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Wolfgang Lefèvre (ed.)

Inside the Camera Obscura – Optics and Art under the Spell of the Projected Image

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PART I

INTRODUCING AN INSTRUMENT

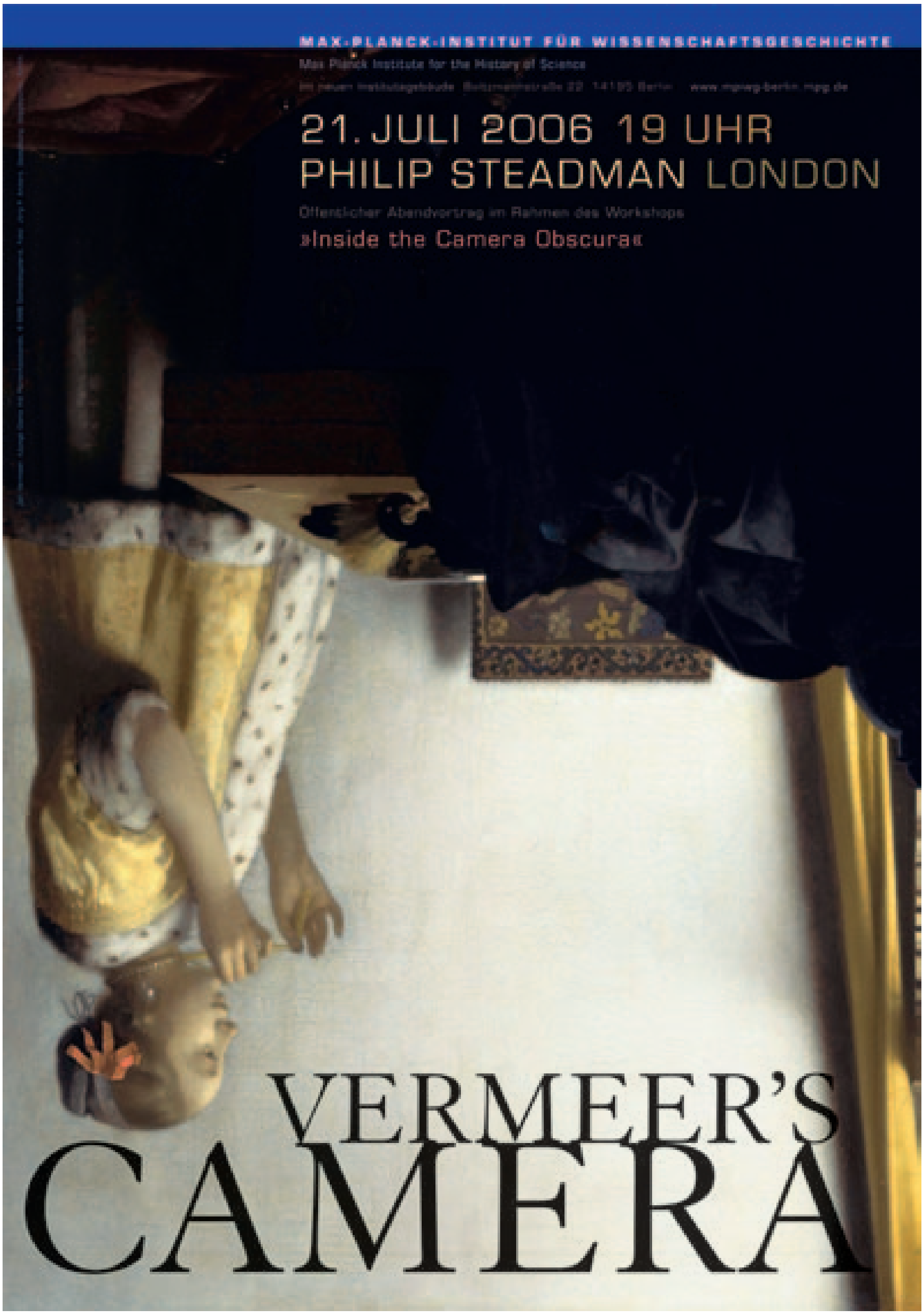

Figure 1: 'Woman with a pearl necklace' by Vermeer van Delft (c.1664). Did Vermeer paint his subjects using a camera obscura? (SMB Gemäldegalerie Berlin. – Poster by *atelier doppelpunkt*, Berlin).

The Optical Camera Obscura I
A Short Exposition[1]

Wolfgang Lefèvre

Painting with the camera obscura?

In Tracy Chevalier's 1999 novel *The Girl with the Pearl Earring* and the 2003 movie of the same title, a camera obscura takes centre stage in a drama between the famous Dutch painter Johannes Vermeer van Delft (1632-1675) and a servant girl called Griet. Vermeer is not only one of the brightest stars among the famous Dutch and Flemish painters of the 17th century. He is also the artist most often assumed to have used a camera obscura to create some and maybe most of his paintings. Such speculations appeared as early as 1891 in a journal of photography. This seems fitting for an artist whose paintings, like those of other Dutch artists of this time, boasted a photographic realism. The incredible precision with which Vermeer rendered details, particularly in his domestic interiors, his novel approach to atmospheric light and colours, and the lustre he applied to reflecting surfaces are all suggestive of a painting practice that employed a camera obscura.

But there's a problem. There is, to date, not a single piece of direct evidence to support this suggestion: there is not one example of a camera obscura or even a single part of one that dates from the 17th century, there are no written documents to confirm such devices were employed by artists of this time, no receipts for related materials or other unambiguous hints. In fact, it is only the paintings themselves that have been used to support the hypothesis that 17th century artists were using this device. Deducing a production technique solely on the basis of the finished product is clearly a questionable position to adopt.[2]

What cannot be questioned is the fascination that the camera obscura exerted on Europeans in the 17th century. The images projected by the camera evoked a kind of wonder and admiration that people accustomed to colour photography, colour movies and colour television can hardly imagine. Among the testimonies to this fascination is a famous letter Constantijn Huygens (1596-1687) wrote from London in 1622, where he had the chance to experiment with the image produced by Cornelis Drebbel's (1572-1633) camera obscura:

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[1] This text, an almost identical version of which will appear in *Endeavour* XXXI/2, is included with permission from Elsevier.

[2] J. Penell, "Photography as a hindrance and a help to art." *British Journal of Photography* XXXVIII (1891). Out of the copious literature on the issue of Vermeer's possible use of a camera obscura, I recommend P. Steadman, *Vermeer's Camera.* Oxford University Press, 2001, and J. Wadum, "Vermeer in perspective." In: *Johannes Vermeer.* (A.K. Wheelock, ed.), Yale University Press, 1995, pp. 67-79. On the general issue of Dutch painting in the 17th century and the camera obscura, three further titles may prove useful: S. Alpers, *The Art of Describing. Dutch Art in the Seventeenth Century.* University of Chicago Press, 1983; M. Kemp, *The Science of Art. Optical Themes in Western Art from Brunelleschi to Seurat.* Yale University Press, 1990, chapter 4; J.-L. Delsaute, "The Camera Obscura and Painting in the Sixteenth and Seventeenth Centuries." In *Vermeer Studies.* (I Gaskell and M. Jonker, eds.) Yale University Press, 1998, pp. 111-123.

> It is not possible to describe for you the beauty of it in words: all painting is dead in comparison, for here is life itself, or something more noble, if only it did not lack words. Figure, contour, and movement come together naturally therein, in a way that is altogether pleasing.[3]

Considering the curiosity the camera obscura became all over Europe in the 17th century, it is unlikely that painters, who pride themselves by their visual sensibility, had not been moved, impressed and excited by these projections. In fact, surely it would have been artists, above most other professions, who would have been most receptive to this new visual experience. However, if this is a reasonable assumption, then it would not be particularly surprising if paintings reflected the painter's experience of seeing camera obscura projections even if they did not use the apparatus in their work.

An old device newly born

But here's the puzzle. How could the images projected by the camera obscura stir up the emotions and widen the horizon of visual experiences of the likes of Huygens and, later on, Vermeer? After all, versions of this instrument had been around long before this period. The pinhole camera, for example, was known and used in classical antiquity in an astronomical setting, particularly for observing solar eclipses. From antiquity up to the Renaissance, the camera obscura never fell into total oblivion. Now and then, it was mentioned and occasionally used, mostly for astronomy. But it did not attract very much attention. At the end of the 16th century, however, its fortunes changed dramatically. The pinhole camera obscura was equipped with lenses and mirrors and transformed into the optical camera obscura of the early modern period.[4]

Although no single optical camera obscura has survived from the 17th century, we know from written sources and a few book illustrations that at least four principal types of this camera were developed and in use. The simplest arrangement, with a lens fastened in the pinhole, projected an inversed and reversed image on a vertical screen opposite the aperture. A variation on this employed a translucent screen, allowing the viewer to see the image from the other side, thereby correcting the left-to-right reversal. These two types of camera projected the image directly and could be combined in one device. There were at least two additional incarnations of the camera obscura, which used a mirror oriented at 45 degrees to the path of light to achieve vertical reversion. Without a translucent screen the projected image remained horizontally reversed, but with a translucent screen this too could be overcome (Figure 2). Judging from contemporary illustrations, standardized forms of these four types were slow to replace makeshift, ad hoc constructions put together on site to meet a specific need. If the earliest optical camera obscuras were indeed temporary devices, this could explain why none appears to have survived.

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[3] All translations of quotations from the Dutch and Latin from S. Alpers, op. cit.

[4] On the history of the early modern camera obscura, three titles may be recommended: J. Waterhouse, "Notes on the Early History of the Camera Obscura." *The Photographic Journal* XXV/9 (1901), 270-290; J. H. Hammond, *The Camera Obscura: A Chronicle.* Adam Hilger, 1981; Steadman, op. cit., chapter 1.

Modeling Vision

This new optical camera was primarily a gadget for creating spectacular entertainment. But it was also used for surveying and mapping, for astronomical observation and possibly even for painting. Beyond this, it was an important part of an optical revolution triggered by optical devices such as crystalline spheres, lenses and mirrors, which had become fashionable items of entertainment in the late 16th century. Indeed, in terms of its impact on 17th century society, it was as significant as the telescope and microscope, which appeared at around this time. The optical camera obscura sits alongside these more prominent scientific instruments, ushering in a new approach to optics, opening up new views of the visible world and shaping a new understanding of vision itself.[5]

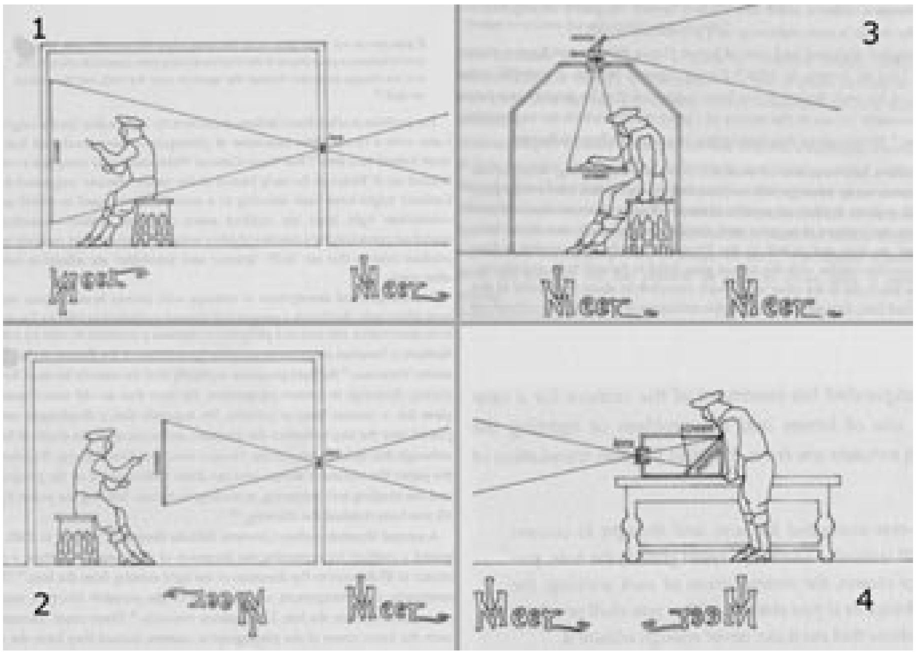

Figure 2: The four principal types of optical camera obscura. (a) The camera projects directly onto the far wall, resulting in an image that is upside down and reversed from left to right. (b) The camera projects directly onto a translucent screen; seen from the back, the image is upside down but not laterally reversed. (c) The tent-type camera involves a 45° plane mirror above the lens to reflect the projection so that it's not upside down. (d) The box-type camera also uses a 45° plane mirror; the image projected reflectedly on the translucent screen is correctly up but reversed left-to-right. Diagrams from Philip Steadman's *Vermeer's Camera*.

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[5] On the optical revolution in general: D. C. Lindberg, *Theories of Vision from Al-Kindi to Kepler.* Chicago University Press, 1976; A.E. Shapiro, "The *Optical Lectures* and the Foundations of the Theory of Optical Imagery." In *Before Newton: The Life and Times of Isaac Barrow* (M. Feingold, ed.), Cambridge University Press, 1990, pp.105-178. On instruments and optics: A. van Helden, *The Invention of the Telescope.* American Philosophical Society, 1977; S. Dupré, *Renaissance Optics: Instruments, Practical Knowledge and the Appropriation of Theory.* Berlin: Preprint of the Max Planck Institute for the History of Science, 2003. On theories of vision: A.C. Crombie, "The Mechanistic Hypothesis and the Scientific Study of Vision: Some Optical Ideas as a Background to the Invention of the Telescope." In *Historical Aspects of Microscopy* (S. Bradbury and G. Turner, eds) W. Heffer, 1967, pp. 3-112. On Leonardo and the eye: J.S. Ackerman, "Leonardo's Eye." *Journal of the Warburg and Courtauld Institutes* XLI (1978), pp. 108-146; F. Fehrenbach, "Der oszillierende Blick. *Sfumato* und die Optik des späten Leonardo." *Zeitschrift für Kunstgeschichte* LXV (2002), pp. 522-544.

In the decades around 1600, the optical camera obscura became *the* model of the eye. The eye was conceived as a spherical, darkened room with a hole containing the lens and a screen acting as the retina on its back wall. No anatomical discoveries fed into this model: a 17th century anatomist's knowledge of this organ did not differ significantly from that of a 15th century artist-anatomist like Leonardo da Vinci (1452-1519). What had changed, however, was the realisation that the perception of light rays does not occur in the vitreous humour but on the retina. And it was the optical camera obscura that led to this important new view of the eye. Johannes Kepler's (1571-1630) wrote in his *Ad Vitellionem Paralipomena* of 1604:

> Thus vision is brought about by a picture of the thing seen being formed on the concave surface of the retina.

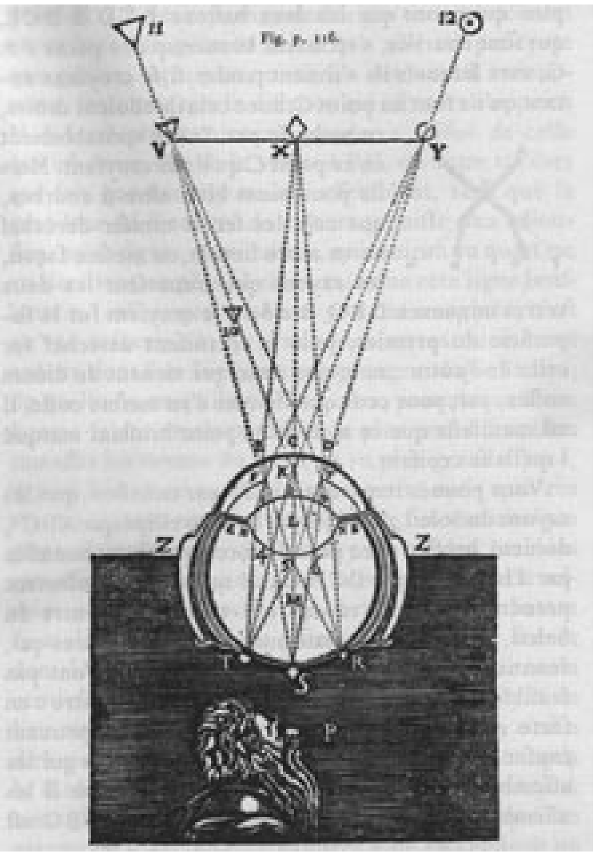

Figure 3: Man observing the retina image by means of an anatomically prepared ox eye. This experiment was actually executed by at least three 17th-century savants: Christoph Scheiner (1575-1650), René Descartes and Gaspar Schott (1608-1666). Reproduced from René Descartes' *Dioptrique* of 1637.

This is a remarkable fact that should be considered in the broader context of the emerging mechanistic anatomy and physiology. As hydraulic machines served William Harvey (1578-1657) as models of the blood circulation, or as pneumatic systems served René Descartes (1596-1650) as models of enervation and muscle contraction, so the camera obscura served as a model of the eye, a model that facilitated a new understanding and further study of how vision works.

Optics reshaped

The influence of the optical camera obscura did not stop with physiology. It also induced fundamental changes to both geometrical and physical optics. The theories of optics developed in Antiquity and the Middle Ages juxtaposed rather than integrated these two branches. Geometrical optics dealt with how light moves; physical optics addressed the nature of light itself and the interaction between light and matter. With the camera obscura acting as a model for the eye, these two branches were forced together. Until this point, it was possible to study geometrical optics without worrying about questions posed by physical optics, such as whether light is emitted or received by the eye. The camera obscura changed all that. Seeing an image projected on an analog of the retina made it clear that light rays are received by the eye. Suddenly, optics was given new direction.

The optical camera obscura also focused attention on the distinction between a “virtual” image, such as that produced in a mirror, and a “real” image like that projected onto a screen. Admittedly, the pinhole camera obscura had been producing “real” projected images for centuries. But first the employment of its optical successor for spectacles and illusional effects crystallised thinking on what was virtual and what was real. By this employment the optical camera obscura was unintentionally transformed into a scientific instrument. The projected image could easily be manipulated by moving the lens, the mirror or combined set of lenses or of mirrors. This suddenly made it possible to study the refraction in an experimental way, providing new insights into optics and, by way of the analogy between the optical camera obscura and the eye, into vision itself. Indeed, Kepler’s essay of 1604 contained the framework of a new theory of optics and vision; and he put this theory to the test in his *Dioprice* of 1611, which gives a groundbreaking account of how a telescope works.

During the course of the 17th century, famous figures like René Descartes, Isaac Barrow (1630-1677) and Isaac Newton (1642-1727) all followed Kepler’s lead, each developing their own theories of optics. The notion of the projected image and the related distinction between virtual and real images were crucial starting points for these new frameworks. Detailed investigations into the operation of new optical instruments like the telescope clearly influenced thinking on the nature of light and its interaction with matter. What is not so clear is exactly how the opportunity to manipulate projections offered by the camera obscura helped to develop the new optical conceptions of the age. This requires further study.

A historical device

The hey-day of the optical camera obcura was between 1600 and 1800. Its significance for astronomical observation, particularly sun observation, for the understanding of the eye, and for the science of optics may even be limited to the first half of the 17th century.

Its employment for painting, which one can reasonably assume but not prove for this century, is well documented for the subsequent 18th century. The *vedute* of Bernardo Bellotto, known as Canaletto (1722-1780), may be the most famous paintings produced with the aid of a camera obscura. 18th-century treatises on painting, particularly when dealing with the aesthetic of colours, show the deep impact of the camera on artistic judgements and opinions. By the end of this century, however, the decline of the optical camera obscura had already begun.[6]

Finally, with the emergence and development of photography in the 19th century, the camera obscura was "morally" downgraded to a mere forerunner of the modern camera. And the camera obscuras of the 18th and 19th centuries that survived were practically downgraded to the status of items of historical museums. The periodical revivals and renaissances that the camera obscura enjoys among professional as well as amateur photographers concern the simple pinhole camera, not the optical camera obscura.

Figure 4: The *Experimental Historical Camera Obscura* is a research tool for historians of art and science who investigate the 17th-century camera obscura. It was designed and constructed for the Max Planck Institute for the History of Science in Berlin, by Carsten Wirth and Henrik Haak.

The optical camera obscura has therefore become a truly historic device. Except for a few artists and photographers, it is of interest first of all to historians – historians of physiology, of astronomy, and of optics on the one hand and historians of visual culture in general and of art in particular on the other.

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[6] E. Fiorentini, *Camera Obscura vs. Camera Lucida – Distinguishing Early Nineteenth Century Modes of Seeing*. Berlin: Preprint of the Max Planck Institute for the History of Science, 307 (2006).

But these historians face a paradox. They are woefully short of sources for the optical camera obscura in the 17th century, the precise period in which this invention really shaped the visual experience of the western world, provoking artists to rethink their craft and scientists to rewrite their understanding of optics and vision. Since the written sources and the few book illustrations we have from this early period do not yield sufficiently detailed information, many aspects of this device still rely on a heavy dose of speculation and plenty of assumptions.

It would be nice, for example, to know the nature and quality of the projected images that the contemporaries of Huygens and Vermeer would have seen. Admittedly, such an experience is, by definition, an impossibility. We live in the 21st not the 17th century – our understanding, views and feelings are not those of someone living in the 17th century. Even if we were in the possession of Drebbel's instrument, its projections would certainly not have the same impact as they did on Huygens. Yet, we would, at least, gain an insight into the horizon of possible experience. This simple thought was the starting point of a project conceived and realized in Berlin in Germany to construct an experimental historical camera obscura, a device that could be used to test all kinds of assumptions about the 17th century experience.

An experimental historical camera obscura

A glance at the apparatus is sufficient to establish that this is no replica of any camera obscura of the 17th century Rather, it is a modern device designed with present-day engineering techniques and assembled out of materials from the modern, industrial world. A replica would have been neither possible nor desirable – the few descriptions and depictions of seventeenth-century cameras are not precise and elaborate enough to allow a reconstruction according to standards that historians would accept. But even if there were sufficiently detailed information about a particular, individual optical camera obscura of the period, a replica of it would not capture the variety of camera obscuras that were of significance to art and science in the 17th century. Instead, the apparatus recently designed and built for the Max Planck Institute for the History of Science in Berlin is a generic device from which all types of camera obscura we know of can be configurated. This should allow us to test present-day assumptions about historical cameras.

It goes without saying that this enterprise was and is beset with plenty of problems. There is, in particular, the issue of lenses and historical optical glass. How is it possible to test the performance of historical camera obscuras if there are no historical lenses that survive? Another challenge is deciding on the constraints to which tests of the cameras' performance should be subjected.

The proof of this experimental historical camera obscura will be in the projection. The historians of art and science that work with it to test their assumptions and conjectures will find out whether it is a useful research tool.[7] The object of their research, the optical camera obscura of the 17th century, is certainly worth the trouble.

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[7] Historians of art and of science as well as artists who consider to experiment with this apparatus may contact the author: wlef@mpiwg-berlin.mpg.de

The Optical Camera Obscura II
Images and Texts

Collected and presented by Norma Wenczel

A. STRAIGHT IMAGE PROJECTION

The Pinhole Camera

The camera obscura has been described since antiquity as a darkened room that admitted light only through a small hole. By this simple device, a horizontally as well as vertically inverted, moving image of the outside scene was cast on the wall opposite the hole. Another type of this device used a translucent screen which one viewed from behind, thus avoiding the left-to-right inversion. In this arrangement, too, the image was upside-down (see Figure 3). These two types of directly projecting camerae obscurae are in use in many contexts up to the present day.

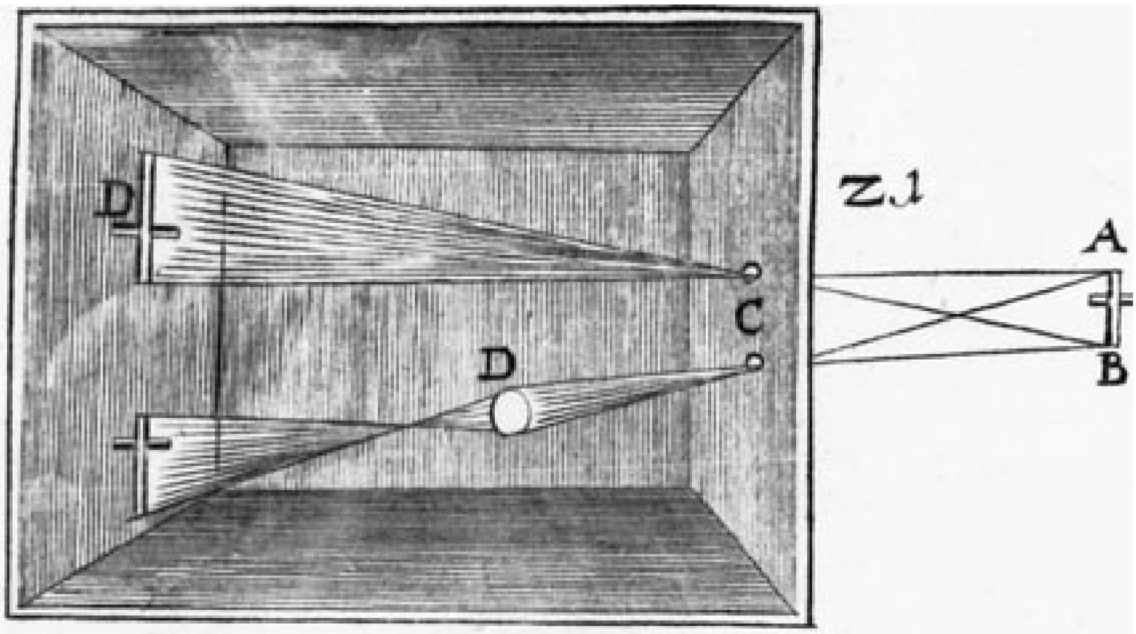

Figure 1: From Zacharias Traber *Nervus opticus* (1675).

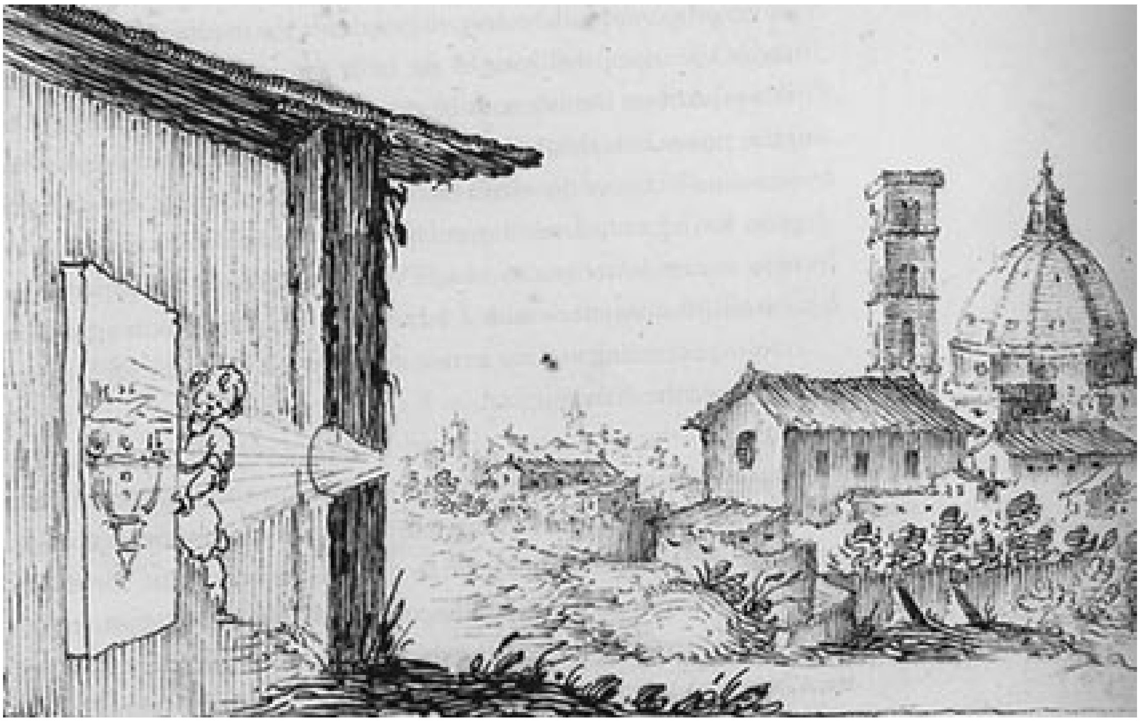

Figure 2: Drawing (c. 1635), attributed to Stefano della Bella (1610-1664).

In 1646, Athanasius Kircher (1601-1680) described a camera obscura consisting of two nested darkened rooms: an outer one with lenses in the center of each wall, and an inner one with transparent paper walls for drawing. The artist was obliged to enter the inner room by a trapdoor.

