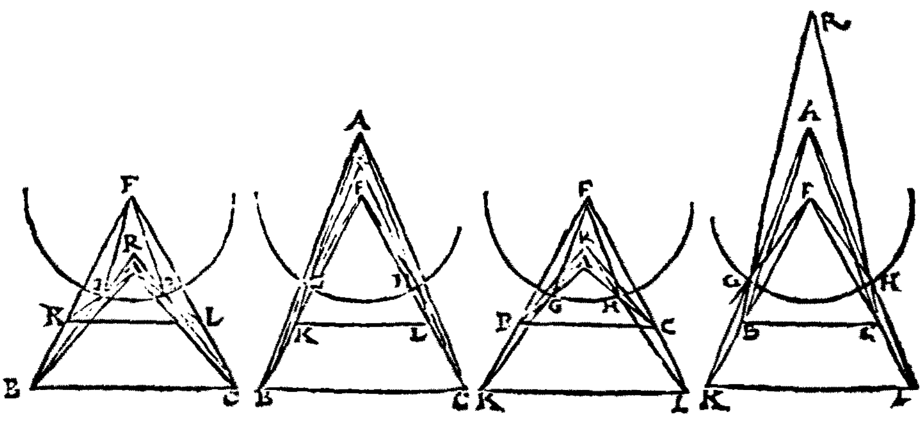

FIG. 10. Formation of images by concave lenses. JOHN PECKHAM (1556) (Editor) (Univ. Libr. Leyde, No. 546).

It is stated by many historians that concave glasses were invented in the fourteenth or fifteenth century, but the idea is already mentioned by Bacon. The question whether or not Bacon's suggestion in this respect was an original one cannot be answered.

Many passages in Bacon's works show that he was a good observer. When he could not prove an assertion by experimental results, he resorted, according to general mediaeval practice, to long and intricate argumentations. He would not have been a scholar of the thirteenth century if he had not sought help in this direction. He was surrounded by colleagues trained in scholastic disputes, who put greater trust in conclusions obtained by means of syllogisms than in visual evidence.

The period was one of system-builders. It was found difficult to accept that anything could be bereft of an explanation. Bacon, in comparison with most of his contemporaries, was a very modest man, who did at times admit that his knowledge was incomplete and that in many cases the use of pure argumentation was insufficient.[80] Other men would have been unhappy without an all-embracing system, and would not have contented themselves with a mere "rhapsody".

Two passages in Bacon's book have attracted the attention of many historians because they seem to prove that Bacon had some knowledge concerning spectacles and telescopes. The following are translations of these passages: "If the letters of a book or any minute objects be viewed through a lesser segment of a sphere of glass or crystal, whose plane base is laid upon them, they will appear far better and larger. Because, by the fifth canon about a spherical medium whose convexity is towards the eye and the object is placed below it and between the convexity and its centre, all things concur to magnify it. For the angle under which it is seen is greater, and its image is also greater, and nearer to the eye than the object itself, because the object is between the centre and the eye. And therefore this instrument is useful to old men and to those that have weak eyes. For they may see the smallest letters sufficiently magnified. But if the medium be the larger segment of a sphere, or but half of one, then by the sixth canon, the apparent visual angle will be greater than the true and the image also greater than the object because the centre of the sphere is between the eye and the object. And therefore this instrument is not so powerful in magnifying as a lesser segment of a sphere. Also instruments made of crystal bodies with plane surfaces, by the first canon about planes, and with concave surfaces, by the first and second canons about spherical surfaces, will perform the same thing. But the lesser of two segments of a sphere magnifies more manifestly than any of them all, by reason of all the three causes. . . ."

The second passage comes from Bacon's *Opus Majus*, and was also translated by Robert Smith: "Greater things than these may be performed by refracted vision. For it is easy to understand by the canons above mentioned, that the greatest things may appear exceeding small and on the contrary; also that the most remote objects may appear just at hand and on the contrary. For we can give such figures to transparent bodies, and dispose them in such order with respect to the eye and the objects, that the rays shall be refracted and bent towards any place we please. And thus from an incredible distance we may read the smallest letters, and may number the smallest particles of dust and sand, by reason of the greatness of the angle under which we may see them; and on the contrary we may not be able to see the greatest bodies just by us, by reason of the smallness of the angles under which they may appear. For distance does not affect this kind of vision, excepting by accident, but the quantity of the angle. And thus a boy may appear to be a giant, and a man as big as a mountain, forasmuch we may see the man under as great an angle as a mountain and as near as we please. And thus a small army may appear a very great one, and though very far off yet very near us, and on the contrary. Thus also the sun, moon and stars may be made to descend hither in appearance, and to appear over the heads of our enemies; and many things of the like sort, which would astonish unskilled persons."[82]

It is small wonder that many (for instance William and Samuel Molyneux and Robert Smith) saw in Bacon the inventor of spectacles and telescopes: "That this learned Frier Bacon who dyed An. 1292, and lyes buried at Oxford, did perfectly well understand all sort of optick glasses, shall be plainly made out, from the natural and easy sense of his own words . . . whereby we shall find, that he not only understood the effects of single convex and concave glasses; but knew likewise the way of combining them, so as to compose some such

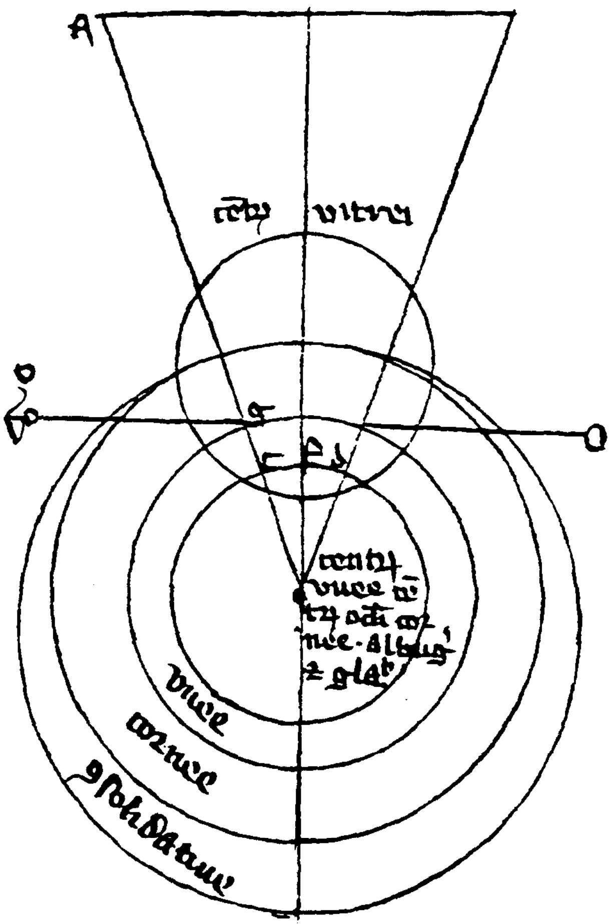

FIG. 11. ROGER BACON, *Perspectiva*. (Ms. Univ. Libr. Prague, No. 1552.)

instrument as our telescope. This perhaps will be looked upon as a great paradox, and as great partiality in an English author to his countryman. . . ."

