

# Ibn al-Haytham, the Arab who brought Greek optics into focus for Latin Europe

## Abstract

Ibn al-Haytham remains an unknown figure in the development of optics from the ancient Greeks to Latin Europe. He put to rest the idea of visual rays being emitted from the eye, demonstrating vision occurs by intromission of light rays to the eye. Through observational experimentation he characterized the behavior of light and described many visual phenomena that are now considered visual perception. Ibn al-Haytham's most significant work, *Kitab al-Manazir* was written in the eleventh century and was translated to Latin, as *De aspectibus* during the middle of the thirteenth century. Its introduction to Latin Europe stimulated the study of optics within the nascent universities of Europe and provided a model to conduct experiments and influenced natural philosophers for centuries.

**Keywords:** perspectivist optics, intromission, extramission, eidola, arabic philosophers, witelo, pecham, kepler

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## Introduction

In antiquity there was no differentiation between the eye, light and vision. Optics was the study of vision. Debate continued for nine-hundred years, from Plato to Kepler, as to whether vision occurred via extramission, where the eye emitted visual rays or if it happened by intromission, with visual rays entering the eye. Abu Ali al-Hasan Ibn al-Hasan Ibn al-Haytham (967-1042) dispelled the theory of extramission in his seven volume *Kitab al-Manazir*, (Book of Optics) which remained the world's most significant investigation of vision and optics for six hundred years.<sup>1</sup> Arguments within optics included a fair understanding of geometry but a poor understanding of anatomy, physiology, physics, color, visual illusions and cerebral function.<sup>2</sup> Ibn al-Haytham's expansive manuscript meticulously describes the experiments he conducted, the specific design of equipment and his observations.

Conflicting theories of intromission, extramission, ocular anatomy and perception abounded in ancient Greece. These were ultimately adopted and refined by Arab philosophers in the following centuries. Ibn al-Haytham melded features of these theories into a single, more comprehensive and more correct explanation of vision, satisfying the differing concerns of natural philosophers, mathematicians and physicians.<sup>3</sup> He elaborated on optics, including phenomena now known as visual perception, to produce a new theory which remained the most accurate model describing vision until Johan Kepler in 1604. Ibn al-Haytham's contributions to mathematics, physics, astronomy and optics are well known to historians of science, yet his work and the primacy of his theories and observations on vision and visual perception remain essentially unknown within optometry and the ophthalmic world today.<sup>4-7</sup>

Ibn al-Haytham was a vizier, judge, astronomer, physician and polymath from Basra at the northern end of the Persian Gulf.<sup>8</sup> Biographers writing two centuries after his death recount his summons to Cairo by Caliph al-Hakim (985-1021) after learning of his proposal to control the annual floods on the Nile River.<sup>9-12</sup> Upon viewing the Nile River, nearby monumental, pharaonic works and his available

resources he realized his plan wasn't feasible, and allegedly feigned madness to avoid the wrath of the Caliph al-Hakim. He remained under house arrest for ten years until the Caliph's death.

Ibn al-Haytham is credited with ninety-two works, of which sixty survive. Sixteen works are on optics (Table 1). In *Kitab al-Manazir*, he discussed the eye, light, vision, burning mirrors and spheres, camera obscura and visual perception. The Latin translation circulated in Europe as *De aspectibus*, with authorship attributed to Alhacen, a Latinized version of his first name. Only two of his other works were known in Latin: *Treatise on Parabolic Burning Mirrors* and the cosmological *On the Configuration of the World*.<sup>13</sup> The impact of *De aspectibus* revolutionized the understanding of optics in Medieval Europe, and of equal import, it became a guide for scientific investigation, an introduction to experiment and recording observations.<sup>14</sup>

**Table 1** Treatises discussing optics by Ibn al-Haytham. Lindberg, *Theories of Vision*. p 60-61

1. Book of Optics (De aspectibus)\*
2. On the Paraboloidal Burning Mirrors\* (De speculis comburentibus)
3. On the Spherical Burning Mirrors\*
4. On the Burning Sphere\*
5. On Light\*
6. On the Rainbow and Halos\*
7. On the Nature of Shadows\*
8. On the Form of the Eclipse\*

Table Continued

9. On the Light of the Moon\*
10. On the Light of the Stars\*
11. Doubts Concerning Ptolemy\*
12. On the Nature of Sight and the Manner in Which Sight Occurs (no longer extant)
13. On Optics According to the Method of Ptolemy (no longer extant)
14. Analysis of Aristotle's *De Anima* (no longer extant)
15. Analysis of Aristotle's *Meteorologica* (no longer extant)
16. On the Perfection of the Art of Medicine (no longer extant).