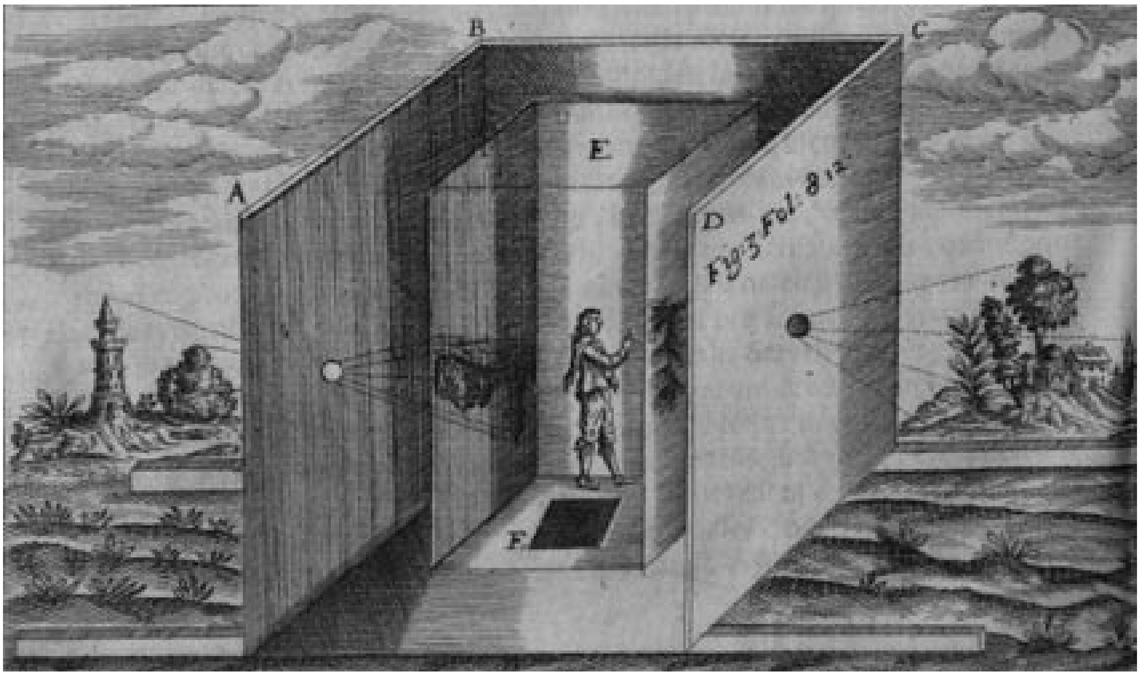

Figure 3: From Athanasius Kircher's *Ars Magna* (1646).

Mirrors and Lenses

In the last decades of the 16th century, a more sophisticated camera obscura emerged equipped with lenses and mirrors. This optical camera obscura became known through the writings of Giovanni Battista Della Porta (1535-1615). In his *Magia Naturalis* of 1558, he proposed the use of a concave mirror for the correction of the inverted image. And it is here that we find the suggestion to use the optical camera obscura for painting. Interestingly, in 1558, Della Porta said nothing about the use of lenses, which were known and used at that time. It was only in 1589, in the second edition of the *Magia Naturalis*, that Della Porta advised the use of a convex lens.

> *If you put a small lenticular Crystal glass to the hole, you shall presently see all things clearer, the countenances of men walking, the colors, garments, and all things as if you stood hard by. You shall see them with so much pleasure, that those that see it can never enough admire it. [...] One that is skilled in painting, must lay on color where they are in the table, and shall describe the manner of the countenance, so the image being removed, the picture will remain on the table, and in the superficies it will be seen as an image in the glass* [that is, reversed left to right]. (G. B. della Porta Magiae naturalis libri XX (2nd ed. 1589) XVII.6)

Portable Cameras

In 1694, Robert Hooke (1635-1703) described his “picture-box,” a device that allowed one to “take the draught or picture of anything,” in a paper to the Royal Society. This cone-shaped camera obscura demanded of the user that his head and shoulders should be inserted in the device. Although certainly not very comfortable, the user could sketch any outdoor scene with this portable instrument. In fact, Hooke recommended it for travelers.

Figure 4: Hooke’s portable camera obscura (1694).

For the illustrations of his *Osteographia* of 1733, William Cheselden (1688-1752) used a camera obscura. He circumvented the problem of the upside down inversion by hanging the specimen upside down in front of the camera.

> *[...] I contrived what I had long before meditated, a convenient camera obscura to draw in , with which we corrected some of the few designs already made, throwing away others which we had before approved of, and finishing the rest with more accuracy and less labour, doing in this way in a few minutes more than could be done without in many hours, I might say in days.* (W. Cheselden *Osteographia*, Introduction)

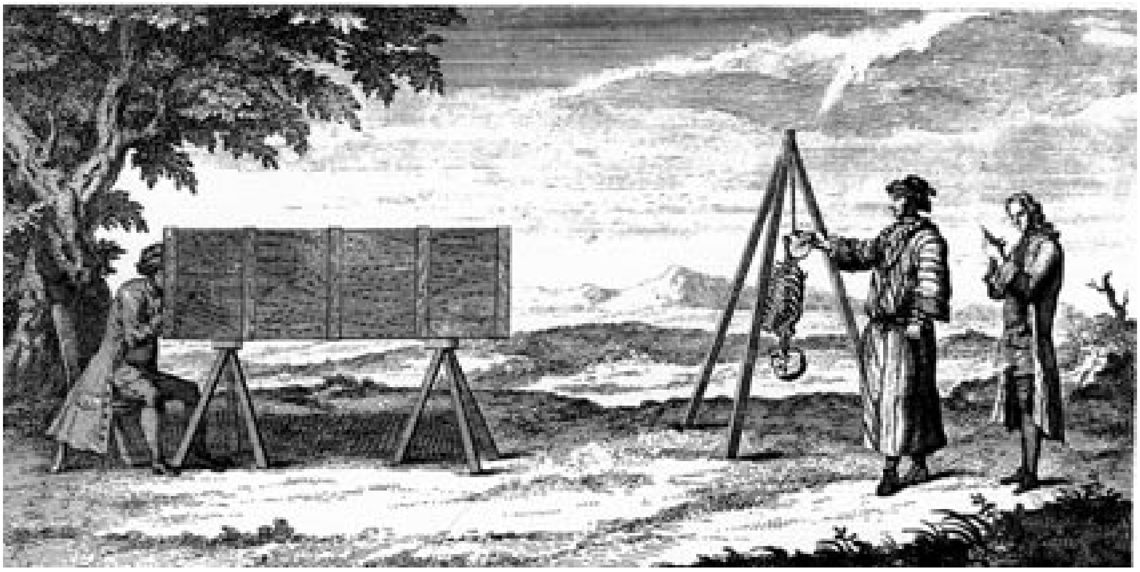

Figure 5: From William Cheselden's Osteographia (1733).

B. REFLECTED IMAGE PROJECTION I – POCKET ART AND SCIENCE

The Box-Type Camera Obscura

By combining the effects of a transparent screen and a 45° mirror, the two inversions of the projected image could be overridden. This is the principle of the box-type camera obscura which emerged in a variety of forms in the second half of the 17th century.

In *Oculus Artificialis Teledioptricus* (1685-1686), Johann Zahn (1641-1707) portrayed two forms of portable box cameras. The long lens tubes were probably for close-up work and for telescopic lenses. The image was reflected by an inclined mirror upwards to a transparent paper screen.

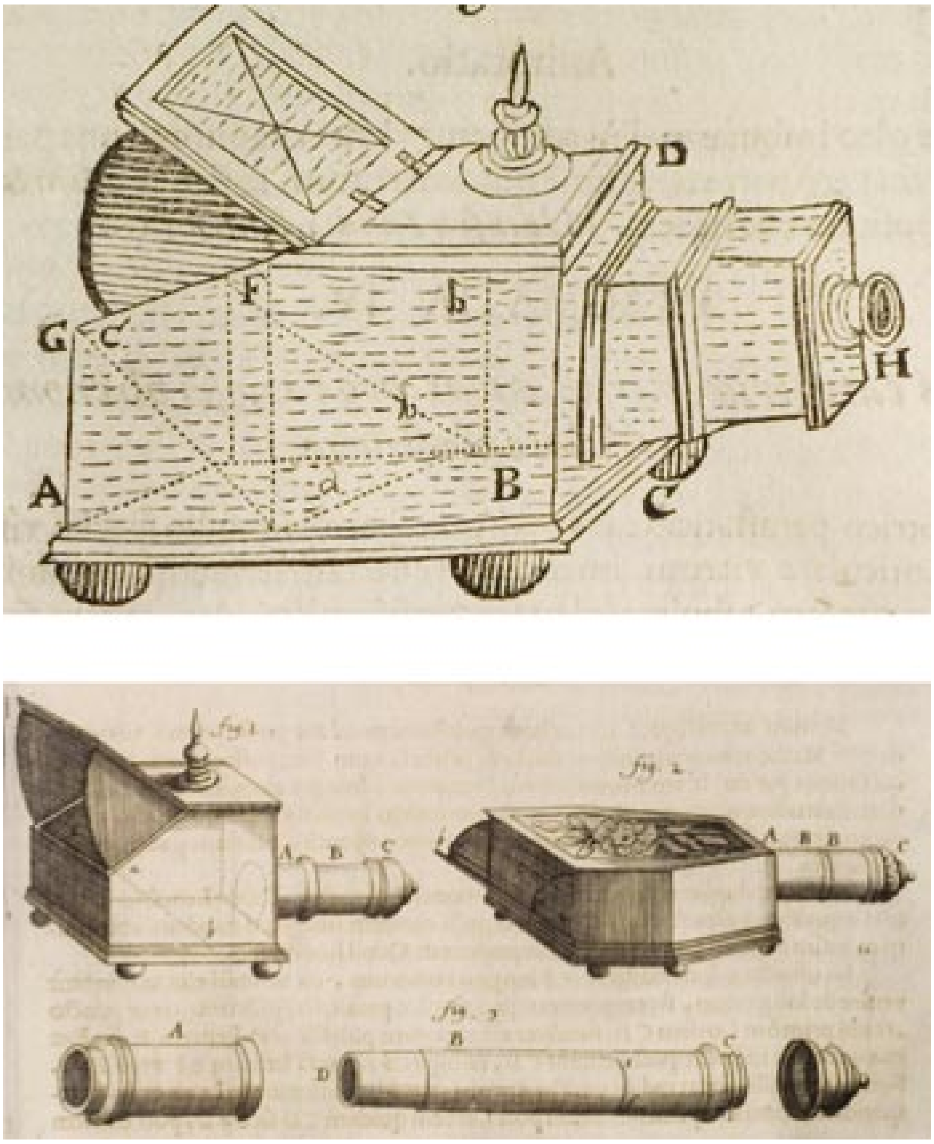

Figure 6: From J. Zahn *Oculus artificialis* (1669).

In *Of The Systematicall And Cosmical Qualities Of Things* (1669), Robert Boyle (1627-1691) described a “portable darkened room.” For this box-type camera obscura oiled, that is, translucent, paper was used for the drawing.

The Instrument and its Popularity

The camera was employed for painting and drawing from the 17th to the 19th centuries. We have documentary evidence that Canaletto and Guardi made use of it. But this practice was not confined to the Venetian vedutisti. Crespi, Claude-Joseph Vernet, Loutherbourg and many lesser known painters resorted to this aid as well.

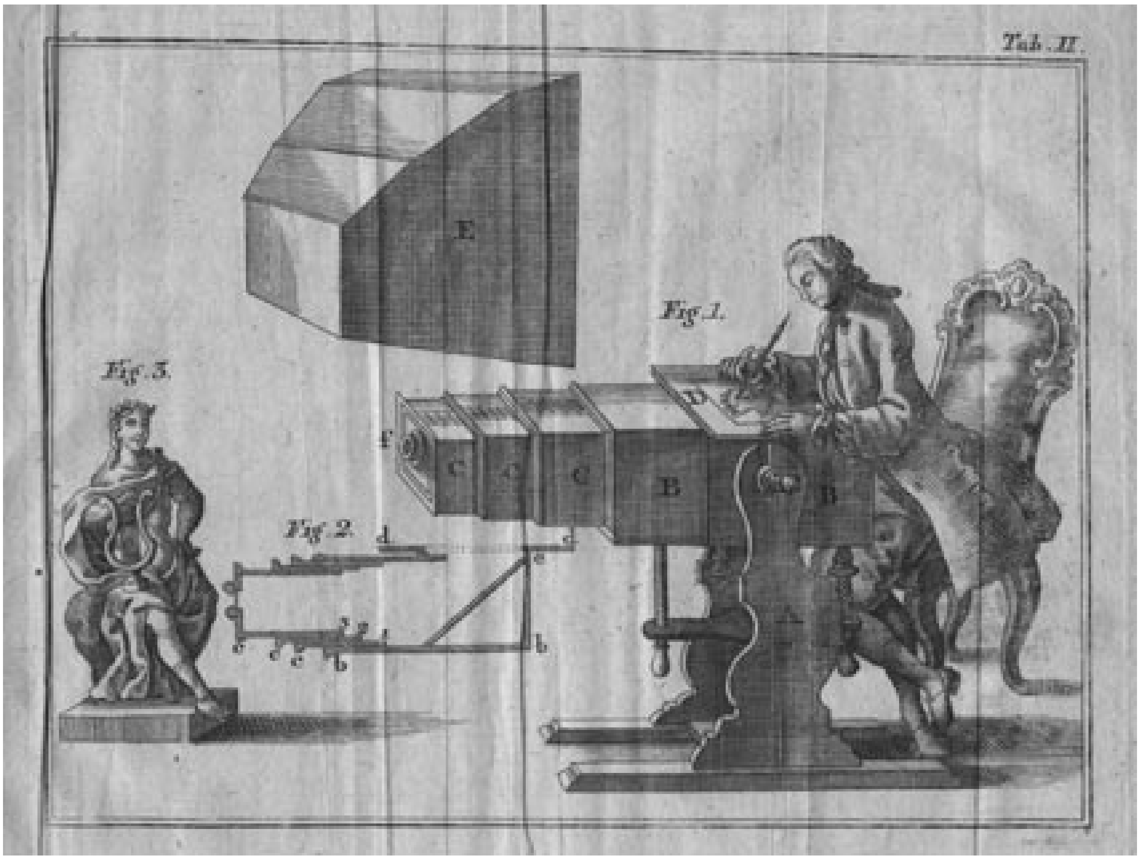

Figure 7: Box-type camera by G. F. Brander (1769).

By the beginning of the 18th century, a viewing camera obscura was built commercially and offered for sale in London. It was called a ‘Scioptricks,’ named after its lens which was known as a ‘scioptric ball.’

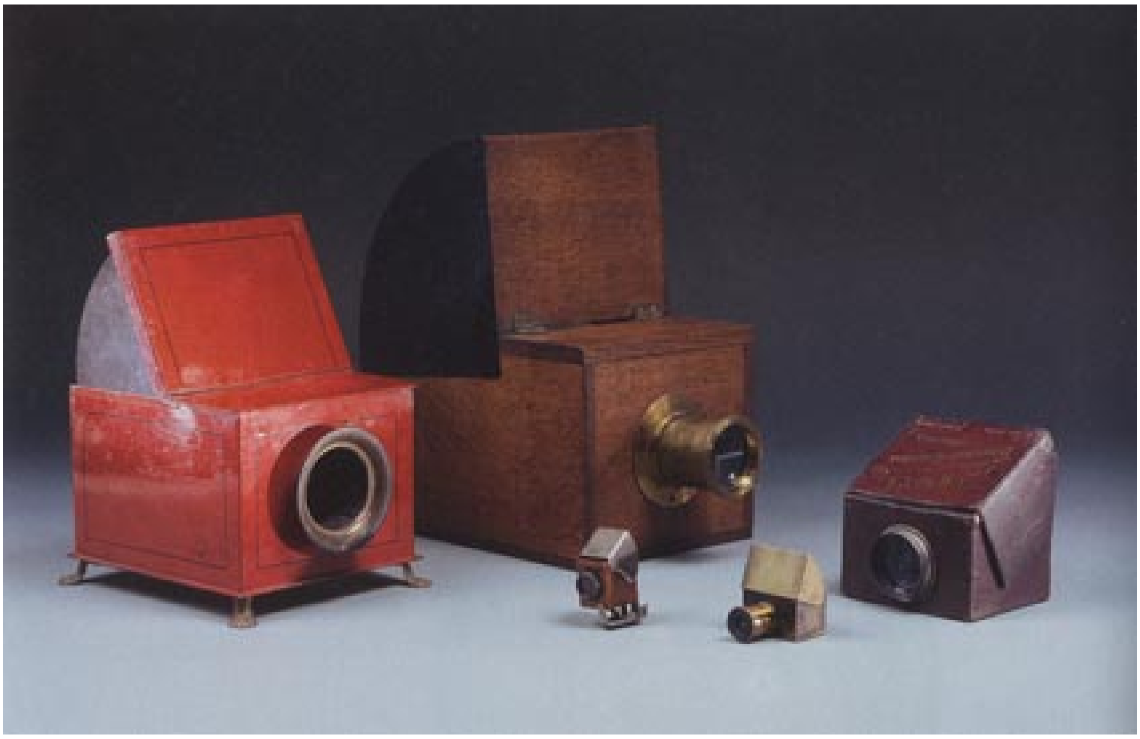

Figure 8: 19^{th}-century box-type cameras.

John Cuff (1708-1772) was a famous instrument maker whose trade brochure is one of the most beautiful examples of the fame and popularity of the camera obscura in the 18th century. The brochure is in the form of a 15 page poem, titled *Verses occasioned by the sight of a chamera obscura* (1747), which especially praises the perfected artistic "skills" of the instrument by comparing its pictures to those of nature itself:

> *Say, rare Machine, who taught thee to design ?*
> *And mimick Nature with such Skill divine ?*
> *The Miracles of whose creative Glass,*
> *Struck with Amaze, the superstitious Class,*
> *Of Fools, in * Bacon's Days, and did for Witchcraft pass ;*
> *Productions strange ! [...]*
> *How little is thy Cell ? How dark the Room ?*
> *Disclose thine Eye-lid, and dispel this Gloom !*
> *That radiant Orb reveal'd, smooth, pure, polite ;*
> *In darts a sudden Blaze of beaming Light,*
> *And stains the clear white Sheet, with Colours strong and*
> *bright ;*
> *Exterior Objects painting on the Scroll,*
> *True as the Eye presents 'em to the Soul ;*
> *A new Creation ! deckt with ev'ry Grace !*
> *Form'd by thy Pencil, in a Moment's Space !*
> *As in a Nutshell, curious to behold ;*

Great Homer's Illiad was inscrib'd of old ;
So the wide World's vast Volume, here, we see
To Miniature reduc'd, and just Epitome : [...]
How wou'd that Painter boast his Pencil's Art ?
Who cou'd such Motions to his Piece impart ?
But, here, thou hast no Rival in thy Fame ;
'Tis thine alone to copy Nature's Frame,
So strictly true, she seems the very same ;
In just Proportions ; Colours strong or faint ;
By Light and Shade ; without the Daub of Paint :
To animate the Picture, and inspire,
Such Motions, as the Figures may require,
From Heav'n, Prometheus like, thou steal'st the sacred Fire.

C. Reflected Image Projection II – Outdoor Experiences

The standard form of the tent camera was equipped with a lens and mirror at the top of the tent that projected the image perpendicularly onto a table. If the beholder faces away from the scene, the image is correctly oriented.

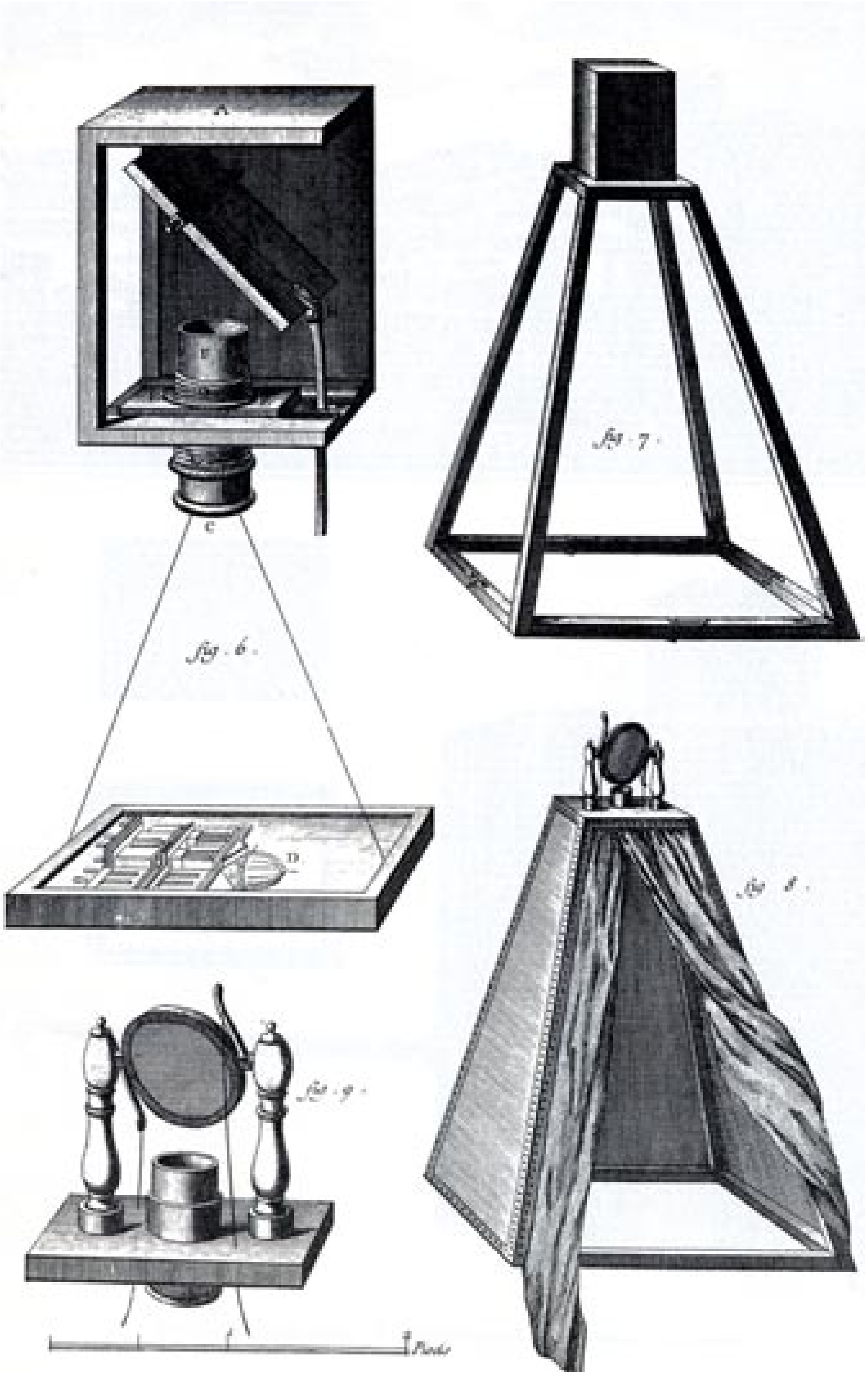

Figure 9: From Diderot's and D'Alembert's *Encyclopédie* (1751-1780).

1620 Kepler and his tent-type camera obscura

The term *camera obscura*, more strictly *camera clausa*, was coined by Johannes Kepler (1571-1630) in his *Ad Vitellionem Paralipomena* (1604). The camera he used was no longer only a camera in the true meaning of the word but a kind of tent camera that projected the image on a sheet of paper inside the tent. According to a letter written to Francis Bacon by Sir Henry Wotton, who met Kepler in Linz in 1620, this portable camera had been invented by Kepler for sketching the complete 360° panorama. Kepler used it for topographical mapping rather than for artistic purposes.

> *He hath a little black tent which he can suddenly set up where he will in a field, and it is convertible (like Wind-mill) to all quarters at pleasure capable of not much more than one man, as I conceive, and perhaps at no great ease; exactly close and dark, save at one hole, about an inch and a half in Diameter, to which he applies a long perspective-trunke, with the convex glass fitted to the said hole, and the concave taken out at the other end, which extendeth to about the middle of this erected Tent, through which the visible radiations all the objects without are intromitted, falling upon a paper, which is accommodated to receive them; and so he traceth them with his pen in their natural appearance, turning his little Tent round by degrees, till he hath designed the whole aspect of the field: this I have described to your Lordship, because I think there might be good use made of it for Chorography* [the making of maps and topographical views]: *For otherwise, to make landskips by it were illiberal, though surely no Painter can do them so precisely.* (Reliquiae Wottoniae, London 1651, pp. 413-414.)

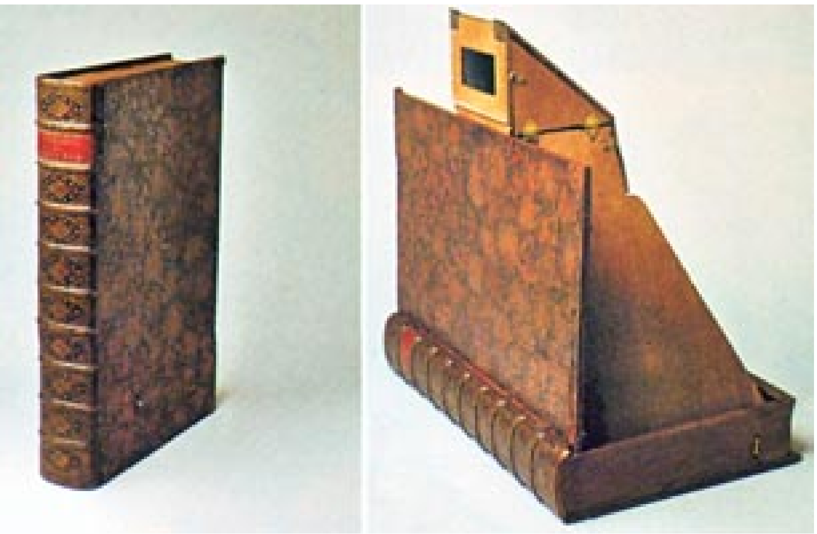

Figure 10: Book-type camera, c. 1750.

1622 Drebble's "Other Instrument"

The Dutch glassmaker, engraver and engineer Cornelis Drebbel (1572-1633) was a very resourceful inventor. Besides constructing a compound telescope, he also developed a machine for grinding lenses, and accordingly placed a lens in the pinhole of his camera obscura.

Constantijn Huygens (1596-1687), who served as the Dutch Ambassador to London from 1621 to 1624, was invited to the homes of many noble households and met British musicians, philosophers and scientists, one of them being Francis Bacon (1561-1626). In Eltham Palace Huygens used to visit Drebbel, with whom he shared a lifelong interest in optics. From Drebbel he acquired a camera obscura and a microscope. In a famous letter to his parents, Huygens even heralds the death of painting while voicing his admiration for the camera's degree of accuracy and brio.

> *I have at home Drebbel's other instrument, which certainly makes admirable effects in painting from reflection in a dark room; it is not possible for me to reveal the beauty to you in words; all painting is dead by comparison, for here is life itself or something more elevated if one could articulate it. As one can see, the figure and the contour and the movements join together naturally and in a grandly pleasing fashion.* (C. Huygens in a letter to his parents of April 13, 1622)

Figure 11: 19th-century tent-type camera.

D. THE CAMERA OBSCURA AS MODEL OF THE EYE

Eye and Oculus Artificialis

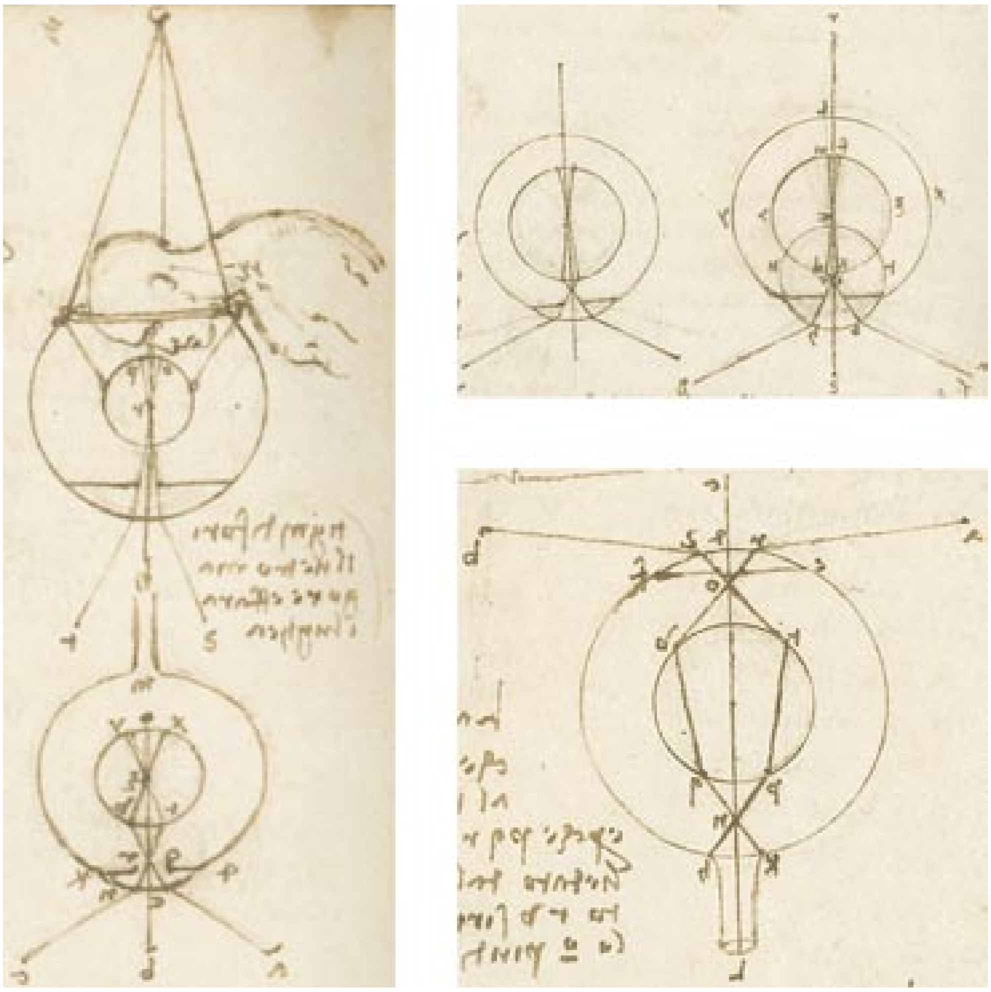

Figure 12: Leonardo's view of the eye's optics. From MS D, 1508.