A comparison with Grosseteste's words, mentioned above, clearly shows that Bacon in this respect was much indebted to his old teacher and friend. That he did not experiment extensively with lenses is apparent from the fact that he sent the Pope a crystal sphere in order to demonstrate its *caustic power*. If he had known spectacles, it should be expected that Bacon would also have mentioned the magnifying power of the sphere—but this he did not mention.

There is a great deal of variation in the illustrations of the several manuscripts of Bacon's optical works. Some anatomical drawings of the visual organ are made with the aid of compasses, others are mere sketchy outlines. A manuscript of the *Perspectiva* in the University Library at Prague (No. 1552) shows a "construction" of the eye reproduced here in Fig. 11. There are three concentric circles which contain between them the words *vuea* and *cornea* (corresponding to the *choroid* and *sclera* of today). A fourth circle, not concentric with the other three, is marked *consolidativa*, the collective name of the components of the contents of the eye-socket apart from the eyeball itself (fat tissue, muscles, nerves, blood-vessels, eyelids, etc.).[83]

The centre of the three concentric circles is denoted: *centrum vuea, centrum oculi, corneae, albuginei et glacialis.*[84] A fifth circle, intersecting the four others, forms with the inner circle a lunula (similar to the shape of a section through a biconvex lens) and constitutes the posterior surface of the lens and at the same time the anterior surface of the vitreous humour. The words *centrum vitrei* are written at the wrong place. *Umor vitreus* is nowadays called *corpus vitreum* or vitreous humour. The gap between the two horizontal lines indicates the position of the pupillary aperture. The triangle contains all the rays which can enter the eye.[85]

The very interesting treatise called *De multiplicatione specierum* is based on Aristotle's theory of vision and contains, in a sense, a theory from which the modern theory of light could be derived.

Many authors in the thirteenth century wrote about the multiplication of *species.*[86] The word *species* often changed its meaning in the course of time. While the history and development of the doctrine of *species* cannot be discussed here in full, some indications may be given.

In general *species* means something which makes communication between the external object and the visual organ possible. It was used to designate those qualities which are common to the visible object and to the impression which that object makes on the sense organ. In connection with variations in the meaning of the term there came into use synonyms, such as *simulacra, intentiones, formae, spectra, similitudines, idola.*[87]

For Bacon *species* was the name of the first effect of any natural agent.[88]

According to Bacon, a *species* is not something material, proceeding from the objects towards the eye, like Lucretius's simulacra. He states that if the *species* were material the objects would gradually lose weight and eventually vanish.

He considers the object as an *agens* which incites the perspicuum (diaphanous medium) surrounding it to convert its potential qualities into actual qualities.[89] Thus this medium is the *patiens.*[90] The alteration of the medium (from potentiality into actuality) proceeds from the object, as central point, along all possible directions in straight paths. Therefore it takes some time before the action of the object can reach the eye. But this interval is so short that it is imperceptible.

The action of the object evokes a reaction from the *perspicuum patiens*; the effect of this reaction is the actualization of slumbering properties.

Some authors stated that *species* were of a spiritual nature. Bacon does not agree with this.[91] *Species* take their origin from matter and they exert force on matter, but they are not three-dimensional, contrary to the opinion of Alkindi and Alhazen. Bacon says that if *species* have three dimensions it will be impossible for two rays of light to intersect and afterwards to go on following their original separate directions. Two bodies cannot occupy the same place at the same moment. *Species* are latent qualities of the medium which have come into a condition of actuality. A given particle of the medium can, at the same moment, manifest several different qualities.

It is hardly possible to give an adequate idea of this book of Bacon's in a brief exposition such as the present one.

While many problems could be solved by assuming that the propagation of *species* occurred along straight paths, it was difficult to explain how *species* could reach the *sensus communis* in the chiasma without deviations from the straight road. Therefore Bacon introduced the hypothesis that in animate bodies rays could follow tortuous paths along the nerves. This happened under the influence of the soul.[92] A visible object, in illuminated surroundings, stimulates the diaphanous medium to actualize its potential qualities. In the medium there are several slumbering qualities, but only the *species* of light and colour affect the eye.

The propagation of *species* from the visible object may be compared with the modern wave-theory. From the object, as centre, the actualization proceeds in all directions along straight paths which cause spherical fronts of actualization.

If several rays, say, red, blue and yellow, meet in one point, one has to assume that the particle of the medium which is at that moment in that point, actualizes simultaneously its red, blue and yellow qualities.

Because the actualization proceeds from particle to particle, it might have been expected that wind, blowing transversely, would impede the straight progression of the rays. But this does not occur. The *species* actualized in a specific particle of the medium is not permanent but is continually renewed. When wind removes a particle its place is taken by another particle, which in its turn actualizes the same quality. Thus the actualization is connected with the properties of space, in this case the direction of the straight ray, rather than with the particles which happen to lie somewhere along that line of direction.

In dark surroundings, according to this theory, one might have expected to see between a source of light and an illuminated wall a continuous connecting bundle of light. Bacon explains that we do not see such a bundle by the assumption that the *species* in the air are weaker than those on the wall. Different substances have different powers in multiplying *species*. In order to support this thesis, Bacon points out that a piece of iron held at some distance from a magnet is more strongly affected by magnetism than the air situated between the magnet and the piece of iron.

There is a passage in Bacon which is somewhat reminiscent of Plato's *Synaugeia*. Every organ creates *species*[93] and therefore the sense organ also must do this. This is proved by the fact that a man can see the eye of another man; thus the eye does produce *species*.[94]

According to Plato's doctrine of *Synaugeia* the two kinds of light become fused. According to Bacon the *species* coming *from* the eyes do not mingle with those coming from the visible objects, because the *species* coming from the eye are derived from an animated body and thus differ from the *species* which come from inanimate objects.[95] In this respect there is a regression in comparison with Alhazen's theory.

Was Bacon the founder of modern *scientia experimentalis*? His own words give rise to doubt in this respect. In his *Opus Tertium* (c. XIII) he mentions a "remarkable and almost unknown genius" (Bridges). This was Peter Peregrinus of Maricourt (Maharncuria or Mahariscuria—Adam de Marisco—?) in Picardy, who has already been mentioned. "One man I know, and one only, who can be praised for his achievements in science. Of discourses and battles or words he takes no heed: he follows the works of wisdom, and in these he finds rest. What others strive to see dimly and blindly, like bats in twilight, he gazes at in the full light of day, because he is a master of experiment. Through experiment he gains knowledge of natural things, medical, chemical, indeed of everything in the heavens or earth. . . . If philosophy is to be carried to its perfection and is to be handled with utility and certainty, his aid is indispensable. As for reward, he neither receives or seeks it. If he frequented kings and princes, he would easily find those who would bestow on him honours and wealth. Or if in Paris he would display the results of his researches, the whole world would follow him. But since either of these courses would hinder him from pursuing the great experiments in which he delights, he puts honour and wealth aside, knowing well that his wisdom would secure him wealth whenever he choose. . . ."[96] One of Peter's letters has been published by Libri.[97] It is a great loss that so little is known about this idealistic scientist.