## Optics from the Greeks

Philosophers and philosophies in an effort to replace mythological and divine explanations of observed phenomena with a more rational understanding of the world flourished in ancient Greece. Three competing ideas emerged to dominate optics.<sup>15</sup> Intromission, attributed to Leucippus and Democritus, postulated that eidola, atom-thin replicas of an object, were constantly cast off, flew through the air and into an observer's eye allowing vision to occur. While Plato and the Stoics argued that pneuma, a visual force from the eye, interacted with the force coming from the object, causing a visual impression to be returned to the eye. Aristotle offered an alternate, vague proposition with the medium of air, or water, made transparent by pneuma from the eye, which in concert with fire or sunlight allowed visual rays to pass from the object and enter the eye of the observer. Color was considered the ultimate visual perception. Sunlight or firelight were the agents that allowed color to be seen.

Natural philosophers who felt the 'intromission' of eidola or some visual impression of the object came into the eye. This idea well represented object proportions, dimensions, distance, spatial orientation and better explained how the visual world was perceived. 'Extramission' of visual rays, as evidenced by the glow of an animal's eyes at night, was championed by the geometer Euclid (c. 300 BC). He proposed visual rays projected from the eye, in the form of a geometric cone with the apex at the eye and the base at the object and would sweep across a scene as does radar today.<sup>16</sup> This cone of discreet visual rays could readily explain how objects appeared larger when intercepting more rays in the visual cone and smaller when intercepting fewer rays. Objects seen by the rays on the left were perceived on the left while objects seen by the rays on the right were perceived on the right. Object details too small or too far to be seen, such as a pin lost on the floor, were thought to fall between visual rays. This geometric construct using extramission satisfied mathematicians though it did not address color, perception or mental processing to produce vision.

A third model proposed visual pneuma descended from the frontal lobes via the optic nerves through the chiasm into the eye, then out to the world. Incorporating roles for the optic nerves, chiasm, cornea, pupil, crystalline lens, and humors of the eye was very satisfying to physicians, including the eminent Galen (ca. 190). Each group pursued

arguments which best explained the aspect of optics in which they were interested while strenuously objecting to the others. Mathematicians argued eidola of large buildings or mountains won't fit through the pupil and thousands of eidola flying through the air would interfere with one another. Intromissionists rebutted that an eye emitting visual rays should be able to see in the dark and fill the heavens out to the stars with visual rays, every time the eyes opened, was just not feasible. Ptolemy of Alexandria (ca. 160) supported Euclid's idea while adding that visual rays were continuous rather than discrete within the visual cone and maintained that visual perception occurred with worldly objects acting on the eye, not unlike the sense of touch where physical contact acts on the body to stimulate perception. Euclid's visual objects were able to physically act upon the inside of the eye.

A variety of visual phenomena were considered visual errors and given inordinate study: the apparent location of the virtual image in a mirror, image displacement in mirrors, magnification seen with a convex lens, an oar appearing bent by refraction when partially submerged, the iridescent color in the feathers of a pigeon, the difference in the size of the moon when on the horizon versus at its zenith and a square tower appearing round as the corners appeared to vanish at a distance. These were all regarded as errors of vision, a failure of optics. Greek philosophers further classified the study of vision such as an object perceived directly by the eye as optics. The deflection of rays at an interface like air and water was classified as dioptrics. Objects reflected in a mirror, where equal angles of incidence and reflection had broken the path of rays were catoptrics. For many natural philosophers, the veracity of visual perception varied, unlike touch. Vision was considered a suspect sense.<sup>17,18</sup>

## Optics of Ibn al Haytham

Ptolemy's authoritative book *Optics* in the Greek as well as much of the Arabic translation, was lost by the tenth century.<sup>19</sup> Ibn al-Haytham had access to the remainder of Ptolemy's work as well as the writings of Hunain Ibn-Ishaq, Ya'kub ibn Ishaq al-Kindi and the lesser known ibn Sahl and Ahmad ibn Isa. These philosophers refined and expanded the corpus of Greek optics.<sup>20,21</sup> Ibn Sahl, manipulating the geometry of conic sections, determined the angle of refraction is related to the refractive index of the medium, predating Snell's law by six hundred years, yet his contribution remained unknown for one thousand years. During his confinement, Ibn al-Haytham relied upon logic and reason while observing the behavior of beams of light in a dark room, a camera obscura. He identified and separated many of the qualities of light, and finally was able to conceptually separate light from vision.<sup>22-24</sup>