Leonardo da Vinci (1452-1519) mentions the camera obscura in his *Codex Atlanticus* and *Manuscript D* giving detailed accounts of the camera obscura effect, diagrams, observations, and explanations of its principle. He, like many scholars before and after him, tried to solve one of the outstanding optical puzzles – how the eye works. But it was not him but Kepler who made the most significant step for our understanding of vision since Alhazen. Being in the position to compare the eye to the optical camera obscura rather than to the pinhole camera, he developed a convincing understanding of the role of the eye's lens and retina. If the back layers of the eye were to be peeled back, there could be seen the inverted image normally cast on the retina. This experiment was actually carried out with an ox eye by the Jesuit scholar Kaspar Schott in 1657.

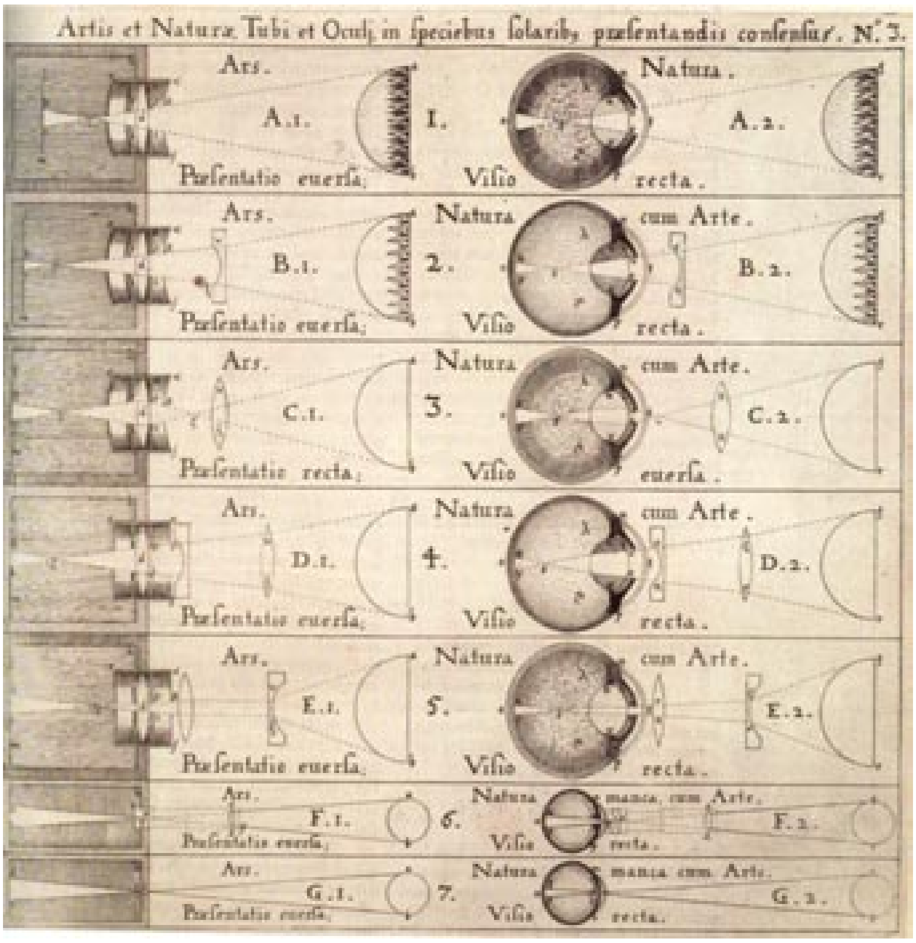

Figure 13: Artificial and natural eye. From Christopher Scheiner *Rosa Ursina* (1630).

Descartes and the Question of Perfection

René Descartes (1596-1650) compared the eye to the camera as well, stating that the retina was the same as the screen of the camera obscura. In his *Dioptriques* (1637), a very interesting and at the same time paradoxical remark can be found about the relation of "perfect images" to the objects they represent:

> *Very often the perfection of an image depends on its not resembling the object as much as it might. For instance, engravings, which consist merely of a little ink spread over paper, represent to us forest, towns, men and even battles and tempests. And yet, out of an unlimited number of different qualities that they lead us to conceive the objects, there is not one in respect of which they actually resemble except shape. Even this is a very imperfect resemblance: on a flat surface, they represent objects variously convex or concave; and again, according to the rules of perspective, they often represent circles by ovals rather than by other circles, and squares by diamonds rather than by other squares. Thus very often, in order to be more perfect qua images, and to represent objects better, it is necessary for the engravings not to resemble them. (Dioptrique,* Disc. 4, transl. by Anscombe and Geach)

The Scioptric Ball

The scioptric ball or “ox-eye lens” was developed in 1636 by the professor of mathematics and oriental languages at Altdorf, Daniel Schwenter. The movable lens-ball in the aperture of the scioptric ball allowed the artist either to draw or to paint panoramic views.

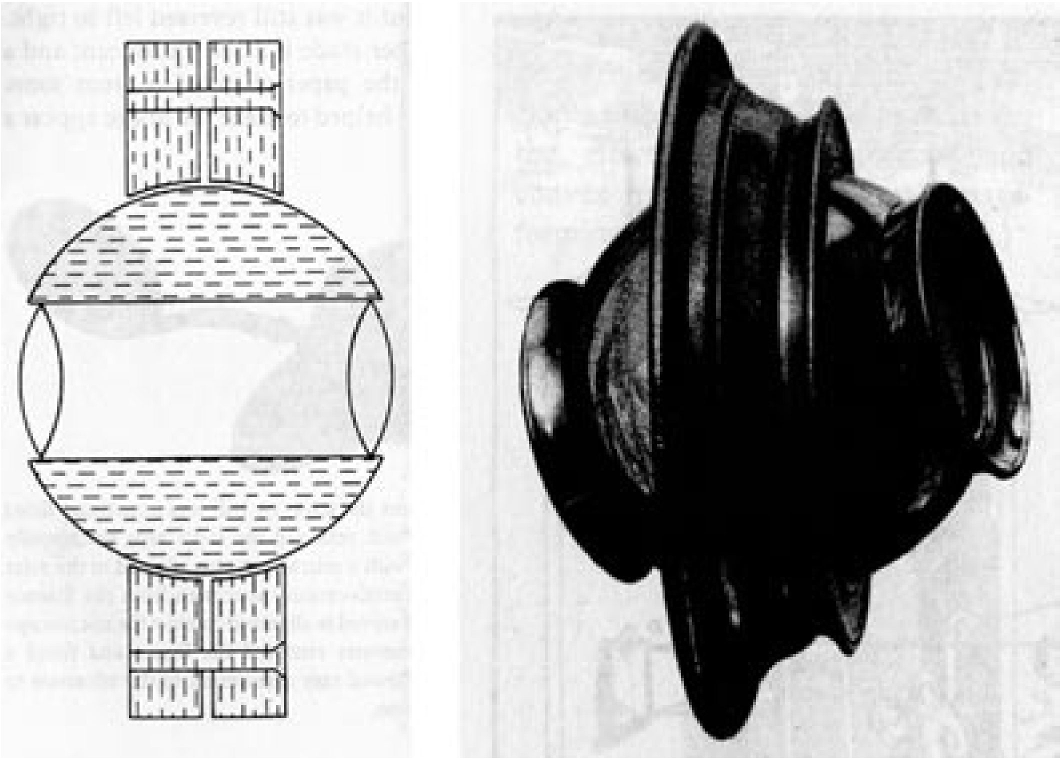

Figure 14: Scioptric Ball.

E. AN ASTRONOMICAL INSTRUMENT

Eclipses on the Screen

The oldest employment of the camera obscura, dating back to antiquity, was for astronomical purposes, for safely observing phenomena connected with the sun, in particular solar eclipses and sunspots. One of the most prominent figures of medieval science, Roger Bacon (1214-1294), who was greatly influenced by Alhazen, wrote in his *De Multiplicatione Specierum* as well as in his *Perspectiva* about the principle of the camera obscura.

Bacon also recommended the use of a kind of lens for magnification to aid natural vision:

> *Great things can be performed by refracted vision. If the letters of a book, or any minute object, be viewed through a lesser segment of a sphere of glass or crystal, whose plane is laid upon them, they will appear far better and larger.*

The Dutch mathematician and physician Reinerus Gemma-Frisius (1508-1555), observed an eclipse of the sun with a camera obscura at Louvain on January 24, 1544. A year later he used this illustration of the event in his book *De Radio Astronomica et Geometrica.* It is the first published illustration of a camera obscura and excellent illustration of the projection of a pinhole image. The inverted image of the sun and moon is clearly visible on the wall of the camera.

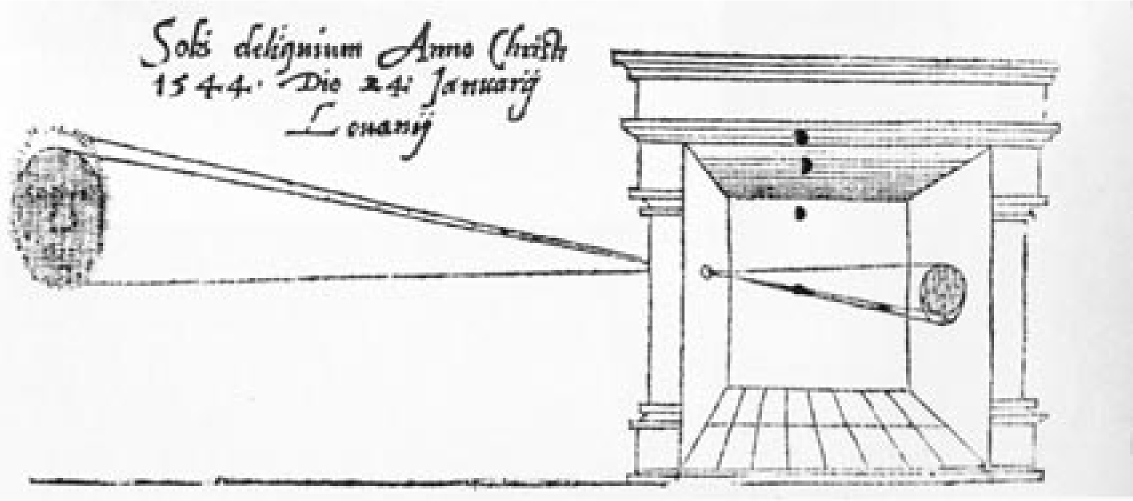

Figure 15: From Gemma Frisius *De Radio Astronomica* (1546).

In his *La Dioptrique Oculaire* (1671), Cherubin d'Orleans (1613-1697) provides an illustration showing the light rays and their inversion at the aperture of a camera obscura.

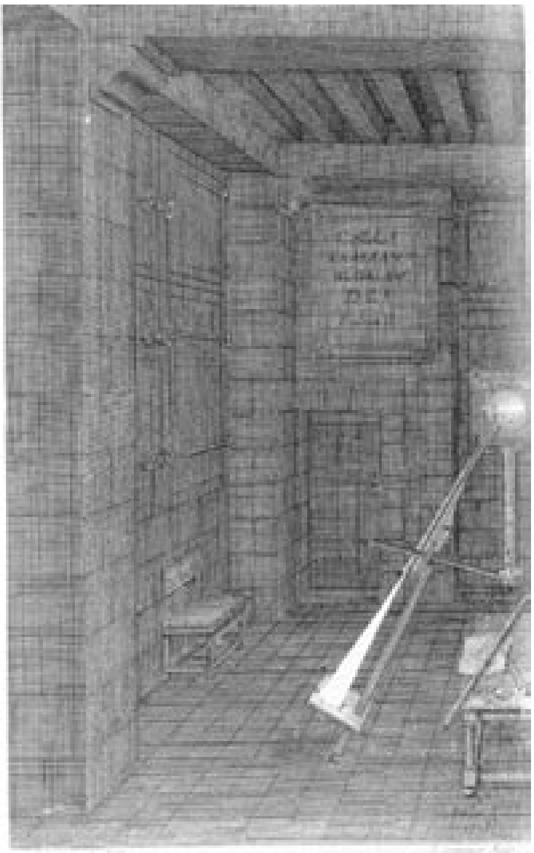

Figure 16: From Cherubin d'Orleans' *Dioptrique* (1671).

Dark Patches on the Day Star

The dark patches on the surface of the sun, which we now call sunspots, were noticed by early observers in China or Greece several thousands of years ago. Despite these early observations, only the invention of the telescope in 1609 made thorough investigations of sunspots possible. Galileo was one of the first to make serious studies of sunspots (1610).

In the 17th century, the principal method of such observations was the projection of the image of the sun by a telescope inside the camera obscura. The first Astronomer Royal, John Flamsteed (1646-1710), reports this use of a camera obscura during the solar eclipse of July 2, 1684: "I observed the eclipse of the sun [...] on a scene [screen] in a darkened room."

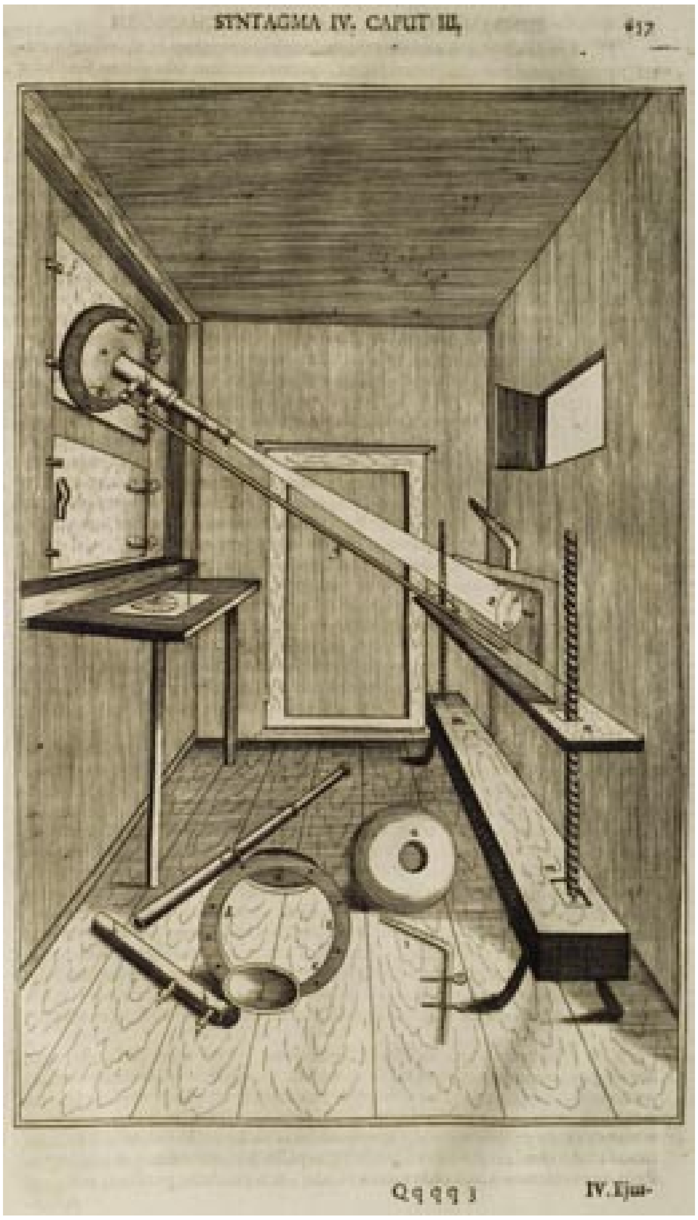

Figure 17: From J. Zahn *Oculus artificialis* (1669).

Christopher Scheiner (1575-1650) used his “Pantograph” or “Helioscope”, a portable camera 22 metres in length, equipped with a telescope to view sunspots. With this instrument, which he described in his *Rosa Ursina Sive Sol* (1626-1630), he was able to project the surface of the sun onto a piece of paper.

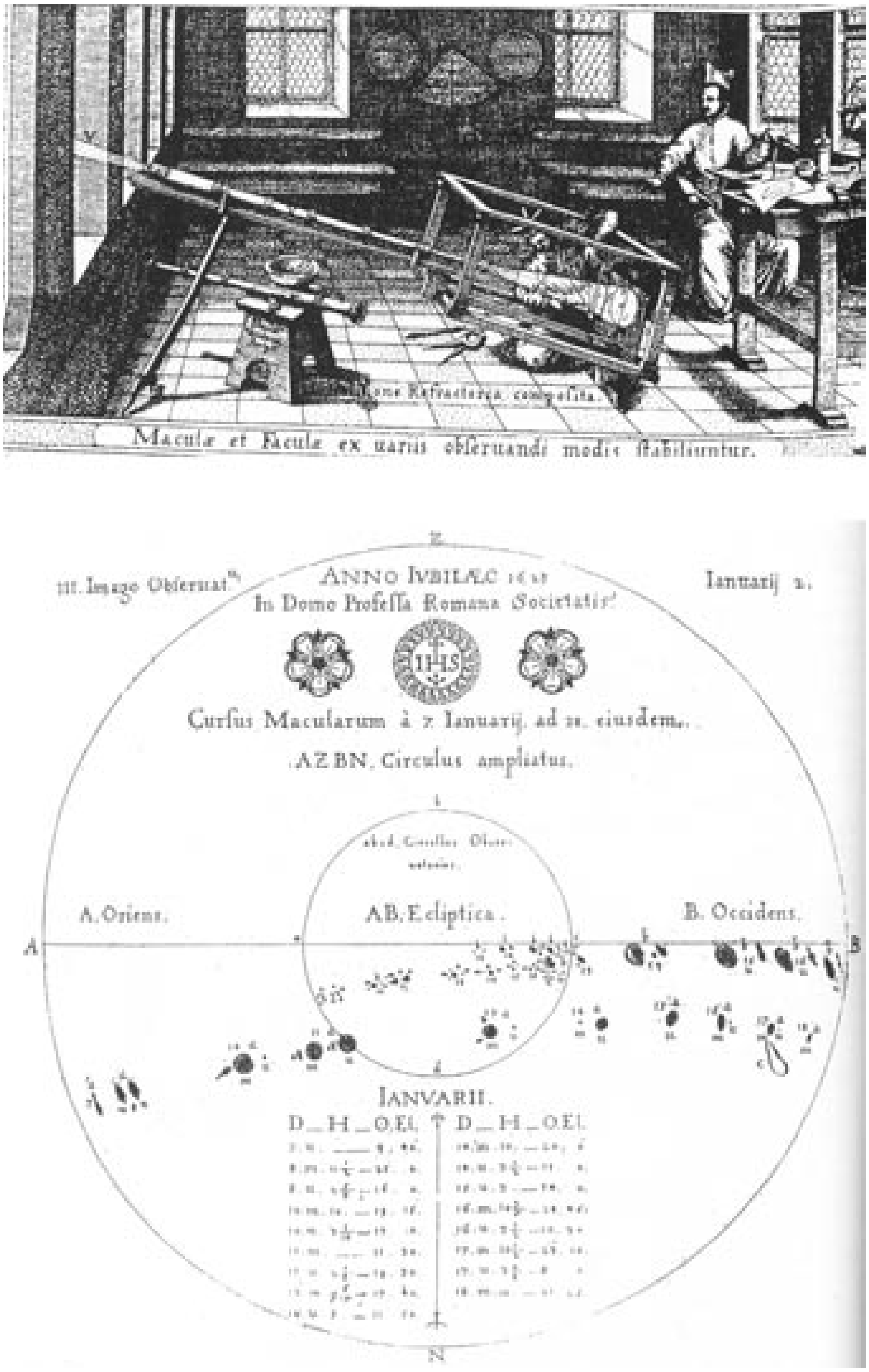

Figure 18: From Chr. Scheiner *Rosa Ursina* (1630).

Projecting Nature in Early-Modern Europe

Michael John Gorman

The history of early modern techniques of optical projection is frequently told as a prelude to the history of chemical photography and projective technologies of the nineteenth and twentieth centuries. The camera obscura was photography *avant-la-lettre*, as the magic lantern anticipated the slide and film projectors.

As Helmut Gernsheim puts it, in describing the reflex camera obscura described by Johannes Zahn in his *Oculus Artificialis* of 1685, "In size and construction, Zahn's cameras are prototypes of nineteenth century box and reflex cameras. It is really remarkable that no further development took place until the middle of the nineteenth-century: in 1685 the camera was absolutely ready and waiting for photography".[1]

Such narratives attribute to instruments and devices a sort of animism, a desire to mature, "evolve" and become that which they are not. They are useful ways to stitch instruments into stories. On being confronted with the illustrations of Zahn's cameras, it is indeed difficult not to see them as "ready and waiting for photography"

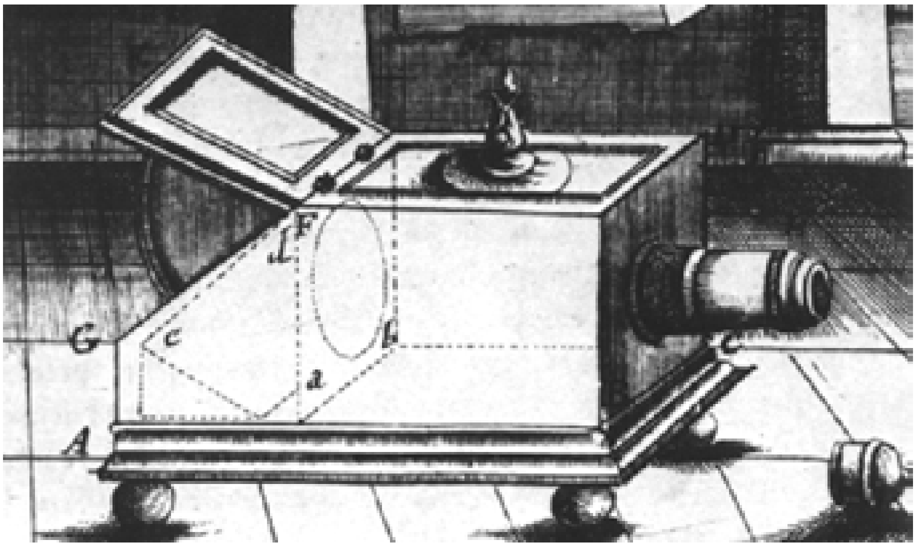

Figure 1: Reflex Camera Obscura, from Johannes Zahn, *Oculus Artificialis* (1685).

Can instruments really have "ancestors" though? Are the purposes for which each instrument was designed not subtly different from those of its predecessors? And do the ultimate uses of devices not frequently subvert the uses intended by their designers, as technologies are "cannabilized", "hacked" and "patched"?

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[1] Helmut Gernsheim, *History of Photography from the Earliest Use of the Camera Obscura in the Eleventh Century up to 1914.* London, New York: Oxford University Press, 1955.

The tendency to consider the camera obscura as an anticipation of photography has been pervasive. David Hockney's claim that realist painters from Van Eyck to Bouguereau traced the images produced by the camera obscura could be viewed as an extreme example of the tendency to project photography backwards through time.[2] Even a more contextualized account of the relationship between the camera obscura and Netherlandish painting, Svetlana Alpers' *The Art of Describing*, has to bear some of the blame for the tendency to see the camera obscura as a prephotographic device that needed manual assistance to produce a durable image.[3]

Here I would like to challenge this tendency, and consider early modern projective devices not as chemically-deficient "anticipations" of photography or film, but as something completely different. Rather than consider the projection-screen as a transitory stage in the evolution of the photographic print, I want to consider projections in their own right, and ask how projections were interpreted, and what kinds of disputes arose about their interpretation. An exploration of the different cultures of projection in early modern Europe can aim to offer a different approach to the complex issue of the connection between optical projection and the mimetic representation of nature to that offered by accounts framed within the prehistory of photography or of cinema. I will argue that optical projection ceased to be a philosophical problem at the end of the eighteenth century, becoming instead a mere means of ostension, in which the phenomenon of projection was "blackboxed", and rendered inappropriate for investigation in and of itself. From being an examplar of the mechanical philosophy, the projected image became a support to work done elsewhere, a way of showing, not of finding out. Where the camera obscura had been a tool for investigating sunspots and the nature of vision, the magic lantern and solar microscope became viewed as, first, examples of the application of the principles of Newton's *Optics*, and by the early nineteenth century, as of little philosophical interest, precisely at the time of their most virtuoso deployment as entertainment devices.

In rescuing early modern optical projection from the linear histories of photography and cinema, Peter Galison's notion of the trading zone, defined as an "arena in which radically different activities could be locally, but not globally, coordinated", might be helpful. Where optical projection became involved in disputes about natural philosophy, as for example in discussing the nature of vision, the behaviour of sunspots, or the causes of influenza, the lines of argument often drew on the other contemporary connotations of projection. Kepler's famous account in the *Paralipomena* of the visual image as a "natural painting", or the "paintbrush of rays" falling on the retina, is merely the most familiar example of such a "pidgin", if we sustain Galison's analogy.[4]

The darkened room filled with optical projections, as it developed from Aristotle until the eighteenth century, was invested with a range of very different practices, including astronomy, theatre, steganography, magic, physiology, painting, optics, meditation, chorography and even warfare. My goal here is to explore the disputed epistemological status of the projected image. I will look at the camera obscura, magic lantern, solar microscope, and also at instruments that allow "virtual" projection through binocular superposition, such as the camera lucida.

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[2] David Hockney, *Secret Knowledge: Rediscovering the Lost Techniques of the Old Masters*, London: Studio, 2001.

[3] Svetlana Alpers, *The Art of Describing*, Chicago: University of Chicago Press, 1983.

[4] Peter Galison, *Image and Logic: A Material Culture of Microphysics*, Chicago: University of Chicago Press, 1997, pp. 803-840.

Figure 2: Frontispiece of Christoph Scheiner's *Rosa Ursina* (1626-30).

To pose the problem, I would like to use the engravings that frame the Jesuit astronomer Christoph Scheiner's great seventeenth century treatise on sunspots, the *Orsini Rose, or the Sun shown to be changeable by the marvellous phenomenon of its flares and stains and shown to be Mobile about its own centre and fixed axis from West to East in annual rotation, and to be rotated around another mobile axis from East to West on an approximately monthly basis, about its own poles, demonstrated in four books* (1626-30).

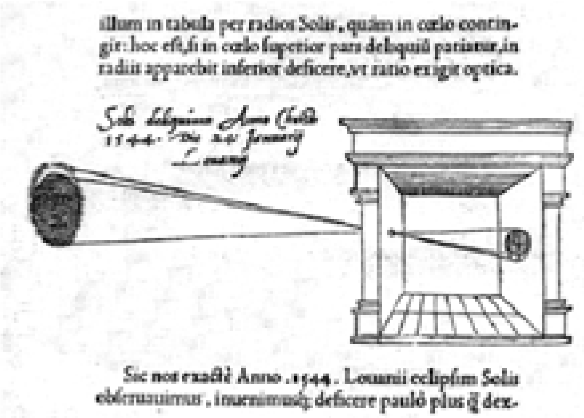
The allegorical frontispiece of Scheiner's work positions the projected image of the sun obtained by means of a telescope in a hierarchy of sources of reliable knowledge. Sacred authority (*Auctoritas Sacra*) and Reason (*Ratio*) produce beautifully clear sunspot images. Sense (*sensus*), is represented by a telescopic projection of the sun, indicating that the projecting instrument is merely an extension of the senses. Finally profane authority (*auctoritas profana*) only gets a rather dim lantern.

What was Scheiner attempting to do here? Contrary even to recent reinterpretations of the sunspots debate between Scheiner and Galileo that have tended to see Scheiner as a defender of Aristotle, Scheiner was in the process of mounting a major attack on Aristotelian cosmology, by proclaiming both that the sun is corruptible and that the heavens were fluid, rather than nested solid spheres.

His weapons against Aristotle were the instrumentally enhanced senses, and citations from the Church Fathers and Jesuit authorities such as Robert Bellarmine supporting the fluidity of the heavens. In this single illustration, then, the projected image is depicted both as more authoritative than the entire writings of Aristotle, and as a natural extension of the human senses. Scheiner's opponents were doctrinaire Aristotelians, including Jesuit philosophers and theologians, who denied the possibility of any changes in the heavens, and also denied that good philosophy could proceed from observations made with specialized instrumentation. To fight them he used a scissors-action, combining careful observations of sunspots using his projective system with suitable quotations from the Church Fathers.