Opinions on Bacon's work as a scientist are very divergent. Some saw in him a genius who invented spectacles and telescopes and predicted the discovery of X-rays. Others regard him as a man more of words than of deeds. His achievement can only be assessed by comparing him with his contemporaries and then the judgment is found greatly in his favour.

One man could not create out of nothing a modern physical laboratory and invent many new methods of experimental research and critical scientific discussion. It is sufficient for Bacon's fame that he acted as a guide showing the way towards a new domain of science. He was a martyr who would not hide his advanced opinions. He was *justus ac tenax praepositi.*

Bacon's so-called prophecy of the discovery of X-rays is founded partly on scholastic reasoning and partly on the myth that a lynx would be able to see a corpse buried under a thick layer of earth. His pronouncements on the possibility of manufacturing spectacles and telescopes were, as has been shown, borrowed from Grosseteste.

Nevertheless it is very much to his credit that, in the thirteenth century, he understood that scholastic argumentation alone was not sufficient to reach the goal which all scholars wished to reach. He was prepared to repudiate authority if the results of observation and experiment were in contradiction with established theories. His knowledge was encyclopaedic. Among his contemporaries Bacon takes a prominent place.

D. JOHN PECKHAM

During the following centuries John Peckham's *Optics* was the most popular book on this subject. It is said that this book was given the name *Perspectiva communis* because it was in use everywhere.[98] It ran into numerous editions. This work probably was so much in favour because of its conciseness. It is a small book in which Alhazen's theory is explained in about 100 propositions.

Peckham's book was *the* text-book until as late as about 1600. At some universities Music, sometimes even Geometry, was replaced by Optics in the study of the Quadrivium. In 1431 students in Oxford had the choice between Euclid's *Elements* and Peckham's *Perspectiva communis*. Optics had officially become one of the Liberal Arts in the Quadrivium.

John Peckham was born in Sussex (perhaps at Petcham). He studied first at Oxford and afterwards at Paris. He entered the Franciscan Order. About 1230 he came back to Oxford. He was elected Provincial Minister of the English Franciscans and Lector Sacri Palati at Rome. In 1279 he was installed Archbishop of Canterbury. He died in 1292. He was a theologian, a mathematician, a physicist and a very voluminous writer.[99]

Although he adopted Alhazen's theory on vision, Peckham was not, like Grosseteste and Bacon, an admirer of Aristotle's: *Johannem Pechanum . . . Peripateticorum novellae doctrinae semper et ubique repugnavisse nemo est hodie qui ignoret.* (Spettmann, loc. cit., p. XV). He also, as a rule, takes only into account rays of almost normal incidence. Yet he has to admit that oblique rays also can sometimes produce vision. It is difficult to understand how he succeeded in reconciling this with his theory.[100]

According to Peckham water produces magnified images because its surface is spherical.[101]

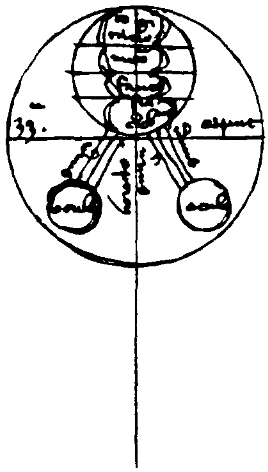

FIG. 12. Anatomy of brain and eyes. JOHN PECKHAM, *Perspectiva communis* (Univ. Library, Basle).

Our ability to estimate the distance between our eyes and visible objects is based on the fact that we are able to feel the length of the rays coming from the objects.[102]

The same book also contains a great deal of scholastic and inconclusive argumentation. On the whole Peckham's work is less original than Bacon's treatise.

Galen had stated that the brain contained three or four ventricles. Most Arab authors considered that these cavities were the seats of different mental faculties.[103] Bacon and

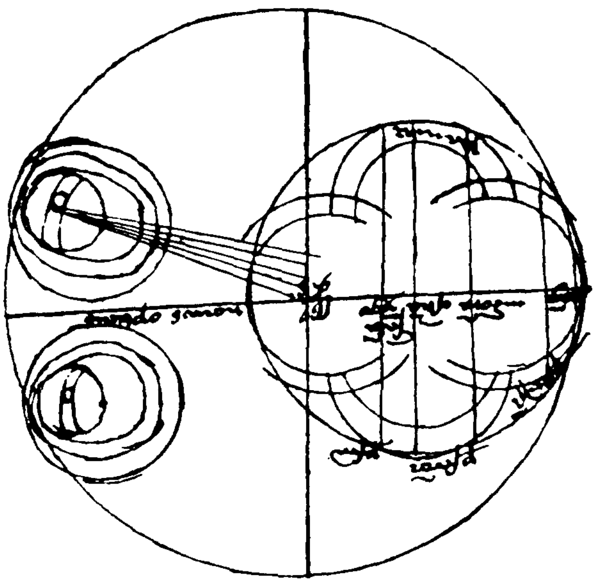

FIG. 13. Eyes and brain, according to JOHN PECKHAM'S *Perspectiva communis* (1430). (Ms. by Czechel, Jagellon. Libr. Cracow, No. 1929.)
Inscription: Above: perfectissima, perfectior, perfecta. Middle: cogitativa, memorativa, estimativa, sensitiva imago, sensus communis, nervus opticus. Below: pia mater.

Peckham also accepted this theory. Fig. 12 shows the localization of *cogitacio*, *memoria*, *fantasia*. In Figs. 13 and 14 are shown the seats of *cogitativa* (*scil. virtus*), *memorativa*, *estimativa*, *sensitiva imago*, *sensus communis*. In the printed editions the crystalline lens is drawn in a number of different and fantastic manners.

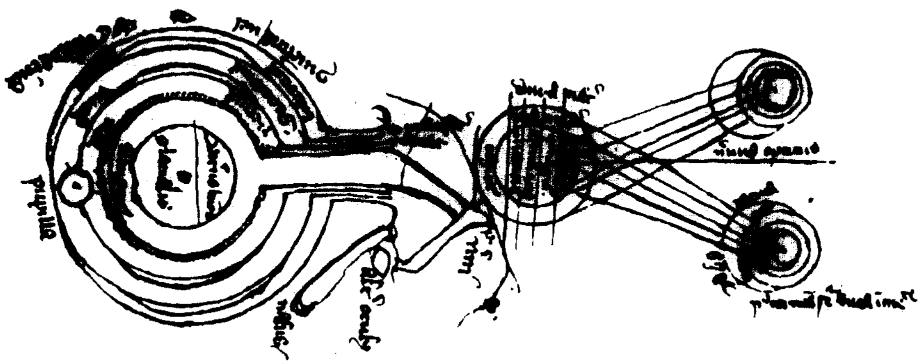

FIG. 14. Eye and brain, according to JOHN PECKHAM (Ms. Nat. Libr. Vienna, No. 5210).