Using the most sophisticated instruments of the time, he conducted experiments using both sunlight and firelight. He observed the behavior of light whether direct, refracted (dioptrics) or reflected (catoptrics), shining through clear air, dust or smoke.<sup>26</sup> Having previously studied the optics of pinholes, Ibn al-Haytham projected complex images of candles within his camera obscura, manipulating their placement and observed the resultant inverted and reversed images. He validated and repeated his observations, describing in great detail the precise arrangements and observed effects including light's absolute linearity.<sup>27</sup> He also noted the painful ocular sensation when looking at a bright light, as well as visual afterimages, logically concluding light acted on the eye.<sup>29</sup>

From these combined observations Ibn al-Haytham deduced visual perception of the world occurs with light rays traveling into the eye. Anticipating Occam’s razor, he concluded it was unnecessary for the eye to emit visual rays which travel to the object and then return to act on the eye. Ibn al-Haytham retained the appealing geometric concept and precision of Euclid’s and Ptolemy’s visual cone with its apex on the eye and base on the object. He simply reversed the direction light traveled, from the object to inside the eye. This also eliminated the need to project visual rays to the stars and instantly see them upon opening one’s eyes. Light, geometrically entering the eye, also resolved the dilemma of eidola from large objects passing through the small pupil.<sup>30</sup>

Ibn al-Haytham built on al-Kindi’s theory that an object emitted reflected light rays from every point, in every direction. This allowed him to conceive a point-to-point, punctiform image to be represented in the eye rather than a flying eidola.<sup>31</sup> Drawing on his prior work, *The Form of the Eclipse*, he knew the eye’s pupil was too large to act as a pinhole, where all rays contribute to the image.<sup>32</sup> Ibn al-Haytham proposed rays of light, bearing the color and detail of the object, reached the crystalline lens, forming a representation of the real world. His punctiform image differed from the pinhole image formed by a camera obscura, as only select orthogonal rays, perpendicular or normal to both the cornea and crystalline lens surface, contributed to visual perception.

It was well established that light rays striking perpendicular to a surface remained straight and thus stronger, as opposed to bent or refracted rays.<sup>33</sup> These unique rays, normal to both the cornea and crystalline lens surface, were thought to produce a stronger image which stood out from the confusion of all rays entering the eye. This facilitated the perception of a single image, eliminating the problem of off-axis rays forming multiple images in the eye. Ibn al-Haytham proposed his upright, punctiform image was registered by the crystalline lens, conveyed to the optic nerve, then thought to be opposite the pupil at the eye’s posterior pole, and on to the chiasm. There it combined with the image from the fellow eye and then transmitted to the brain for ultimate perception.<sup>34</sup> Ibn al-Haytham’s understanding of eye anatomy remained based on Galen’s work from eight centuries earlier, as dissection was proscribed in Islam.<sup>35</sup> The crystalline lens was also thought to be centered in the eye, aligned on the posterior curve of a circle extending from the cornea to the center of the globe. This allowed for an upright image to form on the receptive, and visually sensitive crystalline lens (Figure 1), which alleviated the problem of an incomprehensible, inverted image.<sup>36</sup>



Figure 1 Diagram of the visual system in Ibn al-Haytham’s *Kitab al-Manazir*. Ms Ayasofya, 1493. Courtesy of Süleymaniye Library, Istanbul.