Scheiner's twin concerns: to naturalize projection as an extension of the senses and to authorize the projected image above ancient philosophical authority, are closely connected. As Scheiner has traditionally been seen as the adversary of Galileo in the sunspots debate, Galileo's "straw-man" depiction of Scheiner as a philosophical pedant, has been appropriated by historians. However, though Galileo tended to paint the sunspots debate as a philosophical dispute, in a clever literary move to typecast the Jesuit astronomer as a philosophical conservative, Scheiner's quarrel with Galileo was essentially a priority dispute about who had been first to observe sunspots. Unlike Galileo, in addition to furnishing his instrumentally produced observations, Scheiner needed to convince his Jesuit superiors that his radical anti-Aristotelian claims were sanctioned by a higher authority. Scheiner's original suggestion that the spots were tiny satellites of the sun was just a means of dealing with the fact that the same spots did not return as the sun rotated, as one would expect if the sun was a solid body with permanent spots, it was not an attempt to save Aristotelian cosmology.

It is ironic, in view of the received wisdom on Scheiner's Aristotelianism, that the material arguing from the observed motion of the sunspots for the Sun's rotation in Scheiner's *Orsini Rose* was to provide Galileo with perhaps his strongest argument for Copernicanism in the *Dialogue on the Two Chief World Systems*, namely the argument that if we assume the Earth to be stationary, the solar axis exhibits an "unnatural" conical rotation with a period exactly equal to the solar year. If we assume instead that the Earth is moving around the sun, we can eliminate this "unnatural rotation" and this spectacular coincidence merely by assuming that the sun's axis is tilted with respect to the normal to the Earth's orbital plane.


illum in tabula per radios Solis, quàm in cœlo contingit: hoc eſt, ſi in cœlo ſuperior pars deliquiũ patiatur, in radiis apparebit inferior deficere, vt ratio exigit optica.

Sic nos exactè Anno .1544. Louanii eclipſim Solis obſeruauimus, inuenimusq; deficere paulò plus q̃ dex-

Figure 3: Use of the camera obscura to observe a solar eclipse. From Gemma Frisius, *De Radio Astronomica* (1544).

The camera obscura had been associated with solar astronomy long before the dispute on sunspots. Since at least the tenth century, the camera obscura had been used as a safe way to observe solar eclipses, as depicted in Gemma Frisius's *On the astronomical and geometric staff*, 1544.

Solar projections on meridian-lines on the floors of churches had also been used measure the length of the solar year since Paolo dal Pozzo Toscanelli's meridiana in the Florentine duomo of 1475, and in Ignazio Danti's spectacular meridian of the Torre dei Venti in the Vatican in the 1580s, as described by John Heilbron.[5]

Figure 4: Ignazio Danti's Meridian of the Torre dei Venti in the Vatican.

In 1607, Kepler used a simple camera obscura to attempt to observe a transit of Mercury across the solar disc. It appears that he observed a large sunspot instead, describing it as "a little daub, quite black, approximately like a parched flea" and mistook it for Mercury.[6] The use of the camera obscura for solar observation is thus an important, and long-standing precedent to telescopic astronomy, and the publicly visible projected image, as a source of astronomical knowledge, precedes the privately discernible telescopic image. Small wonder, then, that both Scheiner and Galileo would use the telescope to project images of the sun onto a screen, to observe the movements of sunspots.

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[5] John Heilbron, *The Sun in the Church: Cathedrals as Solar Observatories*, Cambridge, MA.: Harvard University Press, 1999.

[6] Kepler, *Phaenomenon singulare*. Gesammelte Werke, vol. IV, pp. 77-98.

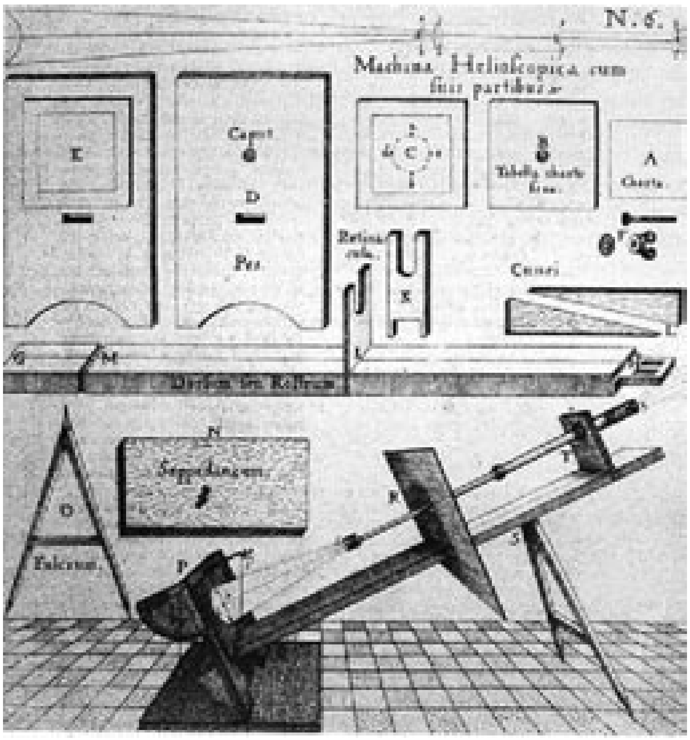

Figure 5: Instrument for observing sunspots. From Christoph Scheiner, *Rosa Ursina* (1626-30).

There is an anomaly here though. In Scheiner's first publication on the sunspots, his *Three Letters on sunspots* written to the Augsburg banker Mark Welser, he described the use of a different system of observation, involving direct telescopic observation, and the use of blue or green filters to protect the eye. In order to bypass the Jesuit censorship system, Scheiner wrote these letters under a pseudonym, *Apelles post tabula latens*, Apelles hiding behind the painting, recalling the story of the ancient painter Apelles hiding behind one of his paintings in order to hear candid criticisms of his work.[7]

Tabula is also the word used for a projective screen in the terminology of the period applied to the camera obscura, and it seems more than likely, given the long history of the camera obscura as a device for solar observation, and suggestive remarks made by Scheiner and others, that Scheiner was hiding not only his identity behind this pseudonym but also the projective method he used to make solar observations, in an attempt to gain a monopoly over accurate sunspot observations. Scheiner's initial system may only have been a pinhole camera, or perhaps a camera obscura equipped with a convex lens, as Eileen Reeves has suggested. Galileo, through the help of one of his students, Benedetto Castelli, began using a telescopic projective system to observe sunspots.[8] Rather than keep his method secret, Galileo described its use in detail so that sunspot

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[7] Eileen Reeves, *Secrecy and Disclosure: Early Modern Descriptions of the Camera Obscura*, paper read at the European Science Foundation workshop in Ghent, Nov. 2003.

[8] Reeves, op. cit.

observations could be carried out by amateurs throughout Europe and shared among members of the Republic of Letters.

Figure 6: Observing sunspots. From Christoph Scheiner, *Rosa Ursina* (1626-30).

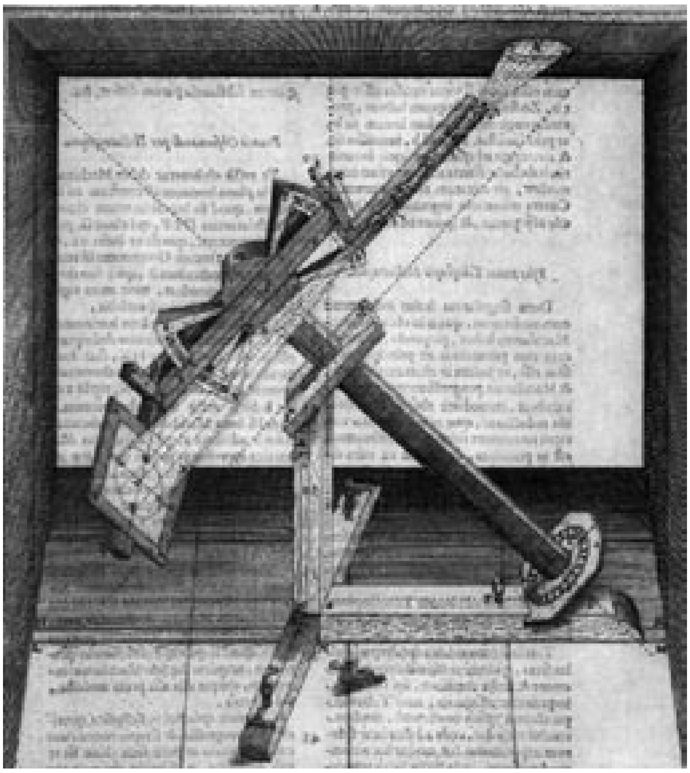

Figure 7: Grienberger's heliotropic telescope, From Christoph Scheiner, *Rosa Ursina* (1626-30).

The reasons for Scheiner and Galileo's different approaches to revealing the projective system may have something to do with their different beliefs about what the spots were. Scheiner could not (initially) believe that the spots were actually part of the sun, because they did not return, as one would expect if they were spots on a solid, rotating sphere – instead he thought they must be groups of small satellites. Galileo had demonstrated the extraordinary "patronage valence", to use Mario Biagioli's term, of small satellites, through his naming of the Medicean stars, and Scheiner may have wanted to guard the patronage possibilities of the solar "satellites" for himself, while demonstrating his priority of observation. Galileo, on the other hand, viewed the spots as fleeting "excrements" of the sun, as Mario Biagioli has argued, and therefore with negligible potential for patronage (who wants to have excrement named after them?).[9] On the other hand, Galileo realized that the apparent movements of the sunspots, given that they were in the body of the sun, could be used to analyze the rotation of the Sun about its own axis, something that Scheiner would do to great effect in the *Orsini Rose*.

The initial projective system used by Galileo and Castelli consisted in a telescope and a "*tabula*". Galileo described how he would use a pair of compasses to trace a circle of the desired size onto a piece of paper, attached to the screen, and then position the screen so that the sun's disc fell exactly within the circle, a technique that allowed him to ensure that the screen was normal to the telescope. He would then mark the positions of the sunspots. This technique was awkward for observations made over long periods, as the telescope needed to be moved frequently to follow the change in the sun's position.

In his *Orsini Rose*, Scheiner published a more sophisticated device invented by fellow Jesuit mathematician Christoph Grienberger, called the "telescopic sunflower or heliotropic telescope". This was the earliest example of an equatorial mount, and allowed the device to be moved easily to track the sun.

A plate printed no less than four times in Scheiner's *Orsini Rose* demonstrated the "wonderful concordance of nature and art" through a systematic comparison of the eye and the camera obscura. Scheiner's image was a powerful piece of visual rhetoric, as he believed that it was "necessary for such a useful matter to be poured not into the ears through words, but into the sight through figures".[10]

As Kepler presented the eye as a camera obscura, Scheiner presented the camera obscura and even the telescope as "merely an artificial, dead eye".[11]

Scheiner's illustration is a vivid demonstration of the analogy between the artificial and the natural projective systems. The images presented with the camera obscura are thus no less natural than those seen with the naked eye. Scheiner was very concerned to demonstrate that his observations of sunspots could not be attributed to the deceptive nature of his projective apparatus. As he had written in his *More accurate Disquisition* "If I now show that the solar spots are also seen without a tube, by the eye of any man, and if any one were to oppose [this method], what would he propose, without being deceived".[12]

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[9] Mario Biagioli, "Picturing Objects in the Making: Scheiner, Galileo and the Discovery of Sunspots." *Ideals and Cultures of Knowledge in Early Modern Europe*, eds. Detel and Zittel, Berlin: Akademie Verlag, 2002, pp. 39-95.

[10] Christoph Scheiner, *Rosa Ursina sive Sol*, Bracciani: apud Andream Phaeum, 1626-30, p. 106.

[11] Ibid. 115.

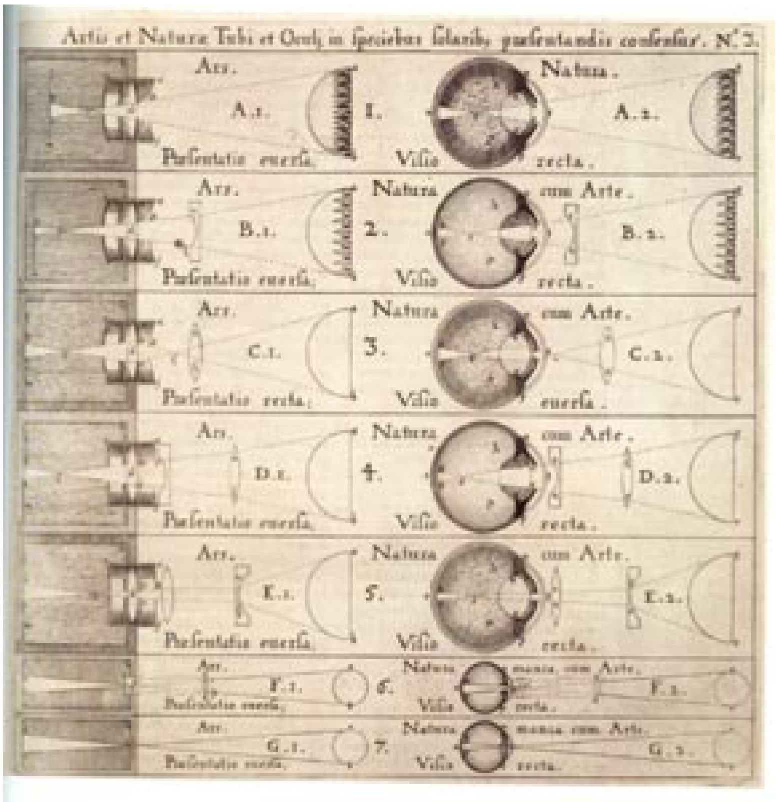

Figure 8: Scheiner's comparison of the camera obscura and the eye. From *Rosa Ursina* (1626-30).

A tradition of inserting the camera obscura into the prehistory of photography could make Scheiner's verbal and pictorial insistence on the objective nature of projected images seem like overkill. If we read Scheiner's image and argument carefully, though, it is clear that projection was an art form all of its own.

Constantijn Huygens' famous exclamation, on seeing the image produced by Cornelis Drebbel's camera obscura that "it is not possible to describe for you the beauty of it in words: all painting is dead in comparison, for here is life itself or something more noble, if only it did not lack words", heralds the camera obscura as an autonomous artistic medium, distinguished from painting by its "living" images, by the movement of its figures. Huygens is not describing the camera obscura as a handy tool for painters here – he is describing it as something completely different from painting.

Galileo's openness to reveal Castelli's projection technique for observing sunspots can be contrasted with his secrecy about another projective observation technique during the same period. Ever since his first observations of the Medicean stars, Galileo had been carrying out concerted attempts to track the positions of the Jovian satellites over time, with the goal of calculating their periods accurately and, eventually, of creating tables for their movements and

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[12] Christoph Scheiner, *De Maculis Solaribus … Accuratior Disquisitio* (Augsburg 1612), in: Galileo Galilei, *Le Opere* (Edizione Nazionale), vol. V, pp. 37-70, here p. 61; transl. by Eileen Reeves.

eclipses which could be used as a global time standard, and thus as a possible solution to the calculation of longitude at sea. To deal with the difficult problem of observing the moons of Jupiter aboard a moving ship, Galileo designed a headmounted telescope and sighting device, the *celatone*. The person observing Jupiter would sit in a chair aboard ship which was on a hemispherical platform floating in oil, and surrounded by springs, to insulate it from the rolling of the ship. The jovilabe, a handheld device allowing the seasonal "correction" or prosthapheresis for the positions of the Jovian satellites to be measured, and bearing accurate tables for the satellites' movements, allowed the time difference between the boat's position and a base meridian to be calculated. In order to develop such precise tables, Galileo needed a technique to measure the positions of the Jovian moons very accurately. Galilean telescopes did not contain micrometers, however, and measuring telescopic observations was a considerable problem. Galileo adapted a technique he had used to measure the magnifying power of telescopes, and availed of "binocular superposition". He attached a small grid to his telescope, which he called a *rastellum* or "little rake". Looking through the telescope with one eye, and at the grid with the other, he moved the grid back and forth until the separations between its lines corresponded exactly with a radius of Jupiter. In this way, by "seeing" the moons of Jupiter superimposed on the grid, Galileo could measure the distance of each moon from Jupiter in Jovian radii. Galileo never publicized this technique, undoubtedly due to the great commercial potential he perceived in creating accurate tables for the Medicean stars, and it was only described in print after his death by Giovanni Alfonso Borelli.[13]

Figure 9: Camera Lucida, 19th century.

The binocular principle behind Galileo's technique is somewhat akin to the much later (monocular) camera lucida patented by William Wollaston in 1806, where a draftsman uses a prism to "see" a subject in the plane of a piece of paper. Galileo's technique is a "virtual" projection onto a screen, visible only to a single viewer through binocular superposition, in contrast to the public nature of solar projection through a camera obscura. Robert Hooke used a similar

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[13] G. A. Borelli – *Theoricae Mediceorum Planetarum*, Florence 1666, Book 2, Chapter 4 (Qua ratione Mediceorum digressions à disco, vel corpore Iovis mensurari possint), p. 141.

binocular projection technique to measure microscopic specimens on a grid, as he recounts in the *Micrographia*:

> My way for measuring how much a Glass magnifies an Object plac'd at a convenient distance from my eye is this. Having rectifi'd the Microscope, to see the desir'd Object through it very distinctly, at the same time that I look upon the Object through the Glass with one eye, I look upon other Objects at the same distance with my other bare eye; by which means I am able, by the help of a *Ruler* divided into inches and small parts, and laid on the Pedestal of the Microscope, to cast, as it were, the magnifi'd appearance of the Object upon the Ruler, and thereby exactly to measure the Diameter it appears through the Glass, which being compar'd with Diameter it appears of the naked eye, will easily afford the quantity of its magnifying.[14]

Interestingly Hooke does not suggest that he used this "double-vision" technique to *draw* the extraordinary plates of the *Micrographia*, although it seems very plausible that he did, at least in the initial stages of drawing.

The *Graphic Telescope*, patented by Cornelius Varley in 1811, made the connections between Galileo's "little rake" and the camera lucida much closer. Effectively it just *was* a camera lucida attached to a telescope, and Varley used it both for astronomical drawing and for sketching portraits.[15]

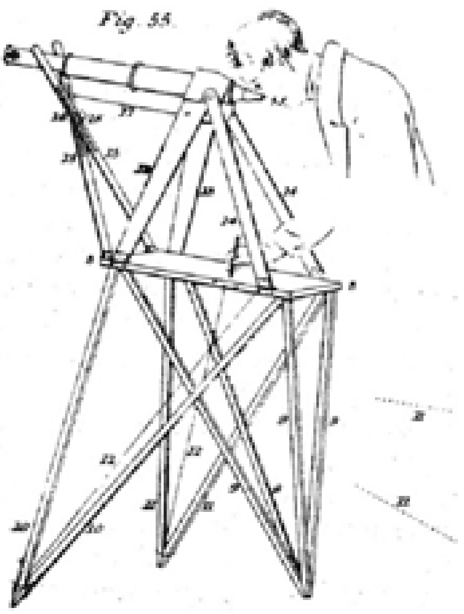

Figure 10: C. Varley's Graphic telescope (1811).

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[14] Robert Hooke, *Micrographia or some physiological descriptions of minute bodies made by magnifying glasses : with observations and inquiries thereupon,* London: Martyn and Allestry, 1665, Preface (without pagination).

[15] Martin Kemp, *The Science of Art*, New Haven: Yale University Press, 1992, p. 202, Simon Schaffer, "On astronomical drawing", in Caroline Jones and Peter Galison, eds., *Picturing Science, Producing Art*, New York: Routledge, 1998, pp. 441-74.

To return to dark-room projections, though, if we abandon the idea that the camera obscura "wanted" to be a camera, or that the magic lantern wanted to be a slide or film projector, and instead ask what kinds of strange practices went on in these darkened spaces, we find a very eclectic assortment.

Neapolitan magician and dramatist Giambattista della Porta first published his *Natural Magic* in 1558. This contained a short description of the camera obscura, describing both a pinhole camera, and a camera obscura making use of a concave mirror. The second, vastly amplified edition of the *Natural Magic*, published in 1589 included a much expanded discussion of the camera obscura, including a more sophisticated system that combined a biconvex lens with a concave mirror to produce an upright image. Before Della Porta, uses of the camera obscura for "performances" had been discussed by Cesare Cesariano, who, in commenting on Vitruvius's *De Architectura*, used the camera obscura as an example of Vitruvius's term "*spectaculum*", a combination of a public experimental demonstration and a performance. Leonardo da Vinci, remarked on the projected image "O marvellous necessity .. O mighty process. Here the figures, here the colours, here all the image are reduced to a point ... Forms already lost, can be regenerated and reconstituted". Other sixteenth century writers including Girolamo Cardano, Ignazio Danti and Daniele Barbaro described amazing feats of projection of objects, with the aid of a convex lens that provided a sharper image. Giambattista Benedetti, on describing this phenomenon, exlaimed that "nothing more beautiful or delectable can be imagined", and this tone is typical of sixteenth century descriptions of the camera obscura.[16]

Della Porta's description, in addition to providing technical suggestions on improving the camera obscura, went into some detail on its possible uses. According to Della Porta, a person who did not know how to paint could use the camera obscura to paint a person's portrait, the use of the camera obscura that has been of particular interest to David Hockney and Charles Falco. The camera obscura could also be used to project dramatic events "for pleasing great Lords". Della Porta describes how it could be used to "see in a dark room a hunt, a battle and other wonders":

> Now, to reach the end of this material, I will add a secret that is surely the most ingenious and beautiful for pleasing great lord. In a dark room, on white sheets, you can see hunts, *convite*, battles of enemies, games, and finally, everything you like, so clear and luminously, and minutely, as if you had them right before your eyes. Let there be a spacious area outside the room where you are going to make these appearances, which can be well illuminated by the sun. In this, you will place trees, houses, woods, mountains, rivers, real beasts or animals fabricated with skill from wood or other materials, which have children inside them who move, as we frequently use in the intermissions of comedies, deer, wild boar, rhinoceroses, elephants, lions and other animals that please you. Each of these emerges one by one from its lair, and comes into the scene, then the hunters come with spears, nets and other necessary instruments, and are seen to hunt the animals, playing horns, trumpets and conches, so that those inside the room see the trees, the animals, and the faces of the hunters, and the other things, so naturally that they cannot tell whether they are real or due to trikkery.[17]

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[16] On theatrical uses/descriptions of projection see Reeves, op. cit.

[17] M. J. Gorman, "Art, Optics and History: New Light on the Hockney Thesis", *Leonardo* 36/4 (2003).

In addition to his work as a natural magician, Della Porta was an accomplished dramatist, and there is documentary evidence to suggest he actually did carry out projected performances of this kind – he spent several months in 1580 in Venice perfecting a concave mirror and lens to be used in a camera obscura which seems likely to have been made for this purpose.[18] The uses of the camera obscura did not end with projected *commedie* though – Della Porta also intimated that it could be used as a telecommunications medium:

> From this you could take occasion to say everything you wish to someone who knows the method secretly, even from a distance, and shut up in prisons. If the distance is great, you can remedy this by increasing the size of the mirror. You have understood enough, many who tried to speak about this secret taught nothing but words, nor do I know if anyone knew it until now.[19]

The fantasy of the use of mirrors and projective devices for the long distance communication of secrets preceded this possible allusion to a rather cumbersome reflective telescope by Della Porta. In his *Three Books of Occult Philosophy*, first published in 1531, Heinrich Cornelius Agrippa von Nettesheim described a device for projecting written letters on the surface of the moon. If the characters were written on a surface, and reflected towards the lunar disk in the proper way, according to Agrippa, they could be read on the moon's surface by any person, even at a great distance. This device was, he claimed, "very profitable for Towns and Cities that are besieged", allowing them to send messages to their allies. While describing this fantastic communicative device, clearly of enormous potential public utility, Agrippa refrains from divulging the secret technique, claiming instead that it was known to Pythagoras and to "some in these days" including himself.

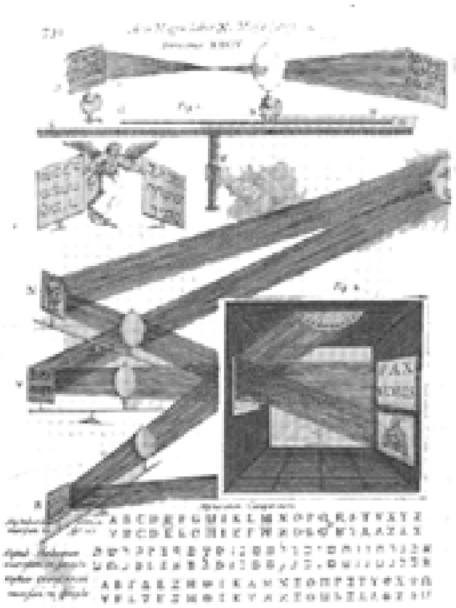

Figure 11: A. Kircher's catroptric steganography. From *Ars Magna Lucis et Umbrae* (1646).

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[18] Ibid.
[19] Ibid.

Figure 12: Rembrandt, *Belshazzar's Feast* (1635-6).

The use of mirrors to project secret messages into dark spaces was taken up in the seventeenth century by Athanasius Kircher, who, though he ridiculed the extravagant claims of Agrippa, described methods for projecting texts using both sunlight and candles, with the aid of both flat and concave mirrors, and a convex lens. Kircher described this art as "Catoptric Stegranography", and if we are to believe that the magic lantern anticipated the slide-show, Kircher's Catoptric Steganography was the early modern version of the Powerpoint presentation. He instructed his readers in writing different alphabets upside-down and backwards, so that they would be displayed correctly, and noted that placing the screen at a larger distance would make the letters larger. As Koen Vermeir has brilliantly suggested, Rembrandt's *Belshazzar's Feast*, painted in 1635-6, appears to use just such a projective technique. The "writing on the wall" traced by the angelic finger, telling King Belshazzar that he has been weighed in the balance and found wanting, appears to be projected from a mirror, making Rembrandt's painting one of the first phantasmagorias. While Kircher's letters were marked on the mirrors using ink, the angelic finger in the painting appears to be tracing the hebrew text on a dusty flat mirror, hence the brightness of the letters. In addition to projecting texts, Kircher also suggested using live flies and shadow puppets placed on mirrors to project dramatic performances. Flies could be enticed by dabbing some honey on the mirror.

Figure 13: "Naturae pictricis operae." From A. Kircher, *Ars Magna Lucis et Umbrae*.

He wrote "It is also to be noted that here you will see letters depicted with all kinds of colours, by I know not which occult trick of nature the painter; which matter is so unusual that it can hardly be said what admiration it provokes in the spectators". Kircher's idea of "*natura pictrix*" – Nature the painter – was one that he frequently applied to projective phenomena. His *Great Art of Light and Shadow* also applied this description to a portable sedan-chair camera obscura, comparing it with an anthropomorphic landscape and "alphabet stones", stones naturally inscribed with letters and faces, in a memorable visual juxtaposition.

Kepler, strongly influenced by Della Porta's description of the camera obscura in developing his theory of vision, developed a rotating *camera obscura* that could be used for chorography (and apparently for creating panoramic views), as recounted by Henry Wotton to Francis Bacon:

> He hath a little black tent (of what stuff is not much importing) which he can suddenly set up where he will in a field, and it is convertible (like a windmill) to all quarters at pleasure, capable of not much more than one man, as I conceive, and perhaps at no great ease; exactly close and dark, save at one hole, about an inch and a half in the diameter, to which he applies a long perspective trunk, with a convex glass fitted to the said hole, and the concave taken out at the other end, which extendeth to about the middle of this erected tent, through which the visible radiations of all the objects without are intromitted, falling on a paper, which is accommodated to receive them; and so he traceth them with his pen in their natural appearance, turning his little tent round by degrees, till he hath designed the whole aspect of the field. This I have described to your Lordship, because I think there might be good use of it made for chorography: for otherwise, to make landscapes by it were illiberal, though surely no painter can do them so precisely.

Christoph Luethy has described the use of the camera obscura by the vedutisti including Canaletto and his predecessor Gaspar Van Wittel (Vanvitelli) in painting cityscapes, arguing that this constituted a much more widespread use of the camera obscura by painters in the seventeenth and eighteenth centuries than portraiture.[20] What is interesting, perhaps is the *attitude* to the use of the instrument, Wotton's suggestion, echoed by Constantijn Huygens in his criticism of Torrentius, that the use of the instrument was "illiberal", and the suggestion in art theoretical works that the camera obscura was only a training device, for young artists to familiarize themselves with a "natural" picture. Where Della Porta had encouraged unskilled artists to make use of the camera obscura, later commentators elaborated on its pedagogical role for painters. As Hoogstraten noted in the camera obscura image "the main or general qualities that should belong to a truly natural painting", Francesco Algarotti waxed lyrical about the similarity of the projected image to the work of a very skilled painter, and effectively critiqued it as he would a painting: "Nothing can be more useful to study than such a picture. For, not to speak of the justness of the contours, the exactness of the perspective and of the chiaroscuro, which exceeds conception, the colours are of a vivacity and richness that nothing can excell".[21]

The suggestion seems to be that by studying the projected image, painters can "internalize" the look of the camera obscura image, and that it can guide their work without their paintings being mere mechanical transcriptions of camera images, in the same way that in the sixteenth century Michelangelo suggested that painters should have "compasses in their eyes", rather than in their hands.