In the process whereby knowledge is obtained about the visible world Alhazen, Bacon, Peckham and Vitellio distinguished two factors, which are nowadays generally called *perception* and *apperception* (*Empfindung* and *Wahrnehmung*, H. von Helmholtz; *Gewaarwording* and *Waarneming*, in Dutch). Light and colour are perceived by means of the *sensus communis* (*solo sensu*).[104] Real understanding of the world depends on other mental faculties, which make apperception possible. Here the role of association and of memory becomes very important.

E. VITELLIO

The most voluminous book on optics written in the thirteenth century is Vitellio's *Perspectiva*.[105] It is little more than a commentary on Alhazen's *Optics*. One of the few additions is a description of perspective phenomena in Euclid's manner.

It is possible, or even probable, that there exists a connection between the books of Roger Bacon and of Vitellio. This hypothesis is based on the consideration of a few facts concerning Vitellio's life.[106]

Vitellio was born about 1230. It is probably that his father was of Thuringian and his mother of Polish origin. Vitellio visited the University of Padua (about 1260). Later he stayed at Viterbo. He was a friend of William of Moerbeke, the Penitentiary of the Papal See.

In the preface of his book, he says that he wrote this work on Optics by special request of van Moerbeke, although he had never before studied this branch of science.[107] It seems that this was a matter of urgency, for he says that in order to complete his task, he left unfinished another book on which he was at work. Vitellio wrote his book about 1270, three years after the reception of Bacon's manuscripts at Viterbo.

All this suggests the following hypothesis: Is it not possible that the ecclesiastical dignitaries at Viterbo—the residence of the Curia—were interested in finding out whether Vitellio, a scholar who was not under suspicion, would pass on Alhazen's optics a judgment similar to Roger Bacon's?

CONCLUSION

In the three following centuries progress in optics was slow.[108] About the year 1300 spectacles are mentioned for the first time. As these visual aids came more and more into use, there were more occasions to observe the properties of lenses. Otherwise there was almost no progress until the fifteenth century (Porta, Maurolycus and De Dominis). The great obstacle remained: scientists found it impossible to understand how an image inverted on the retina could be compatible with upright vision of the outside world. It was Kepler who, in 1604, removed this obstacle: "Vision, I say, occurs when the image of the whole hemisphere of the external world in front of the eye, in fact a little more than a hemisphere is projected onto the pink superficial layer of the hollow retina."[109]

Robert Grosseteste, Roger Bacon, John Peckham and Vitellio had been the pioneers on the road on which Kepler would earn fame and open up the era of modern optics.

Acknowledgements—Finally, I want to thank Dr. M. H. PIRENNE (Oxford) and Dr. A. C. CROMBIE (Oxford) for their support and very valuable advice.

NOTES

1. "The Oxford school of scholars who reacted against the prevalent methods of logic, philosophy and theology by stressing the study of natural sciences and the languages"; PAETOW, L. J. (1931). *A guide to the study of Medieval History.* The author mentions Grosseteste, Roger Bacon and Adam Marsh. "... dass gerade in Oxford eine Schulrichtung blühte, die wesentlich auf naturphilosophische Probleme spezialisiert war und während Bacons Studienzeit in Robert Grosseteste ihren grossen Professor hatte"; LIEBESCHÜTZ, H. (1932). *Der Sinn des Wissen bei Roger Bacon*, p. 29.
2. RAND, E. K. (1929). *Founders of the Middle Ages*, p. 282. Even before the Carolingian period, there had been a few scholars interested in antiquity, e.g. St. Aldhelm (*ca.* 640–709), Doulton near Wells, *fl.* at Malmesbury, who was acquainted with Greek and possibly also with Hebrew; HASKINS, C. H. (1939). *The Renaissance of the twelfth century.*
3. "Deus dicitur lux proprie et non translative", and "substantia habens magis de luce quam alia dicitur nobilior ipsa"; BÄUMKER, C. (1908). *Witelo, ein Philosoph und Naturforscher des dreizehnte Zahrhunderts,* Münster (1908). *Beiträge zur Geschichte der Philosophie des Mittelalters*, **3**, *Heft* 2. According to SIMPLICIUS (sixth century) (*Commentary of Aristotle's Physics*, 142a–143b) PROCLUS (A.D. 412–485) had said, that Space was subtle light. Cf. Hegel, G. F. W., *Encyclopaedie der philosophischen Wissenschaften*, para. 275: "Das Light ist unendliche Erzeugung des Raums."
4. "Unsere bisherige Erfahrung berechtigt uns zu der Gewiszheit, dass in der Natur die Idee einer mathematischen Einfachheit verwirklicht ist."
5. PLUTARCH, *Quaest. conviv.*, Lib. VIII, c. 1: «ὁ θεός ἀεί γεωμέτρει.»
6. "... si enim visus celerrime pervenire debet ad objectum visibile, per rectam feretur lineam, cum haec omnium illarum linearum brevissima est quae ab ipsis duobus terminis comprehendentur"; HELIODORUS of Larissa (*ca.* A.D. 500), Capita Opticorum, Graece et Latine reddita, Pistoria (1758).
7. "Qua propter natura definitum antefert indefinito, utpote melius, ac animantis rationalis magis proprium, videndi potentia in iis, quae ante sunt, maxime operatur"; HELIODORUS of Larissa.
8. "... si visus aliquid recipere debet quam maxime potest ab objecto visibili, in idem proficietur in figura circuli. Demonstratum namque fuit, hunc esse propriorem inter illas figuras et superficies, quae habent aequalem perimetrum"; HELIODORUS.
9. If they had dissected and observed a human eye, they might have seen that the anatomy did not conform to their formalistic conception. But, even if they had dissected eyes, the conviction that their formalistic conception was right would have made them overlook the incongruity. *Vide:* Illustrations (1931). *Sudhoff's Archiv für Geschichte des Medizin*, published by Bednarski, and POLYAK, S. L. (1941). *The Retina.*
10. *Euclidis Optica*, HEIBERG, I. L. (Editor) (1895). Teubner, Leipsig. The same book contains: *Opticorum Recensio Theonis* (Alexandria, *fl. ca.* 378–395), a commentary on Euclid's book. Here we also find the *Catoptrica*; texts of the three books are given with their old Latin translations; ALBERT LEJEUNE (1948). *Euclide et Ptolémée. Deux stades de l'optique géométrique grecque.* Université de Louvain; *The Optics of Euclid* (translated by H. E. Burton) (1945). *J. opt. Soc. Amer.* **35**, 357–372; PAUL Ver' EECKE (1938). *Euclide, L'optique et la catoptrique* (Oeuvres traduites pour la première fois du grec en français avec une introduction et des notes). Desclée De Brouwer, Paris et Bruges.
11. DISNEY, A. N., HILL, C. F. and WATSON, W. E. (1928). *Origin and development of the Microscope.*