Ibn al-Haytham’s explanation of vision remained the most sophisticated, cogent, and correct visual theory for six centuries. His new and more sophisticated explanation, reversing the direction rays travel within the visual cone, drew upon the geometric strengths of extramission and the perceptual advantages of intromission. He incorporated facets of three competing vision theories, imagining a punctiform image formed by orthogonal light rays, interacting with the anatomy of the observer’s eye, while leaving the object in space out in front of the viewer, and offered a mental process of perception, judgment and memory of visual images. This was all to the mutual satisfaction of physicians, mathematicians and philosophers.<sup>37,38</sup>

### Contributions to visual perception

Ibn al-Haytham’s new theory explained how the optics of the eye, including the mental processing of images, lead to visual perception of the world.<sup>39-41</sup> He described many visual perceptual phenomena subsequently attributed to others, in some cases centuries later. Review of *Kitab al-Manazir* and *De aspectibus* over the past century has typically focused on the physics of light and eye anatomy as presented in Volumes II and III, without much comment on visual perception.<sup>42-45</sup>

Building upon Ptolemy’s observations of binocular vision, Ibn al-Haytham confirmed objects in the center of vision are seen more clearly than those located peripherally and that color vision is diminished in the periphery.<sup>46,47</sup> Ibn al-Haytham described afterimages and visual masking of dimmer objects by a brighter object. He described color constancy, where an object’s color appears to remain constant despite a change in the color of light falling on it, concluding light and color are basic qualities of vision. Perception of an object’s visual qualities was accomplished by rational thought, recognizing similarities and differences between objects occurred in stages, incorporating prior recognition or memory, discernment, association, practice, experience and inferential perception.<sup>48</sup> He identified twenty-two factors or qualities contributing to vision and perception, many of which today are considered value judgments, such as beauty, or ugliness.<sup>49</sup>

Visual illusions, including the long-debated perception of the moon on the horizon appearing larger than when high in the heavens, remained a topic of great interest. Aristotle noted objects submerged in water appeared larger, and concluded water vapor in the atmosphere caused the moon to appear larger closer to the horizon. Ptolemy attributed the full moon appearing larger on the horizon in comparison to its zenith a result of atmospheric refraction.<sup>50</sup> Ibn al-Haytham reasoned this illusory difference in size of the moon to an apparent difference in perceived distance when on the horizon, versus when overhead. This size-distance invariance principle is now known as Emmert’s Law.<sup>51</sup> Ibn al-Haytham detailed different types of perceived motion: such as the eye following a bird in flight versus the relative movement of one object compared to another, as when clouds sweep across the moon. He also noted difficulty to visually recognize an object moving quickly past an aperture or during rapid eye movement. He discussed shape constancy, as when circles and squares when viewed obliquely become ovals and trapezoids, yet the true geometries are perceived correctly. These concepts were not analyzed again until 1935, by Gestalt psychologists.<sup>52</sup> Ibn al-Haytham attributed the ability to judge distances to the loss of detail at distance, cues of overlap, color desaturation and size constancy, all of which infer distance and comparative depth. He proposed we learned to interpret these perceptions through practice and viewing the world from various distances throughout life.<sup>53</sup>

Ibn al-Haytham's observations and arguments furthering binocularity were not improved upon until Vieth in 1818, Müller in 1826 and Wheatstone in 1838, while corresponding retinal points were not described again until Panum in 1858. Drawing on Ptolemy, Ibn al-Haytham elaborated on the concept of a cyclopean direction, images from both eyes are fused in the chiasm to describe a single visual direction. He identified diplopic images as crossed or uncrossed. Perception of a single visual image normally occurs when the visual angle of corresponding lines of vision are approximately equal in either eye, and noted the two eyes move in synchrony to avoid diplopia. As with prior philosophers, he too failed to associate visual disparity and triangulation between the two eyes as the basis for stereoscopic depth perception.

Ibn al-Haytham concurred with Ptolemy that two eyes lend to body symmetry and beauty, but also recognized the benefit of a second eye as a back-up. He disagreed with Ptolemy that the locus of points which are perceived at a constant distance, were not a frontal plane, but an arc at equal distance from the eyes, predating the horizontal horopter introduced by Aguilonius (1613) and the vertical horopter by Helmholtz in the nineteenth century.<sup>54</sup> He also noted visual perceptual discrimination could be shown in young children as they can discern among, and will select, fruit that looks better than fruit with blemishes.