In the eighteenth century Abbé Nollet's prime claim in presenting his rather large desktop tent camera obscura was its use in warfare:

> This kind of black chamber could be use to see what is happening outside of a fort under siege, without exposing one's head; because nothing prevents the table, on which the image is projected, from being placed behind a rampart with the mirror raised above it.[22]

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[20] C. Luethy, "Hockney's Secret Knowledge, Vanvitelli's Camera Obscura", *Early Science and Medicine* 10/ 2 /(2005).

[21] Francesco Algarotti, *An Essays on Painting*, London 1764, transl. from A. Scharf, *Art and Photography*, London: Penguin Books, 1968, p. 4.

[22] Jean Antoine Nollet, *Leons de physique expérimentales*, vol. V, Paris: Durand, 1777.

Many different kinds of practice thus vied for dominance within the camera obscura, from steganography to solar astronomy, from theatrical performances to magic, siege warfare and painting.

Given the many cultures and communities that rubbed shoulders in the close space of the camera obscura, Scheiner's challenge in the *Orsini Rose* – to present the projected image as a truly natural image, and to present the camera obscura as a philosophical instrument – was thus considerable.

Rather than a clear-cut separation between the magic lantern and the camera obscura, we are presented with an abundance of devices for projecting static and moving images and words. Kircher's claim to have invented the magic lantern has been disputed, given the misleading illustrations in the second edition of his *Great Art of Light and Shadow,* but the debate about the "true inventor" of the magic lantern is somewhat futile, as the magic lantern, being a family of projective devices, had no "true" inventor. The basic components of candle and concave mirror were in fact described in the first edition of Kircher's work (on different pages than those he cited in the second edition) but instead of using removable glass slides Kircher simply painted the image to be projected on the concave mirror using translucent paint. Kircher cautioned in the first edition of the Great Art, "By this art impious people, painting a picture of the devil on a mirror and projecting it into a dark place could easily force people to carry out wicked deeds"[23]. Thomas Walgenstein and Christiaan Huygen's incorporation of removable glass slides was one of many gradual improvements in projective techniques using an artificial light source. Kircher fully acknowledged the superiority of Walgenstein's instrument to his own projective techniques, recognizing that it made it possible "to exhibit complete Satyric plays, tragedies and similar things in a natural way, without any interruption".[24]

While the efforts of Porta, Kepler and Scheiner helped to make the camera obscura into a "natural picture", the magic lantern had more difficulty in escaping from the twilit zone of "artificial magic", as Hankins and Silverman have suggested.[25] Magic lantern and solar microscope performances were by their nature public spectacles, and their public and commercial nature complicated their claims to objectivity. As Abbé Nollet put it, the magic lantern had been "rendered ridiculous in the eyes of many people by its too great popularity". Magic lantern shows and solar microscope shows were frequently advertised as being of profound philosophical import. An 18th century magic lantern presentation of topographical slides advertised itself as "one of the most compleat Pieces of Natural Philosophy ever offered to the View of the Publick", and claimed that it made use of a "Curious Machine Properly adapted to the Philosophical System of Sir Isaac Newton's Opticks". Willem Jacob 's Gravesande included a magic lantern show of a devil in his *Mathematical Elements of Physics confirmed by Experiments, or introduction to Newtonian Philosophy,* as a demonstration of the laws of geometrical optics.[26]

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[23] Athanasius Kircher, *Ars Magna Lucis et Umbrae*, part II chapt. 4, Rome: Scheus, 1646, p. 812.

[24] Ibid. p. 813.

[25] Thomas L. Hankins and Robert J. Silverman. *Instruments and the Imagination.* Princeton: Princeton University Press, 1995, chap. 3.

[26] Ibid. p. 51.

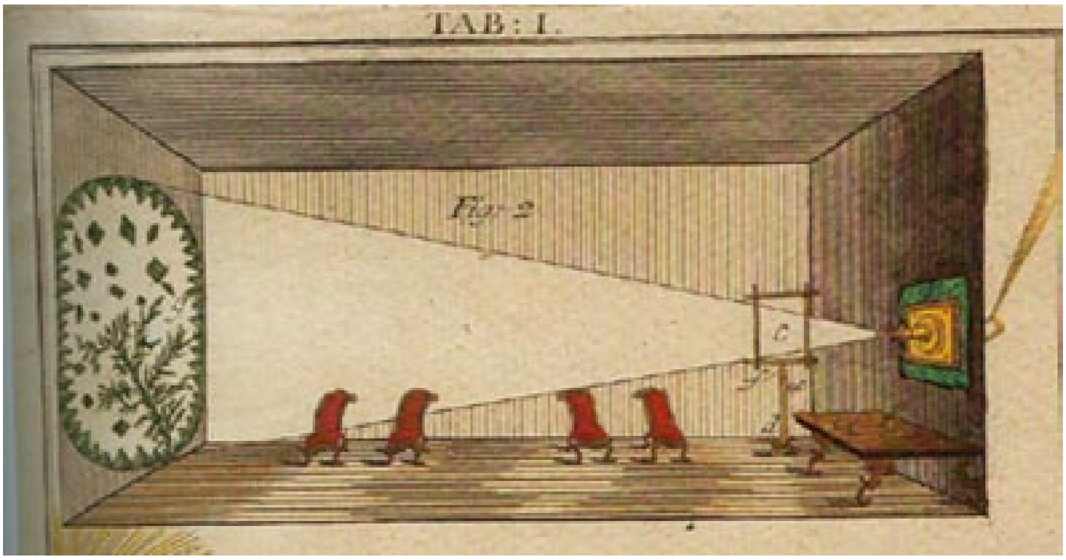

Figure 14: A. W. Winterschmidt's Solar microscope show (1769). From M. F. Ledermüller, *Mikroskopischer Gemuths- und Augen-Ergotzung* (1778).

While the "philosophical" claims of the magic lantern were rapidly eclipsed by its potential for popular entertainment, the solar microscope emerged from seventeenth century beginnings as a more respectable philosophical instrument in the eighteenth century. Where Kircher suggested projecting live insects from mirrors for the presentation of theatrical projections with a six-legged cast in 1646, Johannes Zahn, a Praemonstratensian priest who was a pupil of Kircher's assistant Kaspar Schott in Würzburg, suggested mounting small organisms between two pieces of glass for projection in his magnificent 1685 work *Oculus Artificialis*, effectively making an early projecting microscope. Benjamin Martin contrasted the "useful purposes" of the solar microscope in magnifying the transparent parts of animal and vegetable substances as wings of flies, membranes, etc" to the use of the magic lantern "to surprise and amuse ignorant people".

However, precisely the mimetic respectability of the solar microscope attracted charlatans, most memorably Gustavus Katterfelto, who advertised himself in 1780s London as "the greatest philosopher in this kingdom since Sir Isaac Newton". Katterfelto claimed to be the inventor of the solar microscope, and used it to show his audience the "insects" which had caused the recent influenza epidemic, "as large as a bird, and in a drop of water the size of a pin's head there will be seen above 50,000 insects". After the show Katterfelto sold Dr. Baro's medicine, a sure-fire remedy for influenza. By the end of 1783, Katterfelto was offering the whole of his "philosophical and mathematical apparatus" for sale at £2,500. As there were no takers, he had to resort to travelling from town to town with his electrified cats.[27]

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[27] Richard D. Altick, *The Shows of London*, Cambridge, MA: Belknap Press, 1978; Barabara Stafford and Frances Terpak, *Devices of Wonder. From the World in a Box to Images on a Screen*, Los Angeles: Getty Research Institute, 2002; Thomas Frost, *Lives of the Conjurors*, London 1876, pp. 135-140.

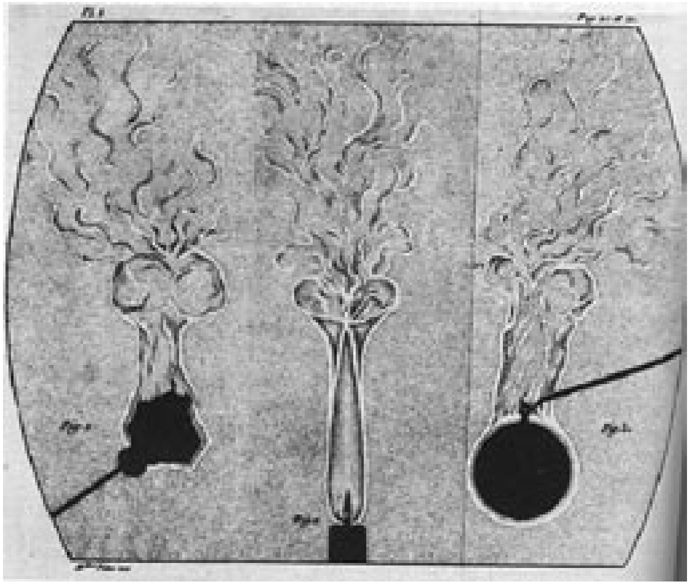

Figure 15: Marat's projections of "igneous fluid".

A contemporary satirical print depicts Katterfelto facing off against another contemporary showman, Dr. Graham, famous for his celestial fertility bed. Beneath Katterfelto's platform is a "reservoir for dead insects destroyd by Dr Katterfelto", in allusion to his microscopic demonstrations.

In pre-revolutionary France, Jean-Paul Marat experimented with the solar microscope. Removing one of its lenses, he found that he could project images of hot bodies onto the screen, and saw "igneous fluid" flowing upwards from the bodies. Marat's views on light, which contradicted Newton, were rejected by the Académie des Sciences, who claimed that what Marat was really projecting was the heated air above the bodies, which refracted light differently, producing shadows. Armed with his modified solar microscope, Marat entered a violent dispute with Jacques-Alexandre-César Charles, inventor of the Mégascope, which projected reflected images of large two and three-dimensional objects. Marat objected that Charles dismissed him in his lectures, comparing him with stage magician and electrophysician "Sieur Comus". The dispute between Marat and Charles is, I want to suggest, a clash between two distinct cultures of projection – projection as philosophical problem, as a means of investigation, and projection as self-assured public demonstration of a closed problem, solved elswhere, away from the contaminated space of projection and the public gaze. The rejection of his experiments led Marat to attack the Académie for privileging geometrical elitism over honest experimentation, a charge that would eventually lead to the academy's abolution in 1793.[28]

The first photographic negative on paper was created by Nicéphore Niépce on paper using a lens taken from a solar microscope, to create a miniature camera obscura, as solar microscopes had themselves fallen from grace by the second decade of the nineteenth century, and lost their capacity to amaze and to instruct. From being a "wonder" in the 16th century, the projected image

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[28] Hankins and Silverman, op. cit., p. 59 ff.

became in the seventeenth century, a philosophical demonstration of central importance. The naturalization and authority of the projected image celebrated by Christoph Scheiner were to become casualties of the success of ever-more sophisticated projective devices. From providing primal experiments to Kepler, Descartes and Newton, projections were gradually devalued to popular entertainments in the eighteenth century, their mechanisms were black-boxed, and were no longer a talking point. Projective devices became pieces of furniture.

Whilst for s' Gravesande, the horned devils on screen were of no importance whatever, in his use of the magic lantern to demonstrate the principles of optics, the mechanisms of projection moved ever further beyond the realm of natural philosophers. While projection became trivial, commonplace, philosophically sterile, the projected image emerged as a key instrument of persuasion in public demonstration lectures. Marat's failure to make his projections tell a philosophically important story mirrors Scheiner's earlier success in securing the conclusions derived from his sunspot observations. By the early nineteenth century, though, projection itself had become too vulgar for the philosophers. Marat was right.

PART II

OPTICS

Alhazen's Optics in Europe: Some Notes on What It Said and What It Did Not Say

Abdelhamid I. Sabra

Avoiding a Misunderstanding

1.1. Two words are distinctly conspicuous by their total absence from the Arabic text of Alhazen's *Optics*, *Kitāb al-Manāẓir,* a large work in seven treatises or books, *Maqālāt.*[1] The two words are "retina" and "lens" – in Arabic, *al-shabakiyya*, and *al-ʿadasa.* Their absence signals that, for the author of the book, the organ of sight, *al-baṣar*, rendered in the Latin thirteenth-century translation as *visus* and *oculus*, is *not* to be understood as a pin-hole camera (as, e.g., in Leonardo) or a lens camera (as, e.g., in Kepler).
This observation should help to avoid a still occasional misunderstanding.[2]

The 'Camera' *in Alhazen's Arabic* al-Manāẓir *and in* De Aspectibus

2.1. In contrast, the Arabic expression '*al-bayt al-muẓlim*,' which literally means *dark room*, or *camera obscura*, occurs many times in Bk I, Chaper 3 of *Kitāb al-Manāẓir*. But this chapter in Bk I, along with Chapters 1 and 2, are missing from the extant manuscripts of the Medieval Latin translation, and they may never have been part of the Latin text, though this is not certain. – In the Arabic I/3 Alhazen describes a series of experiments conducted in a darkened room into which the light shining from the sun may enter through a small hole in a door facing it; and, in I/6, he observes at night the patches of light projected in reversed order upon the wall opposite the hole, from a row of lamps/candles placed outside in a line parallel to the wall with the hole.

2.2. In both of Chapters I/3 and I/6 the aim is to establish the modes of behaviour of light – in particular, the "extension"/propagation of light and clolour, or what Alhazen calls 'the forms of light and of colour,' in straight lines, from every point on the shining object to all points in the adjacent transparent medium. However, whether intentionally or otherwise, in I/6, Alhazen does lay down the principle of the pin-hole camera: he asserts that the forms of light and colour that

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[1] Ibn al-Haytham, *Kitāb al-Manāẓir, Bks I-II-III*, the Arabic text, edited by A.I. Sabra, Kuwait: The National Council for Culture, Arts and Letters, 1983, reprinted, 2006; *The Optics of Ibn al-Haytham*, *Bks I-II-III*, English translation and commentary by A.I. Sabra, 2 vols, London: The Warburg Institute, 1989; A. Mark Smith, *Alhacen's Theory of Visual Perception*, edition and commentary of Alhacen's *De Aspectibus* and translation of Bks I-II-III, 2 vols, Philadelphia:American Philosophical Society, 2001. – References to the texts in Arabic, Latin and English translations from Arabic and Latin are by Book, Chapter and Paragraph (for example: I/6[84]), which are the same in both editions. – Ibn al-Haytham, *Kitāb al-Manāẓir, Bks IV-V*, 2 vols., the Arabic text edited by A.I. Sabra, Kuwait: The National Council for Culture, Arts and Letters, 2002.

[2] There still exists a confusion, which is not excusable, between the *ʿankabūtiyya/aranea/arachnoid,* a web-like membrane that encircles the whole crystalline humour, which is mentioned in I/5[9-10], and *al-shabakiyya/ amphiblēstraoeidēs chiton*, retina, and which is absent from the *Optics*: see Ibn al-Haytham's *Optics I-II-III (*English translation), vol. II, Commentary, esp. pp. 46-47. – Muṣṭafā Naẓīf, who was aware of the distinctin between the *ʿankabūtiyya* and the *shabakiyya*, sometimes used (in a different context) the expression *al-ʿadasa al-jalīdiyya* for Alhazen's "crystalline"; Alhazen always called it "crystalline *humour*".

rectilinearly proceed from points on one or more shining objects, and that *meet* or *come together* at the centre of the hole, continue along their respective lines in the air *without affecting one another*. A transparent medium like air, Alhazen says, “only receives (*yaqbalu, recipit*) the forms of light and colour by way of conveying them [= passing them on], not altering them”/*nisi receptione ad redendum, non receptione ut alteretur*” (I/6[84]); the rectilinearly extending lights and colours “come together” but do not mix or blend together at the meeting point (I/6[87]); and, therefore, he asserts, the qualities/forms transmitted along every single line after the intersection are determined only by the qualities of the initial object-points of radiation.

2.3. And yet, as already noted by M. Naẓīf, there is no report in the *Optics* of a composed *picture* inside the dark room. – To my knowledge the first clear descripion of such a projected picture in the Arabic tradition is found in the *Commentary* or *Revision*/*Tanqīh* of Alhazen’s *Optics* by Kamāl al-Dīn al-Fārisī in the second half of the thirteenth century. In that work, besides the light and colour, al-Fārisī observed the picture of passing clouds and of flying birds in the reverse directions of their motion outside the camera.[3]

2.4. I should add that Alhazen directly tackled a special projection problem in a separate treatise *On the Shape of the Eclipse, Ṣūrat al-kusūf*, which was not translated into Latin.[4] – A German translation is available - see below.

Rejecting the Fundamental Visual-Ray Hypothesis, and its Consequences

3.1. In the Preface (= I/1) to the Arabic *Optics* Alhazen advised his readers to discard an earlier treatise of his on vision in which, he said, he had employed “persuasive arguments,” and which he had disowned in favour of a newly adopted approach based on “true demonstrations” (I/1[8]). – Knowing that Alhazen had once written a treatise following the “method/*ṭarīqa* of Ptolemy’s *Optics;*”[5] and now with his book in our hands, we can tell what had actually happened:

3.2. Briefly stated, Alhazen had become convinced that optics should be understood and practised as a physical as well as a mathematical theory (e.g., I/1[8]). In his proposed synthesis (*tarkīb*) for a complete theory of vision, the term ‘mathematical’ referred to the style of Euclid and Ptolemy in their studies of the subject, while ‘physical’ referred to Aristotelian physics; the first guaranteed rigour, and the second, physical truth. – That was no mere juxtaposition of borrowed

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[3] Kamāl al-Dīn Abū l-Ḥasan al-Fārisī, *Tanqīḥ al-Manāẓir*, Hyderabad Dn: Dā’irat al-Maʿārif al-ʿUthmāniyya (India), vol. II (1348/1930), p. 399; see also Ibn al-Haytham’s *Optics I-II-III (*English translation), vol. II, Commentary, p. li, n. 72, and pp. 68-70; and pp. lii, lxxvi. – Note, however, that Alhazen clearly states: (1) that the sentient body/*al-jism al-ḥāss* in the common nerve is illuminated and coloured by the light and colour of the visible object, and it is from this illumination and colouring that the “last sentient” percieves the light and colour in the object (II/3 [46]); and (2) that he goes on to assimilate (*tashbīh*) the arrival of the forms of light and of colour in the sentient body at the common nerve to the arrival of light through openings/windows *and* apertures (II/3[60-61]; see, especially, Arabic text, p. 240, lines 1-4, English, vol I, p. 146, lines 7-10 in paragraph [60]: “... the form’s arrival in the common nerve is like the light’s arrival from windows/*manāfidh* or apertures/*thuqūb*, through which light enters, at the bodies facing those windows or apertures ...”. – Nevertheless, the analogy cannot be intended here to reproduce *exactly* the working of the *camera obscura*, since the *arrival of forms at the common nerve* does not take place in straight lines *throughout* their extension from the light source.

[4] Ibn al-Haytham, *Optics I-II-III* (English translation), vol. II, Introduction, pp. xxxiii, work no. III 80, and pp. xlix-li.

[5] Ibn al-Haytham, *Optics I-II-III* (English translation), vol. II, Introduction, pp. xxxii, treatise no. Ia, and p. xxxiii, treatise no. III 27.

doctrines, and it reflected the emphasis on mathematics. For example, while Alhazen accepted the Aristotelian ontology of qualities or forms, he was led to introduce the non-Aristotelian concept of *point*-forms (not Alhazen's term) of light and colour that radiate from every "point" on the shining and coloured body in all straight lines that extend to every opposite point in the adjacent transparent medium, *and* from every point on every one of those lines in all straight directions (I/3[143]).[6]

3.3. More than once in *Kitāb al-Manāẓir,* and in agreement with the new synthesis, Alhazen makes two statements tightly associated with each other. The first declares that light does not behave in the way it does "on account of the eye," or "for the sake of the eye" (*li-ajl al-baṣar*), but rather the eye simply receives the light that *happens* to be passing where it is located.[7] – The second, associated statement is that the concept of visual ray, *shuʿāʿ al-baṣar*, is "useless and redundant" (*ʿabath wa faḍl*).[8] We know that the doctrine of visual ray issuing from the eye had been adopted in somewhat different forms by Euclid, Ptolemy and Galen, and, in the Arabic tradition, by al-Kindī and others up to Alhazen's time, as the basic assumption of the account of vision in terms of lines and angles. – Avicenna (d. 428/1037), as a natural philosopher and a Peripatetic, followed Aristotle's *De anima* in avoiding the mathematical approach in terms of linear rays altogether.

3.4. (In parentheses, it may be remarked that Euclid's visual-ray theory was still generally accepted in the Arabic and Persian Middle East throughout the larger part of the seventh/thirteenth century, and it was widely publicised from Marāgha by the influential astronomer Naṣīr al-Dīn al-Ṭūsī who died in AD 1274. – It is worthy of note that al-Ṭūsī's successor under the Īlkhāns at Tabriz, Quṭb al-Dīn al-Shīrāzī (d. AD 1311) had also not read Alhazen's *Optics* before he managed to obtain a copy of the book from a "distant land" for his student Kamāl al-Dīn al-Fārisī to write his important commentary on it. But that is a different story which we need not go into on the present occasion.[9])

Retaining the Single-Ray Assumption

4.1. The visual-ray theory was itself also a single-ray theory. According to the visual-ray theory an object-point is seen when a single ray issuing from the eye reaches the point on the object – whether directly or through reflection or refraction. Alhazen reversed the direction of the ray that, as he insisted, just happens to extend (in direct vision) along the particular mathematical straight line joining the shining point and the eye. – But he still maintains (in Bks I-VI) that vision is effected by the single light-ray that reaches the eye from the object. – We know, however, that we

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[6] See A. I. Sabra, 'Form in Ibn al-Haytham's Theory of Vision," in *Zeitschrift für Geschichte der Arabisch-Islamischen Wissenschaften*, 5(1989), pp. 115-40; repr. in *Optics, Astronomy and Logic*, Chapter XI, Variorum, 1994.

[7] "*ḥaḍara al-baṣaru am lam yaḥḍur*, whether an eye is present or not," I/3[141, 142-143].

[8] For example, at I/6[54]: the forms of light and colour always shine into the air or other transparent bodies whether an eye is present or not; and at IV/5[7], and IV/5[9]: the occurring (*ḥuṣūl*) of an object's form (in this case, a reflected form or image), does not happen on account of the viewing eye, nor does it depend (*lā taʿalluqa lahā*) on the viewing eye.

[9] The story has recently been told in a paper of mine read in my absence at an international conference at The Library of Alexandria (March 7-9, 2006), on"Manuscript Commentaries" and titled: "The Commentary that Saved the Text: The Hazardous Journey of Ibn al-Haytham's *Optics* in the Arabic and Persian Middle East," to be published in *Early Science and Medicine*, in 1907.

neither see by visual rays nor by single light rays. This simple observation, which modern commentators seem to have passed over by ignoring the distinction between 'visual rays' and 'single rays',[10] in fact points to the most important obstacle in Alhazen's project, which obstacle Alhazen did not finally recognize explicitly until Chapter 6 of Bk VII.

Tardy Rejection of the Single-Ray Assumption and Asserting the Constant Role of Refraction in Visual Perception. – Experiment versus Tradition

5.1. From Galen and the more or less continuous anatomical tradition extending all the way from him down to the time of Alhazen, the latter inherited the doctrine that "the crystalline humour itself is the principal instrument of vision, a fact clearly proved by what physicians call cataracts, which lie between the crystalline humor and the cornea and interfere with vision until they are couched."[11] – *Alhazen simply accepted that tradition*, which he then incorporated into a suggested geometrical arrangement of the parts of the eye, designed to convey the point-forms of light and colour that arrive at the surface of the eye (cornea), through the aqueous, crystalline/glacial and vitreous humours until they reach the optic nerves. – Alhazen thought he could achieve this by distinguishing between the physical refractions that happen at the surfaces of these humours and the role of a permeating "sensitive body" (*al-jism al-ḥāss,* pneuma) descending from the brain, whose function is to preserve the integrity of the arrangement of point-forms arriving along the perpendiculars to the eye's surface and the parallel surface of the crystalline.

5.2. We all know what Alhazen missed by taking this course, and he leaves Chapter V in Bk I retaining the false conclusion in his mind that distinct vision of the external world is only possible if we see a shining point on the external object from a *single point* on the eye's surface, and, consequently, from a *single point* on the crystalline's surface – until we reach Chapter VI in Bk VII.

5.3. Alhazen's unexpected position in Bk VII is interesting in more than one sense: it tells us something about him as a scientific thinker who appreciated the primacy of experiment, and, once we recognize this, we must keep it in mind when we consider the works of later thinkers who read Alhazen's *Optics* in Arabic or in Latin. – Right now, however, we have time only for outlining that position.

5.4. The attached diagram represents an argument towards the end of Chapter 6 in Bk VII, to the effect that *all* visual perceptions involve refraction, thus contradicting the conclusion in Bk I that distinct vision of an object-point must take place through a single point on the surface of the crystalline. – The argument describes a simple experiment of which there is no hint anywhere previously in the *Optics.* – A thin needle MYN is held vertically, somewhat close to the surface of the eye within the geometrical cone GEH, where E is the centre of the eye/crystalline; and arcs TV, GH respectively represent the parallel surfaces of the crystalline and the cornea. P is a facing visible point on the horizontal line AB on the opposite wall at the same height of the eye. (No exact measurements are mentioned.) Alhazen reports that, with the other eye closed, he could see P,

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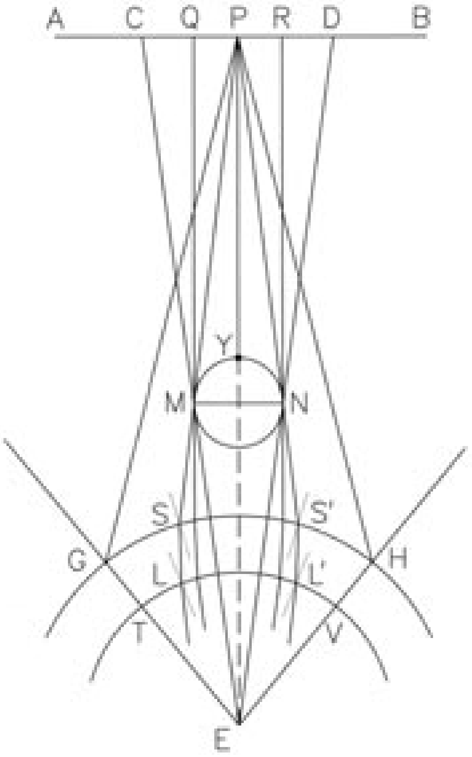
[10] Compare, for example, Samuel Y. Edgerton, Jr., *The Renaissance Rediscovery of Linear Perspective*, New York etc.: Harper and Row, 1976, p. 200: "*visual ray*: The entity believed by classical and medieval optical scientists either to project from the eye or into it from the seen object."

[11] Galen: *The Usefulness of the Parts of the Body* (De usu partium), translated from the Greek with an Introduction and Commentary by Margaret Tallmadge May, 2 vols., Ithaca, New York: Cornell University Press, 1968, vol. 2, pp. 463-64.

despite the fact that the perpendicular ray along PY is obstructed by the needle from reaching the surface of the eye. At the same time, however, P appeared as if it were covered by a shadow. – He concluded that while the "shadow" represented the visible surface of the needle facing the eye, he could only see P through the cone of rays reaching the surface of the eye, which rays *must* then be refracted at the surface of the cornea, and refracted again at the surface of the crystalline. – It followed, as Alhazen recognized, that "all that sight perceives it perceives by refraction".[12] He was also proudly aware that he was the first to discover that crucial fact.



5.5. In a paper of mine presented in a conference held in March 7-9, 2006 at The Library of Alexandria on Arabic "Commentaries,"[13] I argued that there is no evidence of an understanding of optical refraction in the Middle East as explained in Alhazen's book, until Kamāl al-Dīn al-Fārisī (d. January 12, 1319) wrote his *Commentary/Tanqīḥ* on it in the late seventh/thirteenth century at Tabriz – that is, about the time that the book was beginning to receive wide attention in Europe. Al-Fārisī in fact reports that until his teacher Quṭb al-Dīn al-Shīrāzī, who had not himself read Alhazen's book, succeeded to obtain for his student a complete copy of it from a "distant land," he could only find accounts, some of them by "leading" scholars, declaring the equality of the angles of incidence, reflection and refraction!

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[12] See A. I. Sabra, "Ibn al-Haytham's Revolutionary Project in Optics," in *The Enterprise of Science in Islam: New Perspectives*, eds. Jan P. Hogendijk and Abdelhamid I. Sabra, Cambridge Mass. and London: The MIT Press, 2003, pp. 86-118, esp. pp. 99-103.

[13] See note 10 above.