12. Euclid's first supposition is: "Ponatur, ab oculo rectas ductas lineas ferri spatio magnitudinum immensarum"; THEON (quoted in Footnote 10) gives the following version: "Supponamus, radios ex oculo secundum rectas lineas ferri inter se distantes." (The translation given here is from Burton (*op. cit.*).)
13. AETIUS, DIELS' *Doxographi Graeci*, p. 404.
14. APULEJUS, *Apologia*, c. XV.
15. SUETONIUS (1907). *Vitae Caesarum* (Editor Ihm). Leipzig.
16. *L'ottica di Claudio Tolemeo, da Eugenio Ammiraglio di Sicilia, scrittore del Sec. XII* (riduta in Latino, sovra la traduzione araba di un testo greco imperfetto) . . . Pubblicate da Gilberto Govi, Torini (1885); LEJEUNE, A. (1956). L'optique de Claude Ptolémée dans la version latine d'apres l'Arabe de l'émir Eugène de Sicile. (Ed. critique et exégétique.) Université de Louvain.
17. "Das Lesen des Werkes ist eine wirkliche Qual"; HIRSCHBERG, J., *Gesch. d'Augenheilk.*, paragr. 95. (It is a Latin translation of an Arabic version of the original Greek text.)
18. "On y voit des expériences de physique bien faites, ce qui est sans exemple chez les anciens"; DELAMBRE, J. B. (1817). *Histoire de l'astronomie ancienne* **2**, 427.
19. ". . . quod res visae in speculis apparent in concursu visus (visual ray) directe protracti et lineae ductae super speculi superficiem and angulos undique aequales (normal to the surface)."
20. Historians disagree on the question whether the Ancients knew of the magnifying power of lenses. Ptolemy, in his experiments on refraction, made use of a cylindrical lens, but he does not mention its magnifying properties. It is possible that in the last part of his book, which is lost, he spoke about refraction by curved planes. GOVI (cited in Footnote 16) writes (p. 36): "La mutilazione di questo quinto libro ci toglie, per ora almeno, ogni mezzo di conoscere con certezza se gli Antichi avessero o non avessero i ventri lenticolari, non bastando a provare che li avessero quello che Tolemeo vi dici dei mezzi terminati da una superficie piana o da una superficie cilindrica. Chè anzi il non parlarvarsi di vasi sferici, nè di porzioni di sfera potre ben quasi assicurarne del contrario." In the early Middle Ages only the caustic effect of lenses is mentioned.
21. BARROW, I. (1674). *Lectiones opticae et geometricae*, etc. London.
22. "Visus utitur diligenti ratiocinatione cum mirabili celeritate et agit haec insensibiliter propter celeritatem suam." GOVI, G. (Editor) (1885). *L'ottica de Claudio Tolemeo*, p. 33. Torino.
23. *Handbuch der physiologischen Optik* (Third edn.) (1910), 3: "Die psychischen Thätigkeiten . . . sind im allgemeinen nicht bewuszte Thätigkeiten, sondern unbewuszte. Sie sind in ihren Resultate einem Schlusse gleich; . . . in ihren Resultaten den sogenannten Analogieschlüssen kongruent" (p. 25).
24. T. LUCRETIUS CARUS. *De Rerum natura*, 4, v. 42–53:
    (42) "Dico igitur rerum effigies tenuisque figuras"
    (43) "Mittier ab rebus summo de corpore rerum,"
    (51) "Quae quasi membranae vel cortex nominatandast,"
    (52) "Quod speciem ac formam similem gerit imago"
    (54) "Cuiuscumque cluet de corpore fusa vagari."
25. ARISTOTLE: *On the Soul, Parva Naturalia, On Breath.* The Loeb classical library, No. 288 (transl. by W. S. Hett [II, VIII]).
26. «κινητικόν εἶναι τοῦ κατ' ἐνέργειαν διαφανοῦς . . . τὸ χρῶμα κινεῖ τὸ διαφανές.»
27. «ἡ δ' εντελέχεια τοῦ διαφανοῦς φῶς ἔστιν.»
28. «τὸ μὲν χρῶμα κινεῖ τὸ διαφανές, οἷον τὸν ἀέρα, ὑπὸ τούτου δὲ συνεχοῦς ὄντος κινεῖται τὸ αἰσθητήριον.»
29. An excellent survey of Aristotle's theory is given by BEARE, J. I. (1906). *Greek theories of elementary cognition from Alcmaeon to Aristotle.* Oxford.
30. TIMAEUS, 45B–46A.
31. (Translated by J. I. BEARE.)
32. Some knowledge of classic Greek literature was also gathered by travellers who visited Constantinople. But such direct information was much less important than information which was obtained indirectly through Arabic and Latin translations.
33. Alkindi, Tideus and Pseudo-Euclid were upholders of the Emission theory. Their books on optics were published by A. A. Björnbo and S. Vogl . . . *Drei optische Werke* (1912).
34. *Opticae thesaurus Alhazeni libri septem nunc primum editi . . . Item Vitellonis Thuringopoloni libri decem de Optica*, a Frederico Risnero, Basileae (1572).
    The original title of Alhazen's book was: *Kitab-al-manazir*.
35. "The greatest Muslim physicist and one of the greatest students of all time"; SARTON, G. (1927–1931). *Introduction to the History of Science*, p. 721. Alhazen was also astronomer, mathematician, physician and he wrote commentaries on Aristotle and Galen.
36. "Visio non fit radiis a visu emissis. . . ." (*op. cit.*, Vol. 1, 23); "Visio fit radiis a visibili extrinsecus ad visum manantibus. . . ." (*op. cit.*, Vol. 1, 14).