### Ibn al-Haytham's legacy in optics

In medieval Arabia, references to Ibn al-Haytham's other works on light, mathematics and astronomy are plentiful. Given the prevalence of eye disease and visual disability, the abundance of ophthalmic literature and his renown within the intellectual community, it is surprising no significant reference to *Kitab al-Manazir* was made until two-hundred and fifty years after he died.<sup>55,56</sup> Its translation to Latin by the middle of the twelfth century suggests the manuscript had traveled from Cairo to the Iberian Peninsula, where a single reference to *Kitab al-Manazir* in Arabic was made circa 1200. A plague swept across North Africa at the time of Ibn al-Haytham's death, perhaps disrupting intellectual continuity, and delaying *Kitab al-Manazir*'s dissemination. It fell to Kamal al din al-Farisi (1267-1319), studying under Qutb al din al-Shirazi (1236-1311) two and one-half centuries after Ibn al-Haytham, who formally reviewed *Kitab al-Manazir*. As a boy, Al-Shirazi had once seen *Kitab al-Manazir* in a distant library, now as head of the famed Maragheh observatory in the Caucasus Mountains of Persia, al-Shirazi was able to obtain a rare copy of the manuscript. It was Al-Farisi's recension, *Tanqih al-Manazir*, which finally brought *Kitab al-Manazir* to the attention of the Arab world, as the most advanced book on optics and affirmed Ibn al-Haytham as the ultimate authority on vision.<sup>57-60</sup>

### European scholastics and perspectivist optics

Distribution of Ibn al-Haytham's *De aspectibus* followed a more rapid time line in Europe. For centuries its authorship was attributed to Alhacen, a Latinized transliteration of Ibn al-Haytham's first name, al-Hasan.<sup>61</sup> The name of the original translator has been lost, though widely accepted that it was translated in Andalusia, as were so many Arabic works during the Reconquista.<sup>62</sup> The earliest reference to *De aspectibus*, is by Jordanus de Nemore who flourished in the 1230's. In Bartholomeus Anglicus' *De proprietatibus rerum*, dated to the 1240's, Alhazen is again referenced. But it was not until the 1260's that *De aspectibus* really circulated among the learned of Europe.<sup>63-65</sup>

*De aspectibus* arrived too late to influence Robert Grosseteste

(1175-1253) who studied the optics of Plato and Euclid at Oxford University, and as with all medieval philosophers, his work was greatly flavored by religion.<sup>66-68</sup> The first European scholar to significantly benefit from Ibn al-Haytham's explanation of light and vision was Roger Bacon (1214-1294), who followed Grosseteste at Oxford by a generation.<sup>69</sup> *De aspectibus* presented the first structured study in Europe detailing Ibn al-Haytham's procedures and observations, basically a 'how-to' instructional lab manual.<sup>70-72</sup> Bacon incorporated the insights and structured reasoning presented in *De aspectibus* in his attempt to unify and explain all of natural philosophy as the work of God in a grand unified scheme, his *Opus Maius*.<sup>73,74</sup>

Roger Bacon, Thomas Pecham and Erasmus Witelo all wrote within the decades 1260-1280, making them essentially contemporaneous in Medieval Europe and difficult to ascertain who may have influenced whom. Thomas Pecham (1230-1292), Archbishop of Canterbury, derived from *De aspectibus*, a simpler, easy-to-read book, *Perspectiva communis*. Sixty-four manuscript copies are extant and it eventually enjoyed eleven printings, both testaments to its popularity.<sup>76-78</sup> Nearly simultaneously, Witelo (1230-1284), a Polish priest and philosopher produced the intellectually sophisticated *Perspectiva*, which closely parallels Alhacen's *De aspectibus*. *Perspectiva* was first printed two-hundred and fifty years later in 1535. It was subsequently published in 1572 by Friederich Risner, in Basel, as *Optica Thesaurus*, combining Alhacen's *De aspectibus* with Witelo's *Perspectiva* and a third work on astronomical twilight, thought written by Alhacen but more recently attributed to Abu 'Abd Allah Muhammad ibn Mu'adh.<sup>79,80</sup> *Optica Thesaurus* remained popular, extending Alhacen's influence on European natural philosophers to Descartes and Huygens in the seventeenth century.<sup>110</sup> In the fourteenth century *De aspectibus* was translated into vernacular Italian as *Deli Aspetti*, by Guerruccio di Cione Federighi. It is credited with influencing the art of Lorenzo Ghiberti and Leonardo Da Vinci, the architecture of Leon Battista Alberti, and facilitating the development of foreshortening and perspective by Renaissance artists.<sup>81-85</sup>