Playing with Images in a Dark Room
Kepler's Ludi *inside the Camera Obscura*

Sven Dupré[1]

Introduction

In his *Paralipomena* (1604) Johannes Kepler mentioned 'an *experimentum* [...] which I saw at Dresden in the elector's theater of artifices [...] A disk thicker in the middle, or a crystalline lens, a foot in diameter, was standing at the entrance of a closed chamber against a little window, which was the only thing that was open, slanted a little to the right. Thus when the eyesight travelled through the dark emptiness, it also, fortuitously, hit upon the place of the image, nearer, in fact, than the lens. And so since the lens was weakly illuminated, it did not particularly attract the eyes. But the walls were also particularly conspicuous through the lens, because they were in deep darkness.'[2] In one of the rooms of the Dresden Kunstkammer, which had been turned into a room-size camera obscura, Kepler witnessed the images formed by a lens placed in the aperture of this camera obscura, which, in fact, was one of the little windows of the Kunstkammer room through which light from outside was able to enter. In this darkened room Kepler saw that 'the little window and the objects standing about it, which had the benefit of much light, lying hidden beyond the lens, set up a bright image of themselves in the air (between me and the lens)'.[3]

The historiographical debate on Kepler's *Paralipomena* has mainly concentrated on the question of continuity and revolution. On the one hand, Stephen Straker has argued that Kepler's optics represents a mechanistic view – developed in dialogue with an artisanal tradition – which breaks away from the medieval perspectivist tradition.[4] On the other, David Lindberg has argued that Kepler is the culminating figure of the same medieval perspectivist tradition.[5] The debate, in fact, is about the degree of importance of the analogy between the eye and the camera obscura for Kepler's new theory of vision. While Straker has argued that Kepler's theory of the retinal image was the natural outcome of comparing the eye to a camera obscura and applying to the eye the knowledge of image-formation acquired in solving the problem of the camera obscura, Lindberg has downplayed the importance of this analogy, making the key unlocking Kepler's discovery of the retinal image his solution to the preservation of the one-to-one correspondence between points in the visual field and points in the eye, a crucial requirement of perspectivist optics.

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[1] Reseach for this paper has been supported by the award of a postdoctoral fellowship and a research grant of the Research Foundation – Flanders (Belgium).

[2] '[...], cuius experimentum vidi Dresdae in Theatro artificiali Electoris. [...] Discus in medio crassior, seu lens crystallina, pedis diametro, stabat in ingressu camerae clausae contra fenestellam, quae unica patebat, declinantem parùm ad dextram. Dum igitur oculorum acies tenebrosam capacitatem pererrant, fortuitò, et in locum imaginis incidunt, propiorem quidem quàm erat lens. Cum itaque lens malignè illustraretur, oculos non admodum erant conspicui; quia in multis tenebris'. Kepler (1937-), 2: 164-165, translation in Kepler (2000), 194.

[3] 'At fenestella et circumstantes res, quae multa luce fruebantur, post lentem latentes, claram sistebant in aëre (me inter et lentem) sui imaginem'. Kepler (1937-), 2, 165, translation in Kepler (2000), 194.

[4] Straker (1971). See also the summary of his central argument in Straker (1981).

[5] Lindberg (1976), 178-208.

It is surprising, however, that the experiment in one of the dark rooms of the Dresden Kunstkammer hardly received attention from any of the two sides in this debate. Kepler's witnessing of the images inside this camera obscura were, nevertheless, not unimportant to the shaping of Kepler's argument in the *Paralipomena.* Kepler situated the third section of his fifth chapter, from which we have drawn Kepler's report of the *experimentum* in the Dresden Kunstkammer, and in which he established a new concept of vision, in a place like the darkened room of the Dresden Kunstkammer. In this paper I will be concerned with how Kepler used the Kunstkammer experience to rework the optical tradition, in particular, the account of image formation in Giovanni Battista della Porta's *Magiae naturalis* (1589). Put differently, I will not be so much concerned with deciding the longue durée perspective on the history of optics in terms of continuity and revolution, but rather with how Kepler *appropriated* the optical tradition. I will argue that Kepler looked at this optical tradition through the eyes of a mathematician familiar with the type of experiments performed in courtly collections and *Kunstkammern.*

In the first part of my paper I will try to arrive at a characterization of these experiments inside the darkened room of a Kunstkammer. First, I will reconstruct the meaning of Kepler's encounter with the Kunstkammer by placing it in the context of the interest of the Dresden court in Kepler and his optics (an interest which seemed to have been mutual). Second, I will connect Kepler's Kunstkammer experience with contemporary optical games (which are often considered typical for natural magic), and I will argue that the status of the *experimentum* in the Dresden Kunstkammer for Kepler was that of social and intellectual play. Kepler's attribution of the status of play to his experience was crucial for his development of a new theory of optical imagery.

This will be the focus of the second part of my paper. In his *Paralipomena* Kepler distinguished two types of images: *imago* (or the 'perceived' image) and *pictura* (or the 'projected' image).[6] The concept of *imago* was derived from medieval perspectivist optics, but *pictura* was a concept of Kepler's invention. Although projected images were empirically familiar (see the images projected inside a camera obscura for the observation of eclipses), they were conceptually alien to the medieval perspectivist tradition.[7] I will argue that the epistemology of play allowed Kepler to give these projected images a conceptual place in his optics as serious objects of study. Put differently, experimental knowledge of image formation inside the camera obscura was important to Kepler's new theory of optical imagery, but it was only the attribution of the status of play to this experience which allowed Kepler to also use this knowledge. I will concentrate here mainly on how this informed Kepler's reading of Della Porta's theory of optical imagery in the latter's *Magiae naturalis* (1589), in particular, of the 'images in the air' which were prominently present in sixteenth-century optics. In this way I hope to give a more precise content to the oft-repeated claim that Kepler picked up some fruitful hints from the work of Della Porta.

1. Kepler's Games in the Dresden Kunstkammer and Natural Magic

Although we know little of the historical circumstances of Kepler's camera obscura experience in the Dresden Kunstkammer, it should not be doubted that the event had indeed taken place a few

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[6] My understanding of seventeenth-century theories of optical imagery is deeply indebted to Shapiro (1990). For Kepler's theory of optical imagery, see also Malet (1990) and Smith (1998).

[7] Smith (2005).

years before Kepler's memory of it in the *Paralipomena.* In fact, Kepler became well-connected with the Dresden scene as soon as he moved to the court of Rudolf II in nearby Prague in 1600.[8] Among his friends and correspondents were many figures that belonged to the inner circle of the Dresden court, such as Polycarp Lyser, curator of the Electoral Library, the poet and secretary of the Elector, Johannes Seussius, and Johann Georg Godelmann, member of the *Geheimer Rat* of the Elector of Saxony. He also corresponded with the mathematicians Melchior Joestel and his successor Ambrosius Rhodius of the university of Wittenberg, the most important university on Saxon territory around 1600.[9] Moreover, Kepler offered several of his publications on the nova of 1604, including his *De stella nova* (1606) and *Astronomia nova* (1609) to Christian II, the Elector of Saxony.[10] Moreover, when Kepler's position in Prague became insecure, Kepler hinted in a letter of December 1610 at an unknown correspondent at the Dresden court that he was prepared to move to Dresden.[11] After the death of Joestel in 1611 Kepler was shortly considered for the professorship of higher mathematics at the university of Wittenberg, over which the Dresden court held authority, but the *Oberkonsistorium* decided that to go after Kepler for this position was to aim too highly and instead appointed Kepler's friend and colleague, Ambrosius Rhodius.[12]

The Dresden Kunstkammer was one of the more important courtly collections of its kind in central Europe.[13] Originally, the high percentage of tools and mathematical instruments among the objects collected here made this Kunstkammer different from other early court collections, such as those of Albrecht V of Bavaria in Munich and of Archduke Ferdinand II at Schloss Ambras, near Innsbruck. But by the time of Kepler's visit prior to 1604, the founder of the collection, Elector August of Saxony, had died and his successors had made considerable efforts to collect other types of objects, such as naturalia and paintings, which made the balance between the types of objects in the Dresden collection more similar to that at other places. Nevertheless, the Dresden Kunstkammer continued to be a place of knowledge. On the one hand, contemporary mathematical knowledge was reflected in the acquisition, organization and display of the objects in the collection – a few years later a mathematician, Lucas Brunn, was appointed court mathematician in charge of the Kunstkammer.[14] On the other hand, objects in the collection were also used for the creation of mathematical knowledge. For Kepler it was not exceptional to take Kunstkammer objects as the starting point of his mathematical investigations. Beside the camera obscura experience in the Dresden Kunstkammer, Kepler reported two other instances, in which a visit to a courtly collection had inspired him to do mathematics. First, in a letter to his teacher Michael Maestlin Kepler records that his experience of an array of Kunstkammer automata and clockwork was important to the formation of his first cosmological work, the *Mysterium Cosmographicum* (1597).[15] Second, during a visit to the Stahlhof in Dresden, which housed the

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[8] My description of Kepler's connections to the Dresden court is based on joint work with Michael Korey. See Dupré and Korey (2005). An informative summary of Kepler's contacts with Dresden is in Helfricht (2001).

[9] See the letters in Kepler (1937-), 14, 159-160; 15, 81-82, 202-204, 317-318; 16, 344, 348.

[10] As discussed in Helfricht (2001), 35.

[11] Kepler (1937-), 16, 353.

[12] See the documents gathered in Kepler (1937-), 19, 349-350.

[13] My description here of the Dresden Kunstkammer is based on joint work with Michael Korey. See Dupré and Korey (forthcoming). For a good general overview of the localization and organization of the Dresden Kunstkammer, see Watanabe-O'Kelly (2002), 71-99.

[14] Dupré and Korey (forthcoming).

elector's armory, Kepler saw amidst the architectural ornament a dodecahedron; he later said that this inspired him to his study of the symmetry of the snowflake in the *Strena* (1611).[16]

Figure 1: *Kunstkast* or cabinet with *perspectiefje*, 1642 (or later), Antwerp, Museum Rockoxhuis.

But what was the contemporary status of these Kunstkammer objects and of the experiences in which they were used? Horst Bredekamp has characterized the Kunstkammer as a *Spielkammer*.[17] Contemporary visitors of the Kunstkammer referred to their experience as taking part in social play or in a game. Moreover, contempories did not distinguish between *ludus*, or social play, and *lusus*, intellectual play or the jokes of nature and the jokes of knowledge that populated the

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[15] As discussed in Bredekamp (1995), 37.
[16] Kepler (1975), 81.
[17] Bredekamp (1993).

collections and texts of the period.[18] Play often revolved around optical objects. The notion of *lusus* even incorporated the vocabulary of optical illusion. Anamorphoses – around which the mathematician Lucas Brunn, the curator of the Dresden Kunstkammer, would later in the seventeenth century display the perspective instruments and telescopes – were conceptualized in terms of *lusus*.[19] In his *Magiae naturalis* Della Porta discussed numerous optical games which made use of the image formation capacities of lenses, mirrors and camera obscura's. A crystal ball, a gift presented to August I by the Duke of Savoy in 1580 and prominently displayed in the most important room of the Dresden Kunstkammer, was most likely also intended to be used in such social play or games centered around the 'effects and powers of the crystal'.[20] Also Rudolf II, Kepler's patron in Prague, was highly interested in optical games and Della Porta's *Magiae naturalis*, Kepler wrote in a letter to the Dresden court in December 1610.[21] Optical games were, however, not the privilege of courtiers. In early seventeenth-century Antwerp wealthy merchants embellished their houses with a richly decorated cabinet with a so-called *perspectiefje*, an opening in the cabinet which was covered on all sides with plane mirrors placed at angles to each other.[22] (see Figure 1) The optical games in which the owner and visitors to the house were invited to participate involved the movement of eyes and heads, fingers and objects such as coins to see the ever-changing and multiple reflections described in Della Porta's natural magic.

Contempories used the category of *lusus* to grasp the praeternatural: those events and objects which fell outside the ordinary course of nature, but of which the cause was nevertheless not supernatural. It was precisely natural magic 'in which' – according to Benito Pereira's definition – 'wonders are created by the individual artifice of certain people who make use of things which are natural', and Della Porta's optical games were as such paradigmatic for this intellectual category.[23] Interestingly, also Kepler defined his experience inside the camera obscura in terms of social and intellectual play. About the 'image in the air' which Kepler saw in the darkened room of the Dresden Kunstkammer, he noted that 'what I, steeped in demonstrations, stated that I had seen, the others denied. I therefore attribute it, not to the overseer's intent, but to chance', and he concluded his description of the experience by admitting that 'the games [*ludi*] can be made more elaborate'.[24] Moreover, in his *Somnium* Kepler told how he himself performed magical optical games inside the camera obscura at the beginning of his astronomical observations: 'This also is a magical ceremony. [...] During those years in Prague I often carried out a special procedure in

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[18] Findlen (1990). For Kepler, see Findlen (1998), 255-261.

[19] Dupré and Korey (forthcoming).

[20] The specialized book collection within the Kunstkammer included a manuscript giving a 'Description of the effects and powers of the crystal given by the Duke of Savoy to the Elector, Duke August of Saxony'. The manuscript is only known from its title in the early Kunstkammer inventories. See Watanabe-O'Kelly (2002), 254. The crystal ball itself is preserved in the Grünes Gewölbe of the Dresden State Art Collections. For more details on the fate of this crystal ball, see Dupré and Korey (forthcoming).

[21] Kepler to Anonymous in Dresden, 18 December 1610, in Kepler (1937-), 16, 347. For the intellectual climate at the Prague court of Rudolf II, see Evans (1973), especially for the importance of Della Porta and his natural magic at the Rudolfine court, see p. 197. For the role of serious jokes at this court, see Kaufmann (1990).

[22] Fabri (1999) and Fabri (1998).

[23] As quoted in Ankarloo, Clark and Monter (2002), 161.

[24] 'Sed quod ego demonstrationibus imbutus videre me affirmabam, caeteri negabant. Itaque non consilio custodis, sed casui tribuo. [...] Possunt amplificari ludi'. Kepler (1937-), 2, 164-165, translation in Kepler (2000), 194.

connection with a certain observation. Whenever men or women came together to watch me, first, while they were engaged in conversation, I used to hide myself from them in a nearby corner of the house, which had been chosen for this demonstration. I cut out the daylight, constructed a tiny window out of a very small opening, and hung a white sheet on the wall. Having finished these preparations, I called in the spectators. These were my ceremonies, these were my rites [...] In capital letters I wrote with chalk on a black board what I thought suited the spectators. The shape of the letters was backwards (behold the magical rite), as Hebrew is written. I hung this board with the letters upside down in the open air outside in the sunshine. As a result what I had written was projected right side up on the wall within'.[25] Nevertheless, the magical game brought the optical principles underlying the games inside the camera obscura within the realm of knowledge. 'The spectators enjoyed [these games] all the more for realizing that they were games', Kepler claimed.[26] Which then were these principles of optical imagery?

2. Images in the Air: Magic, Demons and Imagination

In his attempts to reveal the principles of optical games Kepler showed himself a follower of Jean Pena's 'De usu optices' (1557), a text which was sufficiently important for Kepler to deserve a review at the beginning of his *Dioptrice* (1611).[27] In this preface to his edition of Euclid's *Optica et catoptrica*, praising the utility of optics, Pena argued that one of the uses of optics was the unmasking of the forgery of magicians involved in catoptromancy, divination and demonic magic. Pena argued that their illusionist tricks were based on nothing but natural optical knowledge – an argument which was oft-repeated in the later sixteenth century, for example, in Reginald Scot's famous study of witchcraft, 'The Discoverie of Witchcraft' (1584).[28]

Pena formulated it in this way: 'What should someone fear who has learned from optics to construct a mirror, in which one and the same thing is seen one hundred times [...]; who understands to place a mirror so that in it you see those things which happen in the streets and houses of strangers? who knows that there certainly is a place, at which, if you look into a concave mirror, you will see but your eye? who knows that a mirror from plane mirrors can be constructed so that, he who looks into it, sees his image flying? Tell me, he who understand these things from optics, [...] does he not distinguish forgery and imposture from the truly physical things?'[29] Pena allowed the 'truly physical things' of natural magic, which Della Porta defined as 'the practical part of natural philosophy, which produceth her affects by the mutual and fit application of one natural thing unto another', but he opposed another kind of magic, which Della Porta called 'sorcery', in which magicians allegedly used demons, evil spirits and the like.[30]

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[25] Kepler (1967), 57. For the jocular character of Kepler's magical games in *Somnium*, see Chen-Morris (2005).

[26] Kepler (1967), 58.

[27] Kepler (1937-), 4, 341.

[28] For Scot and the creation of optical illusions, see Ankarloo, Clark and Monter (2002), 126.

[29] 'Quid enim reformidabit is qui ex Opticis didicerit, speculum construi posse, in quo unus & idem videat sui centum aut eo plures imagines choreas ducentes? Qui intelligat speculum ita collocari posse, ut in eo videas ea quae fiunt & in vicis & in alienis aedibus? Qui sciat certum esse locum, & quo si inspicias speculum concavum, tuum oculum tantummodo visurus sis? Qui sciat speculum è planis speculis ita construi posse, ut qui se in eo aspiciat, suam imaginem volantem videat? Cedo, qui ista ex Opticis intelliget, nonné mulierum Thasselicarum praestigias facilè agnoscet? Nonné fucum & imposturam à rebus verè physicis distinguet?'. Pena (1969), 158.

But for Pena there was nothing wrong with turning the definition of optics as 'ars bene videndi' of his teacher Petrus Ramus on its head and to use optics not only to correct vision, but also to use it to deceive vision for amusement and entertainment insofar as all those involved in playing these optical games knew enough optics to understand these are only games.[31] Pena defined optics and catoptrics in function of the understanding of optical games. One of the famous illusionist tricks made use of a mirror inside a camera obscura to project images 'in the air'. Pena wrote:

> This part of optics, which is called catoptrics, teaches to make a mirror, which does not retain the images of objects, but reflects them in the air. Witelo has written about its composition [...] Thus, should one prohibit cunning women to fool the eyes of men with this mirror, by making them believe they see ghosts raised from death, while they see the image of some hidden child or statue in the air outside the mirror? Because what is most certain is that, if a cylindrical mirror is placed inside a room closed from all sides, and if a mask, or a statue, or whatever else, is placed outside this room, so that there is a fissure in the window or in the door of this room, through which the rays from the mask penetrate [into the room] to the mirror, then the image of the mask, placed outside the room, will be observed inside the room hanging in the air, and, since the reflections from these mirrors are highly deformed and show a misshapen image of a beautiful thing, how hideous and terrible will the image seem of a mask prepared to arouse horror and consternation.[32]

I would like to comment on two aspects of this quote which were central to Kepler's reading of the optical and magical tradition. My first point is about the *image in the air* perceived inside the camera obscura – an oft-repeated observation in sixteenth-century optics and natural magic. The reference, in fact, is to proposition 60 of book 7 of Witelo's *Perspectiva*: 'it is possible to set up a convex cylindrical or conical mirror in such a way that someone looking [into it] can see the image of particular object that is out of sight [floating] in the air outside the mirror'.[33] It is

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[30] 'There are two sorts of Magick: the one is infamous, and unhappie, because it hath to do with foul spirits, and consists of Inchantments and wicked Curiosity; and this is called Sorcery; an art which all learned and good men detest; neither is it able to yeeld any truth of Reason or Nature, but stand meerly upon fancies and imaginations, such as vanish presently away, and leave nothing behinde them [...] The other Magick is natural; which all excellent wise men do admit and embrace, and worship with great applause [...]'. Porta (1957), 1.

[31] For Petrus Ramus geometry was the 'art of measuring well'. Along the same lines, in 'Opticae libri quatuor ex voto Petri Rami' (1606) Ramus and his student Frederic Risner defined optics as 'ars bene videndi' or the 'art of seeing well', that is 'to judge the truth and falsehood of the visible things accurately and carefully'. For Ramus, see Hooykaas (1958), 58-59. 'Optica est ars bene videndi. Optica suo fine definitur, qui est bene videre, id est, de veritate & fallacia visibilium accurate & exquisite judicare'. Risnerus (1918), 3. See Dupré (forthcoming).

[32] 'Docet enim ea Optica pars, quae Catoptrice dicitur, speculum componere, quod objectorum imagines non in se retineat, sed in aëre rejiciat: de cujus compositione & Vitellio scripsit, & nos aliquid dicemus (favente Deo) cùm Catoptrica explicabimus. Quid ergo prohibet mulieres versutas hoc speculo, hominum oculos ludificare, ut evocatos manes mortuorum se videre existiment, cùm tamen aut pueri aut statuae alicujus delitescentis simulacrum in aëre extra speculum videant? Nam quod certissimum quidem est, fidem tamen omnem videtur excedere, Si Cylindricum speculum in cubiculo undecunque clauso statuatur, extra autem cubiculum ponatur larva, aut statua, aut quidlibet aliud, ita tamen ut in fenestra vel ostio cubiculi sit rimula aliqua, per quam radii à larva in speculum irrumpa't, imago larvae extra cubiculum positae, intra cubiculum cernetur in aëre pendens. & cùm reflexiones à speculis illis nonnihil deformes sint, ut rei speciosae deformem imaginem ostentent, quàm terra & terribilis videbitur imago larvae ad horrorem & consternationem comparatae?' Pena (1969), 157.

important to realize that Witelo did not speak of a projected image, a concept which was alien to perspectivist optics, although the meaning of this passage is sometimes miscontrued in this way. The image *in the air* is still perceived in the mirror; 'in the air' referred to a geometrical location -- a location in visual space, not physical space. The image is still located behind the mirror, but at a point outside the circle of curvature defining the invisible part of the mirror.

Figure 2: A magic lantern. From Giovanni Fontana, *Bellicorum instrumentorum liber*, Cod. Icon. 242 (Bayerische Staatsbibliothek, Munich), 1420-1440, fol. 70r.

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[33] 'Possibile est speculum columnare vel pyramidale convexum taliter sisti ut intuens videat in aere extra speculum imaginem rei alterius non vise'. Risner (1972), 308-309. See Smith (2005), 178-180.

My second point is about the *deformation* of these images in the air. Monsters, devils, demons and other strange apparitions were often the dominant images which magicians produced inside darkened rooms. A famous example is in the *Bellicorum instrumentorum liber* of the Italian physician, mathematician and self-styled magician of the early fifteenth century, Giovanni Fontana. In this treatise on military machinery he pictured a kind of magic lantern designed to show images of demons, apparently to terrify the enemy. (see Figure 2) This choice of theme is understandable in the context of contemporary theories of magic, demonology and optics, such as the one developed in *Disquisiinum magicarum libri sex* (1599) of the Antwerp jesuit, Martin del Rio. He strongly opposed two kinds of magic: the first supernatural and the domain of divine intervention, the second praeternatural and the domain of humans, demons and angels who collobarated but only by manipulating natural means.[34] As I already indicated, the wonderful optical apparatus discussed by Pena, Della Porta and Kepler belonged to the category of the praeternatural.

Moreover, it was also thought that the substance of demons was *pneuma*, a notion of Stoic origin, which had left its marks in medicine, optics (visual spirits or optic pneuma sent from the brain to the eyes through the optic nerves was instrumental in the process of vision) and Stoic cosmology, which was still highly influential in Kepler's time (Pena followed neo-stoic cosmological ideas in denying the Aristotelian distinction between heaven and earth and claiming that there was only one substance, *pneuma*).[35] *Pneuma* was the substance of dreams, strange apparitions, etcetera – in short, the substance of the *imagination* which projected its images on *pneuma*.[36] Demons were thus most appropriate images to appear inside the camera obscura. The choice for demons is, above all, informative of the type of image these images *in the air* were. As products of the imagination these images were fundamentally psychological, a definition of *imago* which Kepler borrowed from the optical tradition in his *Paralipomena*: 'An image [*imago*] is the vision of some object conjoined with an error of faculties contributing to the sense of vision. Thus, the image is practically nothing in itself, and should rather be called *imagination*'.[37]

We are now in a position to re-examine Kepler's report of the *ludi* inside the Dresden Kunstkammer and his reading of Della Porta's *Magiae naturalis*. The two passages in Della Porta's *Magiae naturalis* to which Kepler referred are chapters 10 and 13 of book 17 in which Della Porta made *images in the air* appear with a convex lens or crystal ball. Which are the optical effects *perceived* by varying the distance of a candle light to a convex lens and placing the eye at a distance exceeding the center of curvature of the lens? First, when the candle light is close to the lens, a right oriented virtual image is perceived, of approximately the same size as the candle light itself. When the candle light is moved farther away from the lens, a virtual image is still perceived. This image becomes larger until it 'explodes' when the candle light is beyond the point of combustion of the lens. When the candle light is moved farther away from the lens beyond the point of combustion, the image is inverted. It also becomes progressively smaller.

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[34] Del Rio (2000), 57. See Gorman and Wilding (2001), 233.

[35] For stoic influence, see Barker (1985); Barker (1991); Barker and Goldstein (1984).

[36] Vermeir (2005), 133. Compare Del Rio (2000), 111-112. For pneuma, magic and the imagination, see also Vermeir (2004), 569-575, 581-582; Shumaker (1989), 7-8, 86.

[37] 'Breviter, imago est visio rei alicuius, cum errore facultatum ad visum concurrentium coniuncta. Imago igitur per se penè nihil est, imaginatio potiùs dicenda'. Kepler (1937-), 2, 64, translation in Kepler (2000), 77.

The *perceived* image is at the surface of the lens or crystal ball. In his *De Refractione* (1593) Della Porta accepted this location of the perceived image and he attempted to offer a demonstration for it by applying the cathetus rule to image formation in a refracting sphere.[38] The cathetus rule was the accepted perspectivist means to find the *geometrical* locus of images, but its application here was completely arbitrarily, because Della Porta did not know how to apply it to a case with more than one refracting or reflecting surface. (see Figure 3) Della Porta assumed, without justification, that the ray CB is refracted to E, where it is again refracted to the eye at A. To locate the image of G, he took the cathetus from G through the center D, and, then, located the image in E, at the surface of the refracting sphere, where it intersects the refracted ray BE. Della Porta arbitrarily applied the rule to find the *geometrical* locus of images to demonstrate the locus of the *perceived* images.

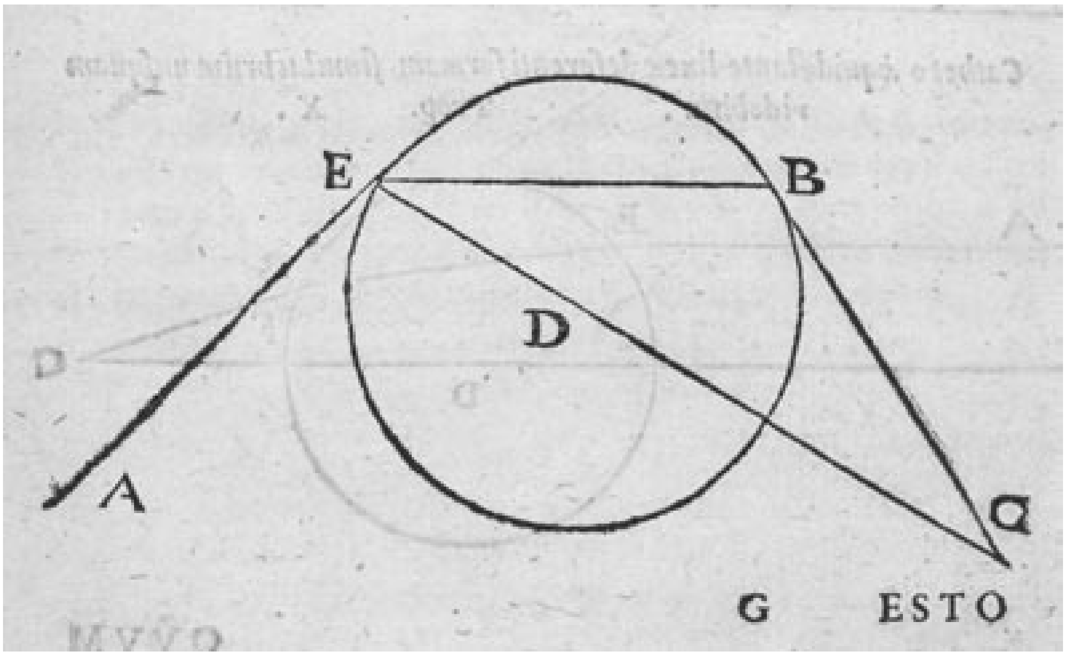

Figure 3: The application of the cathetus rule to image formation in a refracting sphere, from Giovanni Battista Della Porta, *De Refractione*, 1593.

We have already seen that the *image in the air* refered to the *geometrical* locus of an image. My example above was about a cylindrical mirror inside a camera obscura, but *in the air* referred likewise to the geometrical locus of images (by application of the cathetus rule) in concave mirrors, crystal balls or aequous globes. In his *Magiae naturalis* Della Porta confused *images in the air* with images projected on a piece of paper. Thus, Della Porta not only confused *geometrical* images with *perceived* images (as above), he also confused *geometrical* images with *projected* (or *optical*) images. In the section ‘with a convex crystalline lens, to see an image hanging in the air’, Della Porta created confusion between the image seen between this lens and the eye (in the air) and the projected image, because he wrote that ‘if you will place a piece of paper in the way, you will see clearly that a lighted candle appears to be burning upon the paper’.[39]

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[38] Porta (1593), 49. See Dupré (2005), 168.