37. "Visus e singulis suae superficiei punctis singula puncta visibilium videt. . . ." (*op. cit.*, Vol. 1, 15).
38. "Utroque visu una visibilis forma plerumque videtur. Istae ergo duae formae extenduntur a duobus oculis et concurrunt in loco concursus duorum nervorum. . . ." (*op. cit.*, Vol. 1, 27).
39. "Radii incidentiae et refractionis sunt in uno plano. . . ." (*op. cit.*, Vol. 8, 5).
40. He did say that the propagation of species in the denser medium was slower than in the more subtle medium.
41. "Si visus sit in continuato diametro circuli . . . visibile vero inter ipsius centrum et visum, ab eodem centro aequabiliter distet; imago videbitur major visibili" (*op. cit.*, Vol. 7, 44).
42. "Si visus, centrum refractivi convexi densioris, et visibile ultra refractivum positum, fuerint in eadem recta linea; imago videbitur corona seu armilla; et major visibili" (*op. cit.*, Vol. 7, 49).
43. *Dictionary of National Biography;* CROMBIE, A. C. (1953). *Robert Grosseteste and the origins of experimental science, 1100–1700.* Oxford.
44. "Solus unus scivit scientias ut Lincolniensis episcopus"—Roger Bacon.
45. "Et species et perfectio corporum omnium est lux."
"Lux vero omnibus rebus corporalibus dignioris et nobilioris et excellentioris essentiae est. . . . Lux ergo est prima forma corporalis."
46. Grosseteste was probably influenced in this respect by Adelard of Bath (twelfth century), who visited Jerusalem and Spain and became acquainted with Arabic books. Adelard translated Euclid's *Elements* from Arabic into Latin. He was interested in Science [*Quaestiones naturales*; MÜLLER, M. (Editor) (1934). *Beitr. z. Gesch. d. Philos. d. Mittelalters*, Vol. 31]. He may also have read ADELARD's "*De eodem et diverso*", the subject of which was the seven Liberal Arts [Ed. H. WILLNER (1903)].
47. Before Grosseteste the importance of optics was mentioned by DOMINICUS GUNDISSALINUS (Gonzáles, Gundisalvo; twelfth century), who, in his *De divisione philosophiae*, devoted thirty-three out of 140 pages to science and mathematics. His views on optics were based on the centrifugal theory; refraction is not mentioned. This part is borrowed, word for word, from ALFARABI's *De scientiis*. Alhazen is not mentioned. (BAUR, L. (Editor) (1903). *Beitr. z. Gesch. d. Philos. d. Mittelalters*, Vol. 4; MSS.: Oxford, Digby 76, C. Christi 86; Cambridge Univ. Libr. H.h. 4.13.)
48. MSS.: London, Bibl. reg. 6 E V, fol. 242.
Oxford, Merton 295.
Oxford, Digby 104, 98 and 220.
49. MS. : Oxford, Laudon Misc. 644.
50. MSS.: Oxford, Digby 190, 104 and 98.
Oxford, Merton 306.
London, Bibl. reg. 6 E V.
51. MSS.: Oxford, Digby 98, 104, 190 and 220.
London, Bibl. reg. 6 E V.
52. MS. : London, Bibl. reg. 6 E V.
53. "Formam primam corporalem, quam quidam corporeitatem vocant, lucem esse arbitror."
54. This "self-multiplication" will be discussed later.
55. "Lux igitur . . . infinities multiplicata materiam similiter simplicem in dimensiones finitae magnitudinis necesse est extendere"; "ea, quae sunt multa esse multa ab ipsius lucis multiplicatione". "Agens naturale multiplicat virtutem a se usque in patiens, sive agat in sensum, sive in materiam. Quae virtus aliquando vocatur species, aliquando similitudo. . . ."
56. "Natural science, Grosseteste taught, is based on mathematics. . . . He used Optics as best adapted to illustrate the prevalence of mathematical law; but the nature of light had a still wider and deeper interest for him. Light is a force or a form of energy which acts by an instantaneous self-expression in all directions from a centre: it is the simplest and most subtle body, the most akin to spirit, the type and symbol of creative mind." LITTLE, A. G. The Franciscan School at Oxford in the thirteenth century: *Archivum Franciscanum Historicum*, Annus IX (1903), p. 803 ff. See also: Die philisophischen Werke des Robert Grosseteste, Bischofs von Lincoln. BAUR, L. (Editor) (1912). *Beitr. z. Gesch. d. Philos. d. Mittelalters*, Vol. 9.
57. ". . . tunc dissipatur species. . . ."
58. "Et haec est dupliciter; quoniam si illud corpus secundum est densius primo, tunc radius frangitur ad dexteram et vadit inter incessum rectum et perpendicularem ducendam a loco fractionis super illud corpus secundum. Si vero sit subtilius, tunc frangitur versus sinistram recedendo a perpendiculari ultra incessum rectum."
59. The author here makes use of the centrifugal theory.
60. The term "perspective", as a synonym of Optics, is already mentioned by BOETHIUS (*ca.* A.D. 500). It supplanted the word Optica. The treatises written by BACON and PECKHAM were named *Perspectiva* (fem. sing. or neutr. plur.). During the Renaissance *Perspectiva* became the name of the art of suggesting depth in works of art, and *Optics* became again the name of the theory of light and vision.