European authors, including Jean de Meun and Guillaume de Lorris in their popular poem *Roman de la Rose* (c. 1275) refer to Alhacen as an authoritative figure. Peter of Limoges drew upon Alhacen for his sermons for priests on morality, *De oculo morali*. The Reformist priest John Wyclif (1320-1384) allegorically likens the seven deadly sins to the seven distortions in mirrors as described by Alhacen in *De aspectibus*.<sup>86</sup> In *Canterbury Tales* (ca. 1400), Chaucer places him on par with Aristotle in the *Squire's Tale Prologue* and tale:

"Then they referred to many a learned tome

By Aristotle and by Alhacen

And Witelo and other learned men

Who when alive had written down directives

For use of cunning mirrors and perspectives,

As anyone can tell who has explored

These authors"

Building on the advances by Ibn al-Haytham, in understanding light and vision, the adoption and spread of perspectivist ideas by Bacon, Witelo and Pecham explaining how the image of an object occurs in the eye, significantly furthered the study of optics in Europe. Leonardo DaVinci (1452-1519) compared the camera obscura directly to the eye. Francesco Maurolico (1494-1575), Daniello Barbaro

(1513-1570) and Giambattista della Porta (1535-1615) analyzed the eye as an optical device and improved imaging with the camera obscura by incorporating a convex lens in the aperture, yet all failed to place the image on the retina and were unable to resolve the problem of an inverted retinal image.

In an effort to better understand the optics of telescopes, astronomer Johan Kepler (1571-1631) studied the optics of the eye as a problem separate from perception. In 1604, Kepler published his results in *Ad Vitellionem Paralipomena, (Additions to Witelo)*.<sup>87</sup> He worked out the optics of the eye with the anatomical assistance of Jessen and Plater. Using cow eyes he demonstrated the eye worked as a camera obscura, by viewing inverted images on the retina through dissected sclera.<sup>88,89</sup> He coined the word 'pictura' for this image, correctly identified it as being inverted, reversed and on the retina. Kepler also dispelled the significance of orthogonal rays, normal to both the cornea and lens. He argued refracted rays from peripheral objects were indeed seen, contributed to vision and could no longer be ignored. Kepler concluded his investigation of the eye's optics with "leave [it] to natural philosophers to argue about [these issues] for the arsenal of opticians does not extend beyond [the] opaque wall [of the retina]". He offered no explanation as to how the reversed and inverted image on the retina was perceived correctly in the brain. This question persisted until 1637 when Rene Descartes resolved that sight is more than a small image of an object appearing somewhere within the brain.<sup>89</sup>

A catalog of Istanbul library manuscripts compiled by German researchers in 1936 publicized the discovery of five unknown manuscripts of Ibn al-Haytham's *Kitab al-Manazir*.<sup>127</sup> All five manuscripts remain today in the Sulemaniyah Library, Istanbul University. An analysis in Arabic of *Kitab al-Manazir* was published in 1943.<sup>90,91</sup> Digital access is available to *Kitab al-Manazir* manuscripts via the reading room of the Sulemaniyah Library. A trove of Ibn al-Haytham's other manuscripts, and a partial catalogue of his works were discovered in 1975, in the Samara Regional Library, Russia.

The seven volumes of Ibn al-Haytham's *Kitab al-Manazir* follow the organization of Ptolemy's *Optics*. In Volume I he presents his theory separating light from vision, a description of eye structures and their functions, an explanation of how vision works and factors that affect vision. Volume II reviews direct vision, light that is neither refracted nor reflected, along with his theory of visual perception.<sup>92</sup> Volume III discusses visual recognition and perceptual errors or visual illusions. Volume IV presents errors or illusions encountered with reflected light or catoptrics. Volumes V and VI give descriptions for catoptric experiments and visual errors derived from mirrors. Volume VII explains vision errors experienced with refracted light or dioptrics. The optical phenomena of haloes and rainbows were traditionally discussed with weather, a precedent set by Aristotle in *Meteorologica* which persisted thru the 17th century, as Descartes discussed rainbows in *Météore*, his book on weather and not in *Dioptrique*, his work on light.

The Askari Set (1083-84 CE 476 AH) is the oldest of the *Kitab al-Manazir* manuscripts. Named for its copyist, Ibn al-Haytham's son-in-law Ahmad ibn Muhammad ibn Ja'far al-Askari, it was likely copied directly from Ibn al-Haytham's autograph manuscript.<sup>93</sup> Ayasofya Set 2448 (1464-5 CE, 869 AH), copied by order of Sultan Muhammad al-Fatih is probably from the Askari manuscript and the only complete set, which in combination with text and diagrams from Kamal al-Din's recension *Tanqih al-Manazir*, allowed for the first thorough comparative analysis. In 1983, almost one thousand years after it was

written, the first three volumes of *Kitab al-Manazir* were published in Arabic and the four remaining volumes in 2003. An English translation of the first three volumes from the Arabic was published in 1989. An English translation of the Latin *De aspectibus* was published in 2001.