Kepler situated the third section of chapter 5 of his *Paralipomena* inside the camera obscura. He opened this chapter with a description of image formation in a crystal ball in a room-size camera obscura. Unlike Della Porta, he differentiated between perceived and projected images:

> For if one were to stand with a crystalline or aqueous globe of this kind in some room next to a glazed window, and provide a white piece of paper behind the globe, distant from the edge of the globe by a semidiameter of the globe, the glazed window with the channels overlead with wood and lead [...] are depicted with perfect clarity upon the paper, but in an inverted position. The rest of the objects do the same thing, if the place be darkened a little more [...] whatever things are able to reach through the breadth of the little window or opening to the globe are all depicted with perfect clarity and most pleasingly through the crystalline upon the paper opposite. And while the *picture* appears at this distance uniquely (that is, a semidiameter from the globe to the paper), and nearer and farther there is confusion, nevertheless, *exactly the opposite happens when the eye is applied.* For if the eye be set at a semidiameter of the globe behind the glass, where formely the picture was most distinct, there now appears the greatest confusion of the objects represented through the glass. [...] If the eye comes to be nearer to the globe, it perceives the objects opposite erect and large, [...] if it on the other hand recedes farther from the globe than the semidiameter of the globe, it grasps the objects with distinct images, inverted in situation, and small, and clinging right to the nearest surface of the globe.[40]

In the third chapter of his *Paralipomena* Kepler rejected the cathetus rule, because the cathetus had no meaning within his physics of light.[41] To replace the cathetus rule he formulated a more general rule for image location, based on the 'distance-measuring triangle' to explain the judgment of distances.[42] Kepler argued that distances are determined by a triangle that uses the distance between our two eyes, the base of the triangle, and the angle of convergence of the axes of the eyes, converging toward the object, that is, the vertex of the triangle. Since the eye is unaware of any change of direction of rays before they enter the eye, it judges object to be in the place where the reflected or refracted rays come from. Thus, Kepler argued, 'the genuine place of the image is that point in which the visual rays from the two eyes meet, extended through their respective points of refraction or reflection'.[43] In the first proposition of the fifth chapter he applied the principle that the image is at the vertex of the two-eyes-based optical triangle to image formation

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[39] Porta (1957), 368-369, translated in Kepler (2000), 193-194.

[40] 'Etenim si quis cum huiusmodi globo crystallino vel aqueo contra fenestram vitream stet in conclavo aliquo, adhibeatque albam papyrum post globum, semidiametro globi à margine globi remotam, fenestra vitrea cum intextis ex ligno et plumbo canalibus, vitrorum limbos obeuntitibus, clarissimè pingitur super payrum post globum, everso tamen situ. Idem faciunt res caeterae, si paulò plus obtenebretur locus; adeo, ut globo aqueo in cameram, [...] et fenestellae opposito, quaecunque per amplitudinem fenestellae seu foraminis possunt ad globum pertingere, omnia clarissimè et iucundissimè in opposita papyro per crystallinum depingantur. Cumque in unica hac remotione (nempe semidiametri papyri à globo) pictura appareat, ante et post fiat confusio; fit tamen planè contrarium applicato oculo. Nam si oculus constituatur post vitrum semidiametro globi, ubi prius distinctissima erat pictura, iam maxima existit confusio rerum per vitrum repraesentatarum. [...] Si propior fiat oculus globo, cernit oppositas res erectas et magnas, ubi super papyro confunduntur, sin recedat à globo longius semidiametro globi, comprehendit res distinctis imaginibus, everso situ, et parvas, et in ipsa globi superficie proxima haerentes'. Kepler (1937-), 2, 162, translation in Kepler (2000), 191.

[41] For a discussion of Kepler's rejection of the cathetus rule, see Chen-Morris and Unguru (2001); Shapiro (1990), 122-124; Simon (1976), 464-477.

[42] Kepler (1937-), 2, 66-67.

in a sphere filled with water.[44] (see Figure 4) He located the image of point A, seen through the sphere filled with water EFG with two eyes B and C at D, the intersection of the rays AEFC and AGHB. It is evident that Kepler located the image *in the air*. Put differently, by replacing the cathetus rule Kepler tried to bring the *geometrical* locus in accordance with the *perceived* locus.

However, in the following propositions, Kepler adduced reasons why the image is seldom seen at D. In proposition 5 he finally retreated from the claim in his first proposition. He wrote: 'In front of an aqueous ball or globe there is no place for the image of an object hiding behind the globe'.[45] Kepler used the distinction between *projected* images and *perceived* images to criticize Della Porta's account of image formation, which – as we have seen – failed to make this distinction.

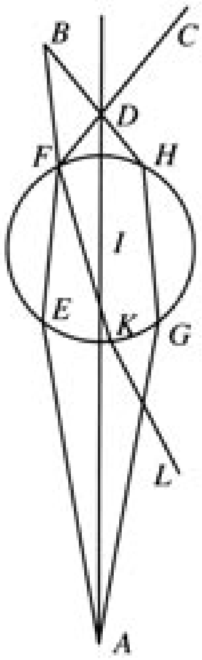

Figure 4: Image location in a refractive sphere with two eyes, from Johannes Kepler, *Paralipomena ad Vitellionem*, 1604.

Pertinent to this is what Porta had taught in chapter 10 preceding, 'with a convex crystalline lens, to see an image hanging in air'. [...] For this reason, he adds,

> 'If you will place a piece of paper in the way, you will see clearly that a lighted candle appears to be burning upon the paper.' [That is, the image will be seen weakly and hardly at all in the bare air itself, by Porta's admission.] But if you put a piece of paper in the way – if, I say, you interpose a piece of paper between the lens and the sense of vision [for, with me, Porta here is still speaking about the image, not yet about the picture, of which this is true, as will be clear

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[43] 'Estque locus imaginis genuinus illud punctum, in quo coëunt producti radii visorii ex utroque oculo, per sua puncta refractionum vel repercussuum'. Kepler (1937-), 2, 72, translation in Kepler (2000), 85.

[44] Kepler (1937-), 2, 162-163.

[45] 'Ante pilam seu globum aqueum nullus est locus imagini rei post pilam latitantis'. Kepler (1937-), 2, 164, translation in Kepler (2000), 193.

> below], the image will now appear, not hanging in air, but fixed on the paper. For the paper, striking the eyes more obviously, steadies them on the place of the image, so that they may be turned towards each other in that direction. And nonetheless, because the paper is then brighter than the image, the paper will be seen primarily, the image secondarily. For it is not mathematical dimensions alone that create the image, but also, and much more, the colors and lights and physical causes. [...] If you should focus the eyesight upon one place, namely, upon the place of the image previously investigated, as it has been described in prop. 1 of this chapter, when a clearly visible object is placed nearby, then the eyes coming together upon this object, will also see the required image secondarily.[46]

Thus, this is not to say that it is impossible for Kepler to *perceive* images at the locus indicated in his proposition 1. A paper support for these images is however desirable to create the conditions under which such an image can be perceived. Moreover, in truly exceptional circumstances, like the one Kepler reported to have taken place in the Dresden Kunstkammer, Kepler *did* perceive the image in the air which under *normal* conditions cannot be perceived. Nevertheless, Kepler immediately cut off this report by stating that he would only discuss 'things that are more obvious and ready at hand'.[47] In what followed Kepler discussed *pictures* or projected images: 'Since hitherto an Image [Imago] has been a Being of the reason, now let the figures of objects that really exist on paper or upon another surface be called pictures [Pictura]'.[48] Kepler then located the *picture* at the intersection of pencils of rays along the axis of the sphere filled with water – a location which was based on his concept of a refracting focus. He demonstrated that 'through a globe of a denser medium, any point more remote than the intersections of parallels strongly depicts itself upon paper, located at the last boundary of the intersection of its radiations, not before and not after this point; and the picture comprising all the points is seen inverted'.[49] Unlike images – products of the imagination –, pictures were made by rays of light only.

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[46] 'Quorsum pertinet et illa, quae Porta capite 10. praecedento docuerat, *Lente crystallina convexa imaginem in aëre pendulam videre.* [...] Propterea addit: *Si papyrum obiicies, clarè videbis, ut candela accensa super papyrum ardere videatur.* Nempe malignè et vix videbitur imago, fatente Porta, in ipso nudo aëre. At si papyrum obiicias, si inquam interponas papyrum inter lentem et visum, (nam hic Porta mecum adhuc de imagine loquitur, nondum de pictura, de qua verum hoc est, ut infra patebit), iam non pendula in aëre, sed fixa in papyro videbitur imago. Papyrus enim evidentiùs feriens oculos, stabilit illos in loco imaginis, ut contorqueri eo possint. Et tamen quia tùm papyrus clarior imagine, papyrus praecipuè videbitur, imago secundariè. Non enim solae mathematicae dimensiones imaginem creant, sed etiam et multò magis colores atque lumina et physicae causae [...] Si convoces oculorum acies in unum, nempe in ante investigatum locum imaginis, qualiter in prop. 1 huius descriptus est, apposita in propinquo re insigni: tunc oculi ad rem hand coëuntus, videbunt et imaginem imperatam secundariè'. Kepler (1937-), 2, 164, translation in Kepler (2000), 193-194.

[47] 'Nos hic evidentiora et promptiora proponemus, ad institutum scilicet accommoda'. Kepler (1937-), 2, 165, translation in Kepler (2000), 194.

[48] 'Cùm hactenus Imago fuerit Ens rationale, iam figurae rerum verè in papyro existentes, seu alio pariete, picturae dicantur'. Kepler (1937-), 2, 174, translation in Kepler (2000), 210.

[49] 'Per globum densioris medii punctum quodlibet, remotius intersectionibus parallelorum, pingit sese fortiter super papyro, collocata in termino ultimo intersectionis suarum radiationum: non ante, non post hoc punctum, et pictura ex omnibus constans punctis, eversa spectatur'. Kepler (1937-), 2, 176, translation in Kepler (2000), 211.

Conclusion

What did Kepler learn from Della Porta? Della Porta's contribution to Kepler's new optics is difficult to grasp in terms of 'influence' or 'transmission'. We could only talk of Della Porta's influence on Kepler's theory of optical imagery at the unattractive risk of downplaying Kepler's indebtness to the perspectivist tradition. I also reminded us, however, at the beginning of my paper that – the other way around – Kepler only became the point of culmination of perspectivist optics by downplaying the influence of the experiences inside the camera obscura. Alternatively, I have attempted to portray Kepler as an early seventeenth-century mathematician-magician who was immersed in a contemporary court culture obsessed with optical games, in which Kepler actively participated in Prague and Dresden. In this guise of mathematician-magician Kepler read the perspectivist tradition. He sorted out the existing conceptual confusion and ambiguity in natural magic between *projected images* and *images in the air* – categorized as objects of play and thus carried over within the realm of optical knowledge – on the basis of his familiarity with the perspectivistic concepts *as well as* his experience of images inside the camera obscura. Finally, I think that we should be cautious of portraying Kepler as carving out a new science of optics out of natural magic. Although Kepler *normalized* or mathematicized those strangely projected images in his *Paralipomena*, he did not step outside his role of courtly mathematician-magician when he reported that he had seen this *abnormal* product of the human imagination, the *image in the air* appearing inside the camera obscura in the darkened Dresden Kunstkammer.

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Images: Real and Virtual, Projected and Perceived, from Kepler to Dechales

Alan E. Shapiro

In his *Ad Vitellionem paralipomena* (1604) Kepler revolutionized the theory of vision when he proposed that the eye is like a camera obscura. The pupil is like the small hole of the camera, the tunics of the eye collectively act like a lens, and the retina is like a screen that receives a real inverted image, which Kepler calls a *pictura*. The *pictura* was a new concept introduced by Kepler in order to distinguish it from an *imago* – and it will soon be evident why I use Kepler's Latin to distinguish it from our concept of image. A *pictura* is a replica of an object that is projected on to a paper or screen. It has a real existence independent of any eye that observes it. In contrast, an *imago* is only a "rational entity" that is perceived by the eye and exists only in the imagination. As truly revolutionary as Kepler's theory of vision was, the concept of *pictura* likewise demanded a revolution in geometrical optics and the theory of optical imagery – even if a lesser one – for projected images had no place in the medieval optical tradition. A less well known aspect of the *Paralipomena* is that Kepler provided a new foundation for a theory of optical imagery. What I wish to describe today is how a new theory of imagery was formulated in the next three-quarters of a century. Kepler bequeathed two concepts of image, *imago* and *pictura*, which to us are simply a virtual and a real image. I will describe how the modern concepts of real and virtual images were developed from the challenge of Kepler's projected image or *pictura*. The mathematical-physical foundation for the new concept of an image derived from combining features of each of these concepts: From the *pictura*, whose formation he explained mathematically as the limit, or focus, of a pencil of rays incident on a lens; and from his *imago*, whose place, he explained, could be determined by a single eye by means of a triangulation, although he did not generally invoke this rule. Equally important for the development of the modern theory of imagery was the invention of the telescope, which Kepler took up in his *Dioptrice* in 1611, for there was then no theory at all of lenses and, especially, multiple lenses.

Kepler on Optical Imagery

The place or location of an image became a central question in seventeenth-century optics, and it plays an important element in the theory of optical imagery that emerged in the wake of Kepler's innovations and in relating his *imago* and *pictura*. In studying the question of the location of an image it is useful to recognize that it actually involves two distinct questions: (i) Where is the image perceived to be located? (ii) Where is the place to which rays from given points of an object diverge or converge? (I have called these the "perceived image" and the "geometrical image," respectively.)[1] The first is a question of physiological optics and psychology, whereas the second is a question of geometrical optics and physics. In the 1660s and 1670s most opticians identified the solution of the first question with that of the second, considering them to be a single question of geometrical optics, and they either ignored physiological or psychological mechanisms of

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[1] Shapiro (1990).

judging distance or brushed them to the side. Kepler, in contrast, directly addressed both questions. The identification of the perceived and geometrical location of an image rests on the principle, or assumption, that an image is perceived in the same way as an object and that when an object sends rays to our eyes, we judge it to be in that place from which the rays actually originate, or in its true place. This turned out to be a rather fruitful approach for the development of geometrical optics.

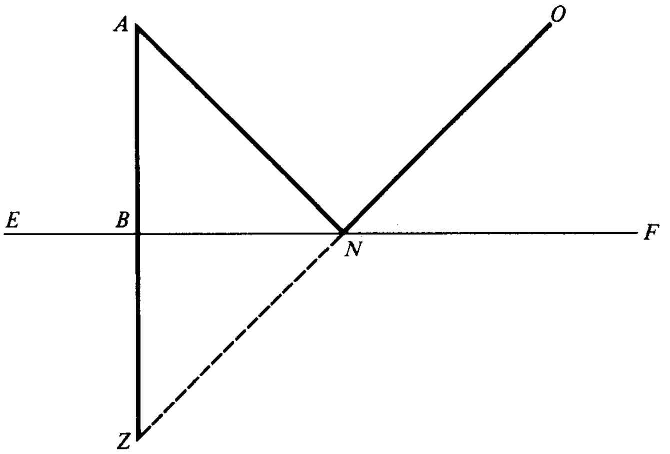

Figure 1: *The position of an image according to the cathetus rule is at the intersection of the cathetus* AB *and the reflected ray produced* ONZ.

As a preliminary to his own theory of image formation and vision, Kepler devoted the third chapter of his *Ad Vitellionem paralipomena* to "the foundation of catoptrics and the place of the image." Kepler's approach to the place of the *imago* was fundamentally a psychological one. He adopts the traditional definition of the image as an error of the faculties in not seeing an object in its true place and size: "An image [*imago*] is the vision of some object conjoined with an error of the faculties contributing to the sense of vision. Thus, the image is practically nothing in itself, and should rather be called imagination."[2] This should be contrasted with his subsequent definition of a picture that "really exists." His initial aim was to reject the then accepted cathetus rule "of Euclid, Witelo, and Alhazen" for image location. According to this rule, the image is located at the intersection of the reflected or refracted ray and the cathetus (produced when necessary), which is the perpendicular drawn from the object to the reflecting or refracting surface (Figure 1). The principle is strictly true for plane mirrors alone. Kepler showed that it does not always apply to reflection from spherical mirrors, and thus a new rule was required. Even when the cathetus rule described the position of the image correctly, the concept of image it employed differs fundamentally from a Keplerian *pictura*, which is formed by a pencil of rays arriving from each point of the object. In the ancient and medieval approach – which is known as the perspectivist tradition – an image of a point is determined by a single ray leaving or entering the eye from that point, so that its optical geometry is founded on a visual pyramid that has its base on the object

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[2] Kepler (2000), 77; Kepler (1939), 64. In Ch. 3, Prop. 4 Kepler calls judgments concerning the direction and place of the image an error, Kepler (2000), 78; Kepler (1939), 65.

and vertex in the eye and is composed of single rays extending from each point of the object to a corresponding point of the eye. It is equally characteristic of medieval optics that the eye is always included in an analysis of images, for without an eye to receive the form or species of an object, there can be no vision or images. Thus, the concept of real images or pictures depicted on a screen by pencils of light rays independent of the eye is a foreign one.[3]

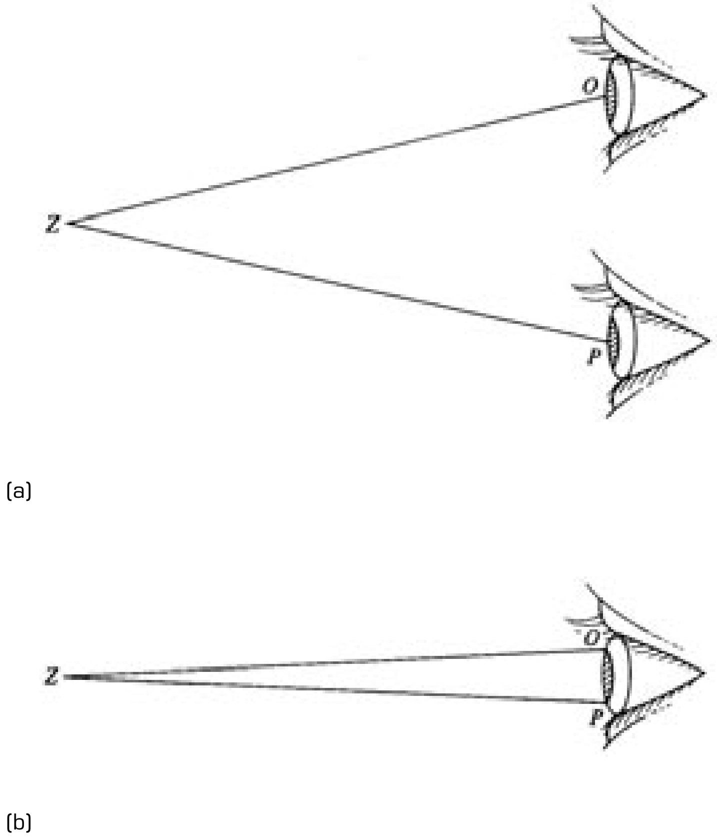

Figure 2: *Determining the place of the image with one eye, according to Kepler;* Paralipomena.

In order to replace the cathetus rule Kepler explains how judgments of distance, or the location of the *imago,* are made. Distances that are not too great are determined by means of a "geometry of the triangle" *(trianguli Geometria) ZOP* in Figure 2.a that utilizes the distance between our two eyes *O* and *P* and the angle of convergence of the axes of the eyes (Proposition VIII). We also learn to make similar judgments of (smaller) distances with a single eye from experience with two eyes, but now we use a "distance-measuring triangle" *(triangulum distantiae mensorium) ZOP* in Figure 2.b whose base *OP* is the opening of the pupil (Proposition IX). Kepler's account of the location of the image with one eye would play a central role in the unifying of the concepts of *imago* and *pictura.* The eye, Kepler explains, imagines objects to be in the place from which the reflected or refracted rays come, since it is unaware of any changes in the direction of the rays before they enter the eye. Consequently, he states in Proposition XVII that "the true place of the image is that point where the visual rays from *each eye* produced through their points of refraction or reflection come

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[3] Smith (2005).

together, according to Prop. VIII of this third chapter." Although Kepler frequently asserts that his discussion of vision with two eyes applies equally to the opening of one eye, it is apparent from the formulation of this rule and his citation of Proposition VIII for two eyes that he is thinking in terms of binocular vision; this will be even more evident from his applications of this rule to refraction.

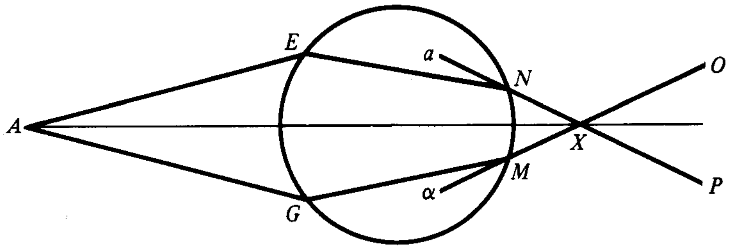

Figure 3: *The place of the image after refraction in a sphere, according to Kepler; after* Paralipomena.

In his account of vision in chapter 5 Kepler uses the refraction of a sphere filled with water, rather than a lens, to represent the refraction of the eye.[4] Lenses are mentioned only incidentally in the *Paralipomena;* they are treated extensively in the *Dioptrice* (1611), which Kepler wrote shortly after Galileo published his *Sidereus nuncius* in order to explain the telescope. He begins this chapter by examining the place of the *imago* of a point viewed through a sphere filled with water. He locates the image of point *A* (Figure 3) seen through the sphere *ENM* with two eyes *O* and *P* at *X*, the intersection of rays *AENP* and *AGMO* (Proposition I). However, with one eye he puts it on the sphere at *M* and *N* (Proposition VI), for with one eye the two rays are so close together that they effectively become one, and the sphere is the first place intersected by the ray at which the eye can locate the image. Yet later in this chapter Kepler describes the formation of *pictura* – real images – in the water-filled sphere by the intersections of pencils of rays, without regard to any eye, and locates them at various places on the axis, depending on the nature of the incident rays. In this example, then, Kepler has by the rule of chapter 3 located the *imago* – the perceived or virtual image – on the axis with two eyes and on the sphere with one, whereas by the geometrical methods of chapter 5 he places the *pictura* on the axis. Kepler's use of two eyes to determine the place of the *imago* is inconsistent with both medieval and early modern optics. Since antiquity the place of the image was determined by a single eye or view point. Isaac Barrow, who succeeded in combining Kepler's image and picture, criticized Kepler on this point. A pencil of rays from point *A* would enter each eye and we should see two images. More significantly, Kepler had eliminated the entire mathematical theory of images in medieval optics and had provided no mathematical replacement for image location, just a psychological one. In the following 70 years this lacuna would be filled.

With these preliminaries out of the way, I can now turn to Kepler's introduction of his two fundamental contributions to optical imagery, *pictura* and pencil of rays, which he presents in his

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[4] Kepler knew that the crystalline lens was lenticular and not spherical, but he argued that because of the surrounding aqueous humor or fluid, the resulting refraction was not much different from that of a sphere.

explanation of vision.[5] When Kepler turned to optics at the turn of the century, that science had already undergone a major revolution in the middle ages at the hands of Ibn al-Haytham, known in the West as Alhazen. Alhazen argued that vision occurs by means of rays which fall on the eye that are emitted from every point by visible objects in all directions. Although he introduced the idea that every point of the object emits a cone of rays to the eye, he thought that this would cause confused vision because at each point of the eye rays would arrive from every point of the object. To eliminate this problem he argued that only one ray from each point of the object, that which falls perpendicularly on the spherical lens, contributes to vision, because it passes through unrefracted and is thus stronger than all the others. By this device Alhazen was able to restore the traditional visual cone of geometric optics which had its base on the object and vertex on the eye with only one ray arriving from each point. Alhazen's new optical theory was adopted in the Latin West. Its most important exponent was Witelo whose *Optica* was printed in 1572 and is the object of criticism in Kepler's *Ad Vitellionem paralipomena*. Kepler rejected the argument that only that ray from each point of an object that falls perpendicularly on the eye is effective in vision. He argued, on the contrary, that the oblique rays adjacent to the perpendicular are scarcely refracted and must be almost as visually effective as the perpendicular rays and thus cannot be ignored. This criticism involved a profound reformulation of optics. In the perspectivist tradition images were formed by a single ray from each point of the object, but Kepler now required that a small bundle or narrow cone of rays or, as he later called them in *Dioptrice*, "pencils," be considered. Kepler applied pencils only to the formation of *picturae* and not *imagines*.

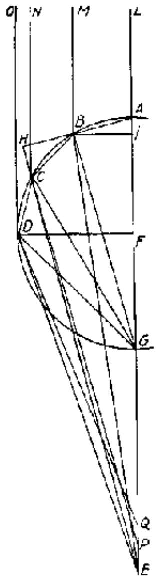

Figure 4: *When parallel incident rays fall on a sphere, the rays that pass closest to the center* AFG *of the sphere intersect the axis furthest from the sphere at* E*. After Kepler,* Paralipomena.

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[5] Kepler defined the term "pencil (penicillum)" in *Dioptrice* in 1611, but he had already applied it in *Paralipomena*. For the development of Kepler's concept of pencil see Straker (1971).

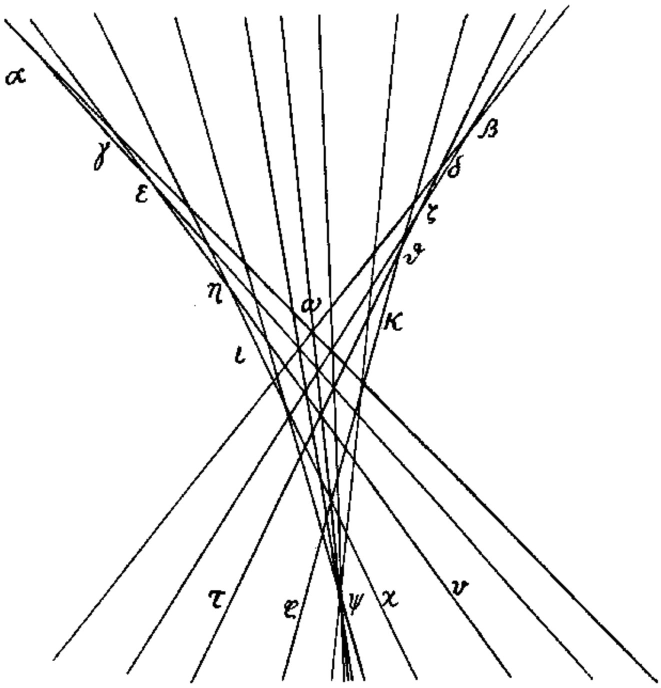

Figure 5: *Kepler's illustration of the intersection of rays near the focal point , or the caustic. From Kepler,* Paralipomena.

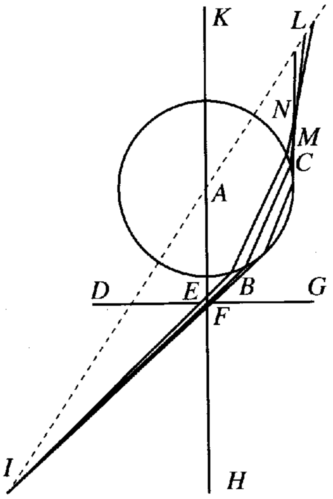

Figure 6: *The pencil of rays from the object at* I *pass through the pupil* EF *and are refracted by the sphere to NM where they paint a pictura on the retina. After Kepler,* Paralipomena.

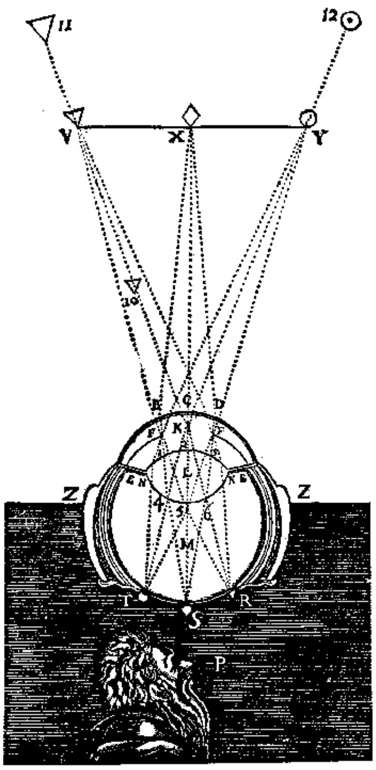

Figure 7: *The image* TSR *of the object* VXY *is seen on the retina. From Descartes,* La Dioptrique.

Kepler considered the eye to be like a camera obscura with the crystalline lens projecting a picture on the retina. Since neither he nor anyone else knew how a lens functioned, he investigated the paths of rays through a water-filled glass sphere under various conditions, guided by his experimental knowledge that under various conditions a lens does indeed produce a picture. Kepler began his analysis, just like his medieval predecessors, with cones of radiation emitted from every point of the object. The crystalline lens is thus covered with an infinitude of cones of rays with their base on the lens and vertex at each point of the object. Since Kepler rejected the medieval solution to eliminating the potential confusion at the eye by considering only the perpendicular ray from each point, he set out to determine the refraction of a pencil of rays in the eye or rather a sphere. His analysis showed that a pencil of rays from a point of the object would after refraction converge (or very nearly converge) to a point on the retina, thereby reestablishing a one-to-one correspondence between points on the object and image. To establish this he first demonstrated that with parallel incident rays, i.e., rays arriving from objects very far away from the refracting sphere, those rays that pass closest to the center of the sphere intersect the axis furthest from the sphere. In Figure 4 ray *MB*, closest to the axis *AGE*, falls at point *E*, while the rays *NC* and *OD* fall at *P* and *Q*. Then he showed that all rays close to the axis (i.e., those making an angle of less than 10° with it) intersect the axis very near the extreme limit of intersections *E*, or what would later be called the focal point. In Figure 5 he described the envelope formed by the points of intersection of the rays, a curve that later in the century was named the caustic. Kepler's determination of the focus of the sphere used the sophisticated concept of a limit. He showed that although all the rays do not converge to the focus , those that are near the axis do converge very nearly to the same point (Props. 15, 19). The picture is projected to this point, as can be seen by inserting a screen there. Kepler's limit approach to defining the place of the *pictura* would be rigorously pursued in the 1650's and 1660 by Huygens, Barrow, and Newton, though they would apply the limit process to determining the focus for all images, real and apparent. I will not pursue the mathematical theory of imagery that was developed in the second half of the century, but I will follow the unification of optical imagery.[6]

After explaining the focusing properties of a sphere, Kepler shows with a ray diagram how the eye acts like a camera obscura (Figure 6), but Descartes's diagram from *La Dioptrique* (1637) is deservedly more famous (Figure 7), because it more clearly shows the pencils of rays and pairs of cones from object to image point with their bases on the crystalline lens. When Kepler returned to optical theory in *Dioptrice* to explain lenses and the telescope, he now explained the camera obscura with a lens rather than with a water-filled sphere. The diagram in this case (Figure 8) clearly shows pencils of rays from points *CAE* on the object being brought to a focus at *FBD*.[7] He now calls the point where the rays meet *concursus punctum*, a term that was widely adopted in mid-century.

To introduce his account of the projected image Kepler defined a new concept, *pictura*:

> Since hitherto an image [*Imago*] has been a being of reason [*ens rationale*], now let the figures of objects that really exist on paper or upon another surface be called pictures [*picturae*].[8]

The *pictura* is here sharply contrasted with *imago*, the former real and the latter imaginary, a product of the mind. The *imago* is unchanged from the perspectivist tradition; it is an image perceived by the eye. The *pictura* would become the real image of modern optics, and Kepler's phrase "really exists" suggested the new name. Kepler treats perceived and real or projected images completely differently. Judging the location of the *imago* is a matter of psychology, an issue for the mind; whereas the position of the *pictura* is determined geometrically and does not involve the mind. Kepler, as we saw, does not use pencils of rays – arguably his most important contribution to geometrical optics – and limit techniques to determine the location of the *imago*. Nonetheless, in general the distinction that Kepler drew between *imago* and *pictura* was not as sharply demarcated as he makes it seem here. Earlier, in Chapter 2, where he explains image formation in a camera obscura, he refers to the image cast on the wall mostly as an *imago* but also as a *pictura*. Kepler's successors certainly understood the two to somehow be related and, like Kepler, they freely interchanged the word *imago* and *pictura* for the projected image. A *pictura* was evidently some kind of image – that is, it belonged to the genus of image – because it was an object perceived in the wrong place, seen by refracted rays rather than by straight or direct rays, like an object. Kepler summarized the accepted definition when he wrote that, "The Optical writers say it is an image [*imaginem*], when the object itself is indeed perceived along with its colors and the parts of

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[6] For a guide to geometrical optics in the seventeenth century see the editors' introduction and notes in Huygens (1888-1950), vol. 13; see also Shapiro (1990).

[7] Kepler (1611), §45, p. 17.

[8] Kepler (2000), 210; Kepler (1939), 174.

its figure, but in a position not its own [...]"[9] Seeking a common basis for the two would have been a meaningless task had they thought that the two were utterly distinct kinds of entity.

That Kepler was able to attain such fundamental and sophisticated results with such a simple – almost trivial – model of refraction in an aqueous sphere was an extraordinary achievement that was guided by astute physical reasoning and meticulous analysis of his experiments. Kepler's geometrical investigation of refraction was largely qualitative, descriptive, and approximate. He used an approximate law of refraction and was able to calculate the paths of the refracted rays in a sphere and determine its focal point to be equal to its radius. "I have," he lamented, "despaired of defining geometrically the precise point where the extreme intersection occurs. I beg you, reader: help me here."[10]

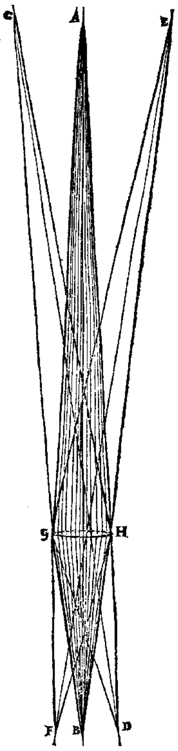

Figure 8: *Pencils of rays from object* CAE *brought to a focus at* FDB*; from* Dioptrice.

After Galileo's announcement of the astronomical telescope, Kepler was able to apply in his *Dioptrice* the concepts and techniques already developed in *Paralipomena* to explain how telescopes and lenses worked, but he succeeded in determining the focal point only for a single spherical surface and for a thin equiconvex lens. Many of Kepler's innovations were ambiguous, unsystematic, or incomplete. An important example of this in his treatment of the telescope, which involves two lenses and therefore, in our view, two images, or at least two focal points. Kepler could treat these cases only qualitatively and descriptively. In his description of the effects of a combination of a convex and concave lens, i.e., an astronomical telescope, he noted that the

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[9] Kepler (2000), Ch. 3, Def. 1, p. 77; Kepler (1939), 64.
[10] Kepler (2000), 205.

concave lens should be placed a "little before" the points of concourse of a convex lens, whose precise location is not specified; and then he could only indicate that after passing through the concave lens the rays converge less, becoming convergent, divergent or parallel.[11]

Despite the limited success of *Dioptrice*, it marked a decisive turning point in the history of geometrical optics. Hitherto that science was dedicated to studying images in reflection from the single surface of a mirror and not in refraction in lenses. The study of lenses and the multiple lenses of the telescope – promoted by a succession of spectacular discoveries – now became the driving force of geometrical optics. A question that naturally arose was how an image after refraction in the first surface or lens was to be treated in subsequent ones. With Kepler's discrediting of the cathetus rule and the new sort of image, the *pictura*, it also meant that the structure of catoptrics would have to be reformulated.

Optical Imagery after Kepler

Now that I have presented Kepler's ideas on optical imagery, which would serve as the elements for a new synthesis, let me briefly sketch the synthesis that emerged between about 1650 and 1670, so that we can then appreciate the significance of the steps in its development. Mathematically, or rather geometrically, Kepler's distinction between *imago* and *pictura* vanished. Both were now treated the same way, by pencils of rays, which Kepler had applied to the *pictura* alone. The key step in assimilating Kepler's perceived *imago* to the *pictura* was through his account of the place of the image with one eye by means of the distance-measuring triangle. Although the distance-measuring triangle is not strictly speaking a pencil of rays, it can be – and was – readily extended to encompass that concept. In determining the location of an image, it was accepted that its location is judged to be that place from which the rays or pencils appear to diverge. This was no longer considered to be an error of vision but a true appearance. The place from which rays of an *imago* diverged was seen to be no different than the place to which rays converged, and afterwards diverged, in a *pictura*. Convergence and divergence would eventually become the distinction between real and imaginary images. A crucial step in analyses of the location of an image was the recognition that optically an object and an image were equivalent. The optics of the telescope played a key role in the development of this insight, for this allowed for easy ray-tracing. After pencils of rays, i.e., an image, pass through one lens, it could be treated as an object for the subsequent lens.

Two different approaches, or informal schools, contributed to the development of this synthesis. One consisted largely of Jesuit mathematicians, Christoph Scheiner, Francisco Eschinardi, and Claude François Milliet Dechales, who were more concerned with natural philosophical questions such as the nature of an image than with sophisticated mathematics. The other were secular mathematicians, Francesco Bonaventura Cavalieri, James Gregory, Isaac Barrow, and Isaac Newton, who applied limit methods to determining the place of an image, i.e., the focal point or point of concourse.[12] Cavalieri and, above all, Christiaan Huygens were unusual

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[11] Kepler (1611), §§104-105, pp. 53-55.

[12] Cavalieri, strictly speaking, was not secular, as he was a member of the Jesuati (not Jesuit) order, but he was a disciple of Galileo and a supporter of modern philosophy. He was also a superior order of mathematician compared to the Jesuits.

in not at all considering the place of the image and treating geometrical optics as just that, geometry.

The Jesuits' engagement with Kepler's optics and problems of imagery began with Christoph Scheiner, who is best known for his investigations of sunspots. His *Oculus, hoc est: Fundamentum opticum* (1619), is devoted to the eye and vision, and its exposition of Kepler's theory of vision was a major source in diffusing Kepler's concept of the retinal image and explanation of the camera obscura. While his experimental investigations contributed significantly to ophthalmology, his discussion of imagery was non-mathematical. He was concerned with trying to understand the nature of Kepler's *pictura*, which had no place in traditional optics, and he accepted that it was "real" and differed from a perceived image. Although Scheiner offered no new insights into the nature of optical images, he drew attention to Keplere's new kind of image. His *Rosa ursina* (1626-30) was devoted to sunspots and techniques of observing them but also treated the telescope and vision. Scheiner recounted his technique of using a telescope and camera obscura to observe and record sunspots, but this work too did not advance understanding of the nature of an image. His report of his experiment in which an image of the external world was observed on the retina of an excised eye of an ox and other animals became justly famous and was often repeated.[13] Scheiner's works were widely cited but largely for his observations and practical optics. Only in mid century did optical theory of imagery develop.

In 1647 Cavalieri took the first significant step beyond Kepler in analyzing the focal properties of spherical surfaces and lenses in his *Exercitationes geometricae sex*. He begins the section "On the Foci of Lenses" by observing that whereas conic sections have precise foci, spherical lenses, as Kepler showed, possess a focus only to a very close approximation, and he extended Kepler's term "focus" from conics to spherical lenses, introducing the modern usage.[14] He then succeeded in deriving a general rule for the focal point for all varieties of lenses, by assuming, as Kepler did, thin lenses and the small-angle approximation. Cavalieri derived these results by means of single paraxial rays – not pencils – very much like a modern elementary textbook. The absence of any reference to the concept of images is striking, and we must conclude that Cavalieri was studiously avoiding this philosophical issue and treating the question of the concourse of rays mathematically. His work marks the beginning of a serious effort to bring the theory of lenses, telescopes, and optical images under mathematical rule. Within a little over twenty years the task would be accomplished.

The Place of the Image Defined by Vision with a Single Eye

Four years after Cavalieri's work appeared, the mathematician Gilles Personne de Roberval edited and posthumously published Marin Mersenne's *L'optique, et la catoptrique* (1651). The last part of the book was written by Roberval, who here took up Kepler's idea that the eye judged the place of an image with a single eye by means of a distance-measuring triangle. Kepler, as we have seen, did not adopt this method for locating the image, which he thought was a psychological problem, not a geometrical one. Although Roberval did not publish a diagram to illustrate this concept, we

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[13] Scheiner (1626-30), 100.

[14] Cavalieri (1647), 458. The section "De perspicillorum focis" (pp. 458-95), consisting of Props. VII-XIX of "Exercitatio sexta. De quibusdam propositionibus miscellaneis," is on optics.

can use James Gregory's for he adopted the identical principle (Figure 9). Given a point on an object, a mirror, and an eye with a "sensible magnitude," it is necessary to find the point of reflection corresponding to two different points on the eye. When the two points are found and the reflected rays are extended back, their point of intersection will be the apparent place of the image.[15] If the rays do not meet in a point, the image will be confused. The problem of finding the point of reflection, which Roberval simply assumes to be solved, is a very difficult one, known as Alhazen's problem. Roberval also discusses the place of a projected or real image or *pictura*, though without any special terminology for it. He explains its formation and says that when viewed the same rule applies to its apparent place as already explained, since it is the same as viewing an object.[16] His entire account of mirror images is descriptive or non-mathematical although carefully set forth. Henceforth determining the place of the image by means of a single eye would be widely adopted, for it assigned a geometrical rule to replace the discredited cathetus rule for determining the place of an *imago*.

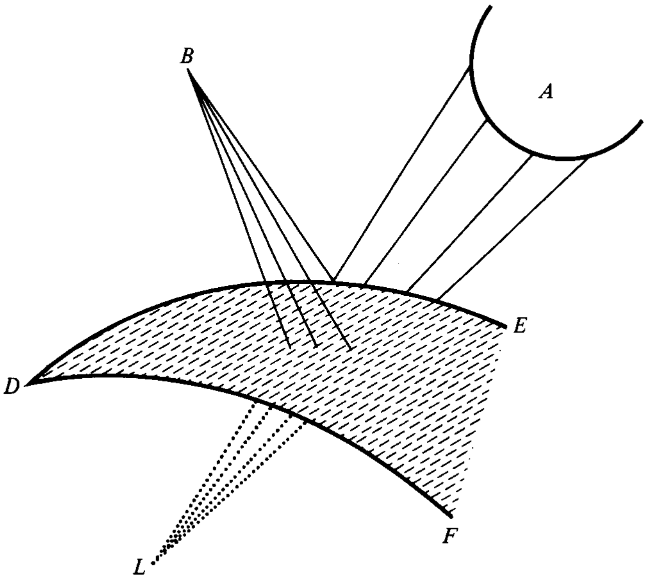

Figure 9: *An image seen with one eye is judged to be at the point of intersection of a pencil of reflected rays; after Gregory,* Optica promota.

James Gregory in 1663 in his *Optica promota* further pursed the problem of image location, though there is no evidence that he knew Mersenne's work with Roberval's ideas. Kepler would suffice as common source. Gregory introduced the concept of a pencil of rays for determining the place of the image with one eye. He asserted that the place of the image seen with one eye is judged to be at the point of intersection of a pencil of reflected or refracted rays, and thus he unambiguously identified what I have called the perceived and geometrical images. In Proposition 36 – given the positions of a surface, a visible point, and an eye, to determine the place of the image

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[15] Mersenne (1651) in Niceron (1652); see Lenoble (1957).
[16] Mersenne (1651), Prop. 13, pp. 119-120.

– Gregory applies this principle of image location to vision by reflection and refraction. Gregory's solution to this problem (Figure 9) for a mirror *DEF* is straightforward:

> From the points of the pupil [*A*], draw through the points of reflection all the lines of reflection, in whose concourse *L* (provided they concur) will be the apparent place of the image of the point *B*. If, however, they do not concur in one point, no distinct and fixed place of the image of the visible point *B* will exist.[17]

Although Gregory transformed Kepler's rule to one of geometrical optics, he did not adopt Kepler's concept of an image point as the limit of intersecting rays, for in this case he considered the image "indistinct" and "indeterminate." Rather, Gregory restricted himself to the perfect imagery of conics and could not exploit his rule for image location to obtain further results. As I will show shortly, that task was taken up by Barrow. It is quite likely that he took this path independently of Gregory, since Barrow, like all participants in my story, was thoroughly familiar with Kepler's optical writings.

Francisco Eschinardi, a Jesuit mathematician who taught at the Collegio Romano, played a significant role in developing the modern concept of the optical image, that is, in uniting the concepts of *imago* and *pictura*, or imaginary and real images. Indeed, he very nearly introduced that terminology in 1666 and 1668 with *Dialogus opticus* and *Centuria problematum opticorum*, *in qua praecipuae difficultates catoptricae, & dioptricae, demonstrativè solvuntur (A Hundred Optical Problems in which the Principle Difficulties of Catoptrics and Dioptrics Are Solved Demonstratively)*, which cover a broad range of optical topics, such as general principles, vision, lenses, and telescopes. In Prolegomena 5 to the *Centuria* (1666) which treats the distance of the focus from convex lenses, he considers the case of a plano-convex lens when the object is closer than the diameter of the lens. In this case the rays do not converge, yet there is a new focus, which he calls an "imaginary focus": "When we therefore say an imaginary focus, we understand a point in which we imagine two real and true rays to converge, but which are not truly produced to such a concourse, but if they were produced, they would concur there [...]."[18] It is important to note that the term focus then had a different meaning than today. It then meant that point at which rays from a single point of the object intersected; we now call this an "image point." Eschinardi called the locus of points of all the foci from every point of the object the "total focus" or the "image" or "distinct base." It was then quite natural for him to extend his new terminology to the entire image. In discussing the image in a plane mirror he says the image "is not real, but fictitious and merely imaginary."[19] Eschinardi has thus introduced the terms "real" and "imaginary" or "fictitious images," with their modern meaning. The term "virtual image" would be introduced a few years later by Dechales.

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[17] Gregory (1663), 46-47.

[18] Eschinardi (1666-68), vol. 1, 30, 31; volume 1 contains the first 51 problems and volume 2, which has a separate title page, *Centuriae opticae pars altera, seu dialogi optici pars tertia in quae [...]*, contains the other 49. In 1668 Eschinardi began the second volume with a series of definitions and formally introduced these terms, p. 2: "19. Focus, one true and real and the other fictitious and imaginary. The first is the true and real concourse, or angle, in which the visual lines truly and really intersect or concur. The second is that in which they do not truly intersect or concur or make an angle, but they would make it, if the said straight lines were imagined to be produced further towards that part."

[19] Eschinardi (1666-68), vol. 1, p. 103. It should be noted that here, and occasionally elsewhere, Eschinardi uses the phrase *idola seu imagine* (apparition or image), as Kepler did.

Eschinardi's analysis of the concept of image continued with his discussion of the place of the image. He recognizes that the apparent place of the object is determined by the understanding (*intellectus*), or that the place of the perceived image is a psychological problem. Nonetheless, he declares that unless other causes enter, geometrical optics determines that the object is always judged to be in that place to which the rays entering the eye tend. That place is determined by two rays drawn from the surface of the eye that form a cone at a point of the object, which is exactly the approach of Roberval and then Gregory.[20] Eschinardi then proceeds to draw a significant consequence from determining the place of the image with a single eye, namely, the optical equivalence of object and image, that is, an image propagates rays to the eye just like an object. "This principle," he declares, "leads to the perfect understanding of the combination of lenses." We can determine how far the image is from the objective and from the ocular lenses and so predict the appearance of the object to the eye. He insists that the rays that travel from the image to the eye after passing through lenses and being refracted or deflected several times are a perfect representation of the object. "It will be nothing but a question of a name whether or not it is called an image (*imago*), for it is certain from experience (*experientia*) that when received on a chart, it artfully represents all the lines and colors of the objects with a similar proportion." This principle is fundamental to geometrical optics, and we all learn it in elementary optics. After the image in the first surface or lens in a system is determined, it is then treated as if it were an object for the second surface or lens and so on. The arduous alternative that Kepler used in his path-breaking determination in the *Paralipomena* of the *pictura* in a sphere was to calculate the path of each ray through the sphere. Eschinardi justifies the principle by telling us that "in the use of telescopes this surprising principle fulfills its usefulness, which we owe especially to Giovanni Campani."[21] Moreover, this principle applies not only to real but also to fictitious and imaginary images, and the rules of geometrical optics applies to both sorts of image.

The importance of the optical equivalence of image and object can be seen from the priority dispute between Eschinardi and French savants. The circumstances of the dispute are unclear, but Huygens was undoubtedly involved, since Eschinardi's "Response to objections transmitted from France" was found among his papers. The third objection, as summarized by Eschinardi, was that "James Gregory's *Optica promota* must be cited." He notes that he cited and praised Gregory as necessary in the *Centuria*, which is true, though whether he should have cited him even more is not my concern. He was apparently on good terms with Gregory, who is thanked in the *Centuria* for sending him a manuscript.[22] Nonetheless, he refuses to acknowledge Gregory as the inventor of the principle of the optical equivalence of image and object. He refers to passages stating this principle in his *Microcosmi physicomathematici,* which was published anonymously in 1658, five years before Gregory, and which he quoted in the *Centuria.*[23] Huygens was undoubtedly involved in this critique, since there are some very brief notes critical of Eschinardi amongst his papers, though not dealing with this principle, and he had a copy of Eschinardi's reply. Huygens had

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[20] Eschinardi (1666-68), vol. 1, 72-73.

[21] Eschinardi (1666-68), vol. 1, 101-102.

[22] Huygens (1888-1950), vol. 6, 324-325, "Responsio ad objectiones transmissas ex Gallia," [1668?]. Eschinardi acknowledges Gregory work and his manuscript in Eschinardi *(*1666-68), vol. 1, 25.

[23] He wrote, "on page 84 are these precise words, 'Note, however, that the image or apparition is like the object, as if it emitted species, etc.' and page 85 'The image must be considered as if it were the object';" Eschinardi *(*1666-68), vol. 1, 102. Eschinardi is referring to Eschinardi *(*1658), which I have not yet seen.

assumed the equivalence of object and image without stating it as a principle since he began his *Dioptrica* in 1653. The equivalence principle is incorporated in his language. He often uses the term *visibilia* without distinguishing between image and object, though this will not be apparent to readers of the French translation in the *Oeuvres* which sometimes translate *visibilia* as image and other times as object.[24] In medieval optics the term was used for an object, a usage also adopted by Kepler. But before I turn to Huygens, I wish briefly to treat Dechales who wraps up one part of this tale.

Dechales' *Cursus seu mundus mathematicus* (1674) was a popular three-volume, compendium of all of the mathematical sciences, and a second edition in four volumes appeared in 1690. The *Cursus* is a rather derivative work and does not adopt novel approaches, but it is clear and comprehensive. Even with all the authors that Dechales does cite, I find the omission of Cavalieri, Gregory, and his fellow Jesuit Eschinardi striking, for he seems dependent on all of them. The optical sections of the *Cursus* represent a competent summary of contemporary geometrical optics, but it does not enter into the more rigorous territory charted by Barrow five years earlier. Dechales treats imagery in his section on catoptrics, but does not introduce any unique terminology to distinguish real and virtual images. It is only in the following section on dioptrics that he introduces new terminology, apparently adapting Eschinardi's "fictitious" and "imaginary" focus and image. In describing refraction in a meniscus lens he introduces the term "virtual focus," and explains in a corollary that, "It must also be noted why I call point *K* virtual focus (*focum virtuale*), namely, all the divergent rays proceed as if they came from point *K*."[25] Later in this book he nicely ties together the new terminology and the projected image, or Kepler's *pictura*. Prop. 56 states that "All convex lenses depict an image of the object in an inverted position at the distance of its focus, and concave lenses a virtual image also at the distance of its focus but not inverted." He then explains that a convex lens has a "true and real focus" and at that distance an image can be seen on a chart. In a corollary he states that "In a concave lens the image is only virtual just as the focus is only virtual, that is because the rays belonging to the same part of a remote object are not united, but after the lens diverge, so that they proceed as if from the same point of the focus."[26] We have now have "virtual images" rather than "fictitious" and "imaginary" ones to complement "real images." Dechales' *Cursus* was a popular work, and William Molyneux adopted Dechales' terminology and introduced it into English in his *Dioptrica Nova* in 1692.[27] The distinction that the Jesuits Eschinardi and Dechales introduced was not simply terminological but added physical meaning to the concept of image. In contrast, the secular and sophisticated rigorous mathematicians such as Barrow and Huygens completely ignored the distinction. Before I explain why I think this happened, let me briefly explain their approach, for they contributed enormously to the theory of optical imagery.

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[24] See, for example, Huygens (1888-1950), vol. 13, i, 185, 207, 221, 265.

[25] Dechales (1674), Tractatus XXI, Bk. I, Prop. 27, Corol. 3, vol. 2, p. 635.

[26] Dechales (1674), Tractatus XXI, Bk. I, Prop. 56, vol. 2, pp. 651-652.

[27] It is interesting to observe that Eschinardi's approach to the concept of images was not taken up by his confreres, Honoré Fabri (1667), or Andreas Tacquet (1669).

The Mathematical Tradition

Huygens began his *Dioptrica* in 1653 and continued to add to it throughout his lifetime, but it was published only posthumously in 1703.[28] It is a far more sophisticated and comprehensive work than any of his predecessors and contemporaries, with the exception of Barrow's *Optical Lectures*. Huygens uses limit arguments with pencils of incident rays to determine the points of concourse or foci of single surfaces and lenses without making any formal distinction between real and imaginary images other than considering whether rays diverge, converge, or are parallel. Thus, Huygens developed the method that Kepler had applied to *pictura* alone and applied it to any image. With his general mathematical approach he was able to derive a general solution to the image in any lens. Huygens also distinguishes himself from his contemporaries by not at all invoking an eye, except when it is an integral part of the problem such as in determining the apparent size of an image, and also by not at all considering the place of the image, which he considered to be a psychological and not a geometrical problem. Since Huygens procrastinated in publishing his *Dioptrica*, Barrow deprived him of priority on many of his contributions.

Barrow's principal achievement in his *Optical Lectures* (1669) was to determine the location of the image after *any* reflection or refraction in plane and spherical surfaces, and he thereby created the mathematical foundation of a comprehensive theory of optical imagery and began the exact study of astigmatism and caustics. His starting point was the principle of image location that was becoming widely adopted by the 1660s: An image is located at the place from which the rays entering a single eye diverge.[29] Indeed, because of Barrow's fruitful application of this principle in his influential book, in the late seventeenth and eighteenth centuries it was generally attributed to him. Since Barrow, unlike most 17th-century optical writers with the exception of Cavalieri and Huygens, was not generally concerned about perfect images, where all the rays diverge from a point exactly, but with refraction at planes and spheres, he adopted Kepler's approach and considered the image point to be the limit of intersections of neighboring rays. Barrow's achievement was to convert these two ideas into a mathematical theory, that is, to apply to Kepler's *imago* the limit approach with pencils of rays that Kepler had applied to *pictura* alone. The first step for Barrow in locating the image is to determine the reflected or refracted ray that passes from the visible point through the center of the eye when the position of each is given, which generates Alhazen's problem. For his next step, to determine where on the principal ray the image of the point is located, he finds the intersections of the principal ray with those rays that are infinitely close to it and enter the pupil of the eye. With exhaustive rigor he then demonstrates that the closer the rays are to this principal ray the nearer their intersection falls to a limit point, which is his strict definition of the image point. This approach is consistently followed for reflection and refraction at plane and spherical surfaces.

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[28] The *Dioptrica* is included in Huygens (1888-1950), vol. 13 and was first published in Huygens (1703).

[29] Barrow's formulation of the principle is: "a visible point appears to be located on that ray which proceeds from it (directly or by inflection) and passes through the center of the eye, and consequently the location of objects is judged from the position of rays so passing," Barrow (1669), III:1, p. 36; "inflection" is his inclusive term for both reflection and refraction. The *Lectures* is included in Barrow (1860), and has been translated into English, *Barrow* (1987). For a thorough account of Barrow's *Optical Lectures* see Shapiro (1990).

Barrow tells us that he only treated "that part of optics which is more properly mathematical," so that he omits applied optics and such topics as the eye and vision, and the telescope and microscope, which were among the principal areas of seventeenth-century optics. Indeed, this lack of concern for applied optics probably led him to his pioneering, general investigation of rays at arbitrary angles of incidence, which are of little interest for microscopes and telescopes where the rays are nearly all incident at small angles to the optical axis. His solution for the image point in lenses was the first published general solution, but it was clumsy and not at all physical or intuitive. He has no ray diagrams, but rather geometrical constructions. He explains that the conclusions of the preceding lectures can be applied to finding the image for any number of surfaces simply by treating the image resulting from the preceding surface as if it were a real object or radiant point with respect to the following surface.[30] This, of course was the principle for which Eschinardi was defending his priority against the French. Barrow's solutions for various lenses are classified according as the rays are convergent or divergent, and no mention is made of real or virtual images or projected images. He also appended his young protégé's – Isaac Newton – graphical solution for the focal point of any lens for any case, which is more general and neater, but it too is not at all intuitive and lacks rays, but rather has construction lines. Likewise, no mention is made of or virtual, real, or projected images.

Why did sophisticated mathematicians, such as Huygens, Gregory, Barrow, and Newton, ignore the distinction between real and virtual images? Moreover, is that distinction particularly significant, since they were able to make substantial progress in geometrical optics without invoking it? It is certainly not the case that they did not use or understand real, projected images. The camera obscura was an essential experimental component in Newton's development of his theory of color, and Huygens used it for observing eclipses. They distinguished between the two sorts of image mathematically, according to whether the rays were convergent and divergent. One could equally well argue – as I am inclined to do – that the concepts of real and virtual images were quite fruitful, since they were quickly adopted by the scientific community shortly after they were introduced and have been standard concepts ever since. It should be apparent that by the 1660s the nature of optical imagery, especially the mathematical aspects, was much better understood than at the beginning of the century. This is especially true for refraction. Before Kepler there was no mathematical theory of lenses and their combinations. Not only were the focal properties of lenses and combinations of lenses and such recondite topics as astigmatism and caustics now understood, but such important physical principles as the equivalence of object and image were recognized. Moreover, Barrow had reformulated catoptrics without the cathetus rule.

Let me return to my initial question: Why did our sophisticated mathematicians ignore the distinction between real and virtual images? The answer I suggest is their adherence to the new or mechanical philosophy. Descartes rejected the species of the scholastics – "all those small images flitting through the air, called *intentional species,* which worry the imagination of Philosophers so much" – and insisted that images in our brain do not resemble the external world.[31] In his philosophy it is the sensation or appearance that is the natural philosopher's concern. In his *Dioptrique* (1637) Descartes uses the terms *image* and *peinture* – corresponding to Kepler's *imago* and *pictura* – indifferently. He calls the image cast on the retina and in a camera obscura both an

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[30] Barrow, (1669), XIV.1.

[31] Descartes (1965), Discourse 1, p. 68; Descartes (1964-73), vol. 6, 85