61. "... apud nos intacta et incognita usque ad tempus hoc permansit": BAUR, L. (Editor) (1912). *R. Grosseteste. Beitr. z. Gesch. d. Mittelalters*, Vol. 9 (1917), *ibid.*, Vol. 18.
62. Grosseteste also says: "tres dicti sensus, scilicet visus, auditus, olfactus, exeunt ab instrumentis, sicut aqua exit a canalibus." BAUR: *op. cit.*
63. "Dico igitur, quod incessus radii in secundo diaphana est secundum viam lineae dividentis per aequalia angulum, quem continet radius imaginabiliter in continuum et directum protractus et linea a puncto incidentiae radii ad angulos aequos super superficiem secundi diaphani in profunditatem eius ducta." BAUR: *op. cit.*
64. In spite of the fact that these assertions concerning relationships between angles seem based on purely formalistic speculations, the author says that they are corroborated by experiments: "Quod autem sic determinetur anguli quantitas in fractione radii, ostendunt nobis experimenta similia illis, quibus cognovimus, quod refractio radii super speculum fit in angulo aequali angulo incidentiae"; "Omnis operatio naturae est modo finitissimo, ordinatissimo, brevissimo et optimo, quo ei possibile est." BAUR: *op. cit.*
65. "Necesse est ergo, quod iris fiat per frationem radiorum solis in roratione nubis convexae. Dico ergo, quod exterius nubis est convexum et interius illius est concavum." BAUR: *op. cit.*
66. ANAXAGORAS (*ca.* 500 B.C.) spoke about: «ἀνάκλασιν ἀπὸ νέφους πυκνοῦ τῆς ἡλιακῆς περιφεγγείας.» DIELS, C. H. *Vorsokratiker* (2nd ed.), Vol. 1, s.309.
"Stoici, qui sic in nube quomodo in speculo lumen volunt reddi, nubem cavum faciunt et sectae pilae partem [segment of a sphere]; SENECA, L. ANNAEUS. *Quaestiones naturales*. Vol. 1, 8, 4. The Ancient spoke of reflection, Grosseteste of refraction.
67. "Color est lux incorporata perspicuo"; "Lux igitur clara in perspicuo puro albedo est. Luc pauca in perspicuo impuro nigredo est." BAUR: *op. cit.*
68. *De iride seu de iride et speculo*; BAUR, L. (Editor), pp. 74–75: "Haec namque pars Perspectivae (sc. de refractione) ... Ostendit nobis modum, quo res longissime distantes faciamus apparere propinquissime positas et quo res magnas propinquas faciamus apparere brevissimas et quo res longe positas parvas faciamus apparere quantum volumus magnas, ita ut possibile sit nobis ex incredibili distantia litteras minimas legere, aut arenam, aut granum aut gramina, aut quaevis minuta numerare."
"... et patens est eisdem modus figurandi diaphana ita, ut illa diaphana recipiant radios egredientes ab oculo secundum quantitatem anguli, quem voluerint, in oculo facti, et restringant radios receptos, quomodocunque voluerint, super res visibiles, sive fuerint illae res visibiles magnae sive parvae, sive longe sive prope positae; et ita appareant eis omnes res visibiles in situ, quo voluerint, et in quantitate, qua voluerint; et res maximas, cum voluerint faciant apparere brevissimas, et e contrario brevissimas et longe distantes faciant apparere magna et optime visu perceptibiles."
69. Is there any connection with SENECA (*Quaestiones naturales*, Vol. 1, 6, 5); "Omnia per aquam videntibus longe esse majora. Literae quamvis minutae et obscurae per vitream pilam aqua plena majores clarioresque cernuntur. ..."?
70. HEIBERG, I. L. (Editor) *Catoptrica*, p. 287: "Si res aliqua in vas coniecta et tam remota erit, ut non iam cernetur, si eadem distantia manente aqua infusa erit, res in vas coniecta cernetur." Classic authors also repeatedly mention "the broken oar". Did Grosseteste know other facts mentioned by the Ancients?
71. *The Opus Majus of Roger Bacon.* BRIDGES, J. H. (Editor) (1897). 2 vols. (based on Oxford MS. Digby 235).
"Rogerii Bacconis ... *Perspectiva* ... opera et studio Johannis Combachii, philosophiae professoris in Academia Marpurgensi ordinarii, Francofurti" (1614), (copied "e vetustissimis membranis in Oxoniensis Academiae bibliotheca").
72. *Dictionary of National Biography.*
73. ADAM de MARISCO ("doctor illustratus"), Grosseteste's assistant and Bacon's friend, was also a Franciscan. He wrote a book on optics: "Inventi sunt enim viri famosissimi, ut episcopus Robertus Lincolniensis et frater Adam de Marisco et multi allii qui per potestaten mathematicae sciverunt causa omnium explicare et tam humana, quam divina sufficienter exponere." (*Opus Majus*, Vol. I, p. 108.)
74. Roger Bacon was more interested than Bonaventura in natural phenomena, but, apart from this, their respective conceptions in general do not give the impression that there was any great disagreement between them. But a difference which seems slight to us may have been regarded as important in the thirteenth century. On the whole it seems that Bacon's "restraint" at Paris was more due to his revolutionary ideas about Church Reform than to his scientific opinions. (BONAVENTURA, *Beitr. z. Gesch. d. Philos. d. Mittelalters*; LUYKX, B. A., Vol. 23; and *ibid.* (1909), Vol. 6, LUTZ, E.)
75. Issued 22 June 1266, from Viterbo, which was the Papal Residence from 1266 till 1271.
76. In 1277 Pope John XXI ordered Stéphane Tempier, Bishop of Paris, to trace the errors in contemporary science. On 7 March 1277 was issued a decree against 277 errors connected with Averröes's doctrine. Bacon was found guilty of repudiation of authority, and also in connection with his belief in astrology. "Hic Generalis frater Hieronymus ... condemnavit et reprobavit doctrinam fratris Rogeris Bachonis

Anglici, sacrae theologiae magistri, continentem aliquas novitates suspectas. . . ." (MANDONNET (1911). *Siger der Brabant et l'Averroïsme de trieziène siècle*, I, p. 245.)

77. Gregorius X's successor was a famous ophthalmologist, Petrus Hispanus (P. Ulyssiponensis, P. Compostellanus). He was born at Lisbon (*ca.* 1215), was elected Pope in 1276 (John XXI), and in 1277 he died at Viterbo. During his short pontificate he did nothing in favour of Bacon. (His "*Liber de oculo*" was edited by M. A. BERGER (1899): *Die Ophthalmologie des Petrus Hispanus*, with a German translation.)
78. Cl. BÄUMKER: *Witelo*, p. 186.
79. Neither Bacon nor Peckham mentions the name of Ricardus Anglicus (died 1252 in London). He wrote an *Anatomy* (Oxford, Cod. Ashmolean. 399), which was not modern, in so far as the latest Arab author he mentioned was Constantinus Africanus. (Der Micrologus-Text der Anatomia Richards des Engländers; K. SUDHOFF, *Archiv für Geschichte des Medizin*, Vol. 19, s.3.)
80. *Opus Majus*: ". . . et ideo nullus sermo in his potest certificare; totum dependet ab experientia. Et propter hoc non reputo me attigisse hic plenam veritatem. . . . (p. 201); ". . . nec ago potui invenire adhuc. . . ." (p. 208); ". . . et nego me in praesenti tractatu de tanta difficultate certificasse" (p. 210); "Protestor tamen quod in tanta difficultate non loquor praecise, sed multum propinque veritati certificandae. . . ." (p. 273).
81. (Translated by ROBERT SMITH (1738). *A Compleat System of Optiks*. Cambridge. Vol. 2, Remarks 113.) ROGER BACON: *Perspectivae Pars tertia:* Dist. 2, p. 157. BRIDGES (Editor): "Si vero homo aspiciat literas et alias res minutas per medium crystalli vel vitri vel alterius perspicui suppositi literis, et sit portio minor spaerae cujus convexitas sit versus oculum, et oculus sit in aere, longe melius videbit literas et apparebunt ei majores. Nam secundum veritatem canonis quinti de sphaerico medio infra quod est res vel citra ejus centrum, et cujus convexitas est versus oculum, omnia concordant ad magnitudinem, quia angulus major est, sub quo videtur, et imago est major, et locus imaginis est propinquior, quia res est inter oculum et centrum. Et ideo hoc instrumentum est utile senibus et habentibus oculos debiles. Nam literam quantumcumque parvam possunt videre in sufficienti magnitudine. Si vero sit portio major sphaerae vel medietas tunc secundum canonem sextum accidit majoritas anguli, et majoritas imaginis, sed propinquitas deest, quia locus imaginis est ultra rem, non ita valet hoc instrumentum, sicut si esset minor portio sphaerae. Et instrumenta planorum corporum crystallinorum secundum primum canonem de planis, et sphaericorum concavorum secundum primum canonem et secundum de sphaericis, possunt facere hoc idem. Si inter omnia portio minor sphaere, cujus convexitas est versus oculum, evidentius ostendit magnitudinem propter tres causas simul aggregatas. . . ."
82. (Translated by ROBERT SMITH (1738). *A Compleat System of Optiks*. Cambridge. Vol. 2, Remarks 113.) ROGER BACON: *Perspectivae Pars tertia:* Dist. 3, p. 165. BRIDGES (Editor): "De visione fracta majora sunt; nam de facili patet per canones supradictos, quod maxima possunt apparere minima, et e contra, et longe distantia videbuntur propinquissime et e converso. Nam possumus sic figurare perspicua, et taliter ea ordinare respectu nostri visus et rerum, quod frangentur radii et flectentur quorsumcunque voluerimus, ut sub quocunque angulo voluerimus videbimus rem prope vel longe. Et sic ex incredibili distantia legeremus literas minutissimas et pulveres ac arenas numeraremus propter magnitudinem anguli sub quo videremus, et maxima corpora de prope vix videremus propter parvitatem anguli sub quo videremus, nam distantia non facit ad hujusmodi visiones nisi per accidens, sed quantitas anguli. Et sic posset puer apparere gigas, et unus homo videri mons, et in quacunque quantitate, secundum quod possemus hominem videre sub angulo tanto sicut montem, et prope ut volumus. Et sic parvus exercitus videretur maximus, et longe positus appareret prope, et e contra: sic etiam faceremus solem et lunam et stellas descendere secundum apparentiam hic inferius, et similiter supra capita inimicorum apparere et multa consimilia, ut animus mortalis ignorans veritatem non posset sustinere."
83. The "consolidativa", having no optical function, had not to be concentric with the other spheres.
84. "Umor albugineus" is a limpid liquid surrounding the lens, the aqueous humour. "Umor glacialis" is the crystalline lens.
85. The whole diameter of the visual field is here less than 60°. In the printed edition (1614) the triangle is equilateral, so that the visual field has an extent of 60°.
86. For example, VINCENTIUS BELLOVACENSIS, *Speculum naturale*: "Lucis ergo sunt proprietates simplicitas et puritas et sui multiplicatio" (Ed. 1624, p. 35).
87. ". . . cum objectum non contingat oculum se ipso, contingit illud per aliquid sui quo tendit ad oculum: et hoc communiter vocatur species intentionalis seu forma rei visibilis; sive illa fiat qualitas quaedam subtilissima, sive lumen reflexum, sive lumen proprium, sive aliud quidpiam tale, quo res visibilis tendit ad oculum"; M. A. DE DOMINIS, *De radiis visus ect.*, p. 8.
88. ". . . primus effectus cuiuslibet agentis naturaliter. . . ." *De multipl. Specierum*, p. 411.
89. "Fit species de potentia activa materiae patientis." BACON: *op. cit.*
90. "Omne agens physice patitur et transmutatur, insimul dum agit, et omne patiens agit." BACON: *op. cit.*
91. According to BACON (*De multipl. Specierum*), this is a confusion of "spiritualis" with "insensibilis" and "immaterialis".

92. "Sed in medio amimato per virtutem animae dirigitur species secundum exigentiam operationum animae, et quia operationes amimae circa species fiunt in nervis tortuosis, sequitur species tortuositatem nervi propter necessitatem animae. . . ." BACON: *op. cit.*, Vol. 2, c. 2.
93. ". . . omnis substantia corporalis potest facere speciem." Heat, odour and magnetism are also propagated by species. "Quoniam . . . et substantiae viliores quolibet sensu faciunt speciem, necesse est quod sensus faciat." Vol. 2, 424.
94. ". . . quia homo videt oculum alterius sine speculo . . . sed nihil videtur sine specie, et hoc nullus potest negare absolute. . . ." (p. 452).
95. "Species autem oculi est species animati corporis, in qua virtus animae dominatur, et ideo non habet comparationem ad speciem inanimatae rei. . . ." (p. 53).
96. (Translation: J. H. BRIDGES.)
97. Epistola Petro Peregrini de Maricourt ad Sygernum de Fontancourt militem, de Magnete; LIBRI, GUILLAUME (1838). *Histoire des Sciences mathematiques en Italie*, Vol. 2, pp. 487–505. Libri says: ". . . il mérite une place distinguée parmi les hommes qui ont contribué à la gloire de la France."
98. CANTOR, M. *Vorlesungen über Geschichte der Mathematik*, Vol. 2, p. 88: "Peckham's *Perspectiva Communis* wurde in den folgenden Jahrhunderten geradezu Leitfaden für die betreffende Universitäts-vorlesungen."
    The book was printed as *Perspectiva communis domini Johannis*, etc.: Milan, 1482, Leipsig, 1504, Venice, 1504, Nuremberg, 1542, Cologne, 1508, 1542 and 1627; an Italian edition appeared at Venice. In 1556 the book was printed at Liége under the title: *Perspectiva tribus libris succinctis per Pascalium Hamellium.* There are still further editions.
    MSS.: Oxford, Digby 218, 28, 98
    Oxford, Bodleian 30
    Gymnasialbibliothek, Thorn R 4°. 2.
    The author's name has many variants: Patsan, Betsan, Peckham, Pecham, Pisanus, Londoniensis, etc.
99. SPETTMANN, P. H. (1918). *Beitr. z. Gesch. d. Philos. d. Mittelalters*, Vol. 19.
100. Vol. 3, 13, ". . . radii tamen fracti ad hoc valent, ut res, ex concursu utriusque luminis [viz. irrefracted and refracted rays] clarius videtur." "Per radios qui oblique super oculum oriuntur visio vigoratur et ampliatur."
101. "Aqua enim est superficies sphaerica, tametsi nobis propter magnitudinem apparet plana." Vol. 3, 10.
102. "Longitudinem radiorum a visu comprehendi." Vol. 1, 58; this had also been Ptolemy's idea.
103. GALEN, *De Usu partium*, Vol. 10, c. 10.
     AVICENNA, *Beitr. z. Gesch. d. Philos. d. Mittelalters*, Vol. 5.
     ALFARABI, *ibid.*
     AVICENNA, e.g. said: "prima cellula: sensus communis, imaginatio;
     media cellula; phantasia, virtus cogitativa et aestimativa;
     tertia cellula; memoria; reminiscentia."
104. "Nullam intentionem visibilium, praeter lucem et colorem, solo sensu comprehendi." PECKHAM, Vol. 1, 62.
105. *Vitellionis περὶ ὀπτικῆς id est de natura, ratione et projectione radiorum visus, luminum, colorum, atque formarum, quam vulgo perspectivam vocant*, Vol. 10 (1st ed.) (1535): GEORGIUS TANSTETTER and PETRUS APIANUS (Editors), Norimbergae apud Io. PETREIUM; (2nd ed.) same title (1551), same editors and printer; (3rd ed.) (1572) *Opticae libri decem*, Basileae (together with Alhazen's *Optics* by F. RISNER.)
106. DOESSCHATE, G. TEN (1940). Lorenzo Ghiberti's third commentary in connection with medieval optics. *Thesis* University of Utrecht (in Dutch).
107. ". . . ut hoc laboris tibi placiti onus subirem hisque materiis mihi nondum cognitis animum applicarem."
108. BIAGIO DA PARMA (BIAGIO PELICANI, d. 1416) wrote a large treatise on optics. This is no more than a commentary on Peckham's book. MS.: Bibl. R. Parma, 3572: *Super perspectiva communi dubitationes per magistrum Blaxium de Parma.*
109. KEPLER, J. (1604). *Ad vitellionem paralipomena, quibus astronomiae pars optica traditur*, Vol. 2, p. 168. Francofurti. "Visionem fieri dico, cum totius hemisphaerii mundani, quod est ante oculum, et amplius paulo, idolum statuitur ad album subrufum retinae cavae superficiei parietem."