Critical study of Kamal al Din's *Tanqih al Manazir* in 19th century Europe proved *De aspectibus* to be the Latin translation of *Kitab al-Manazir*, and confirmed Alhacen to be the highly regarded mathematician and astronomer, Abu Ali al-Hasan ibn al-Hasan ibn al-Haytham.<sup>94,95</sup> In-depth study of *Kitab al-Manazir* suggests that perhaps Ibn al-Haytham did not perform at least one of his experiments. Observing the refraction of light, incident in ten-degree increments, into and out of various media: air, water and glass. He failed to note that when light passes from a medium of greater optical density to lower at a greater angle, refraction ceases. Total internal reflection occurs at an incident angle of  $41^\circ$  going from crown glass ( $n=1.50$ ) to air and  $48.6^\circ$  from water ( $n=1.33$ ) to air, suggesting he did not perform the experiment and did not comment on what surely would have been surprising results. Nor did Witelo make that observation in *Perspectiva*.

Manuscript copies are similar, but inherently differ in content, quality of execution and emphasis as they were often produced on commission and tailored for a particular audience. By 1910, research revealed Alhacen's *De aspectibus* differed from Kamal al-din al-Farisi's review *Tanqih al-Manazir*. The first three chapters of Arabic Volume I are missing from all Latin manuscripts and Chapter IV of the Arabic had been edited in the Latin to produce four numerical chapters. The Latin translation of Volumes I-III are faithful to the Arabic, while books IV-VII appear to be the work of a less skilled translator. Seventeen mostly complete manuscript copies of the Latin *De aspectibus* are extant with an additional four fragments known. The unique Italian manuscript resides in the Vatican's Biblioteca Apostolica. The oldest Latin manuscript, (ca. 1269), is in the Crawford Library, Edinburgh Royal Observatory (Figure 2). Fifteen copies of Kamal al din al-Farisi's *Tanqih al-manazir* survive in libraries around the world including the Butler Library, Columbia University, while the best copy is at the Sulemaniyah Library, Istanbul University. Bacon's *Opus Maius* exists in thirty-nine copies today, with thirty-four being fairly complete. Twenty-nine manuscript copies of Witelo's *Perspectiva* are known to exist, of which twenty-two are complete.



**Figure 2** Diagram of the eye in Alhacen's *De aspectibus*, ca 1260. The crystalline lens is essentially centered in the globe. Courtesy of Crawford Library of the Royal Observatory Edinburgh, Scotland.

## Conclusion

Ibn al-Haytham wrote extensively on physics, astronomy, and mathematics and remains a significant figure in the history of optics, refining ideas from Greek antiquity while furthering Arab and European science. He preceded the Renaissance and Age of Enlightenment with a more correct model of vision, resolving the debate over visual extramission versus intromission, while incorporating ocular anatomy, visual physiology and describing many facets of visual perception. Theories and details of his experimental work, uniquely presented in *De aspectibus*, allowed it to become a manual for scientific investigation and experimentation in Europe. Ibn al-Haytham's role in the development of optics, visual perception and rational thought remains under-appreciated in the optometric and ophthalmic world today.<sup>96,97</sup>

Near the east margin of Mare crisium (15.9 N/71.8 E), a lunar crater 33 km in diameter bears ibn al-Haytham's Latinized name Alhazen. The College of Optics, University of Arizona, offers the ibn al-Haytham Scholarship to aspiring students of optics.<sup>99</sup> Arabic communities, including Amman, Jordan and Baghdad, Iraq, have hospitals named in honor of Ibn al-Haytham. Acknowledgment of Arabic contributions to the study of the eye and vision was arguably made in 1895 at the Basel Anatomical Nomenclature Convention with formal adoption of cornea, transliteration of the Arabic 'al-quarny'ah,' as opposed to Galen's competing Greek term 'keratoëidés hitón.'<sup>100–102</sup>

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## Conflicts of interest

I have no conflicts of interest in this work.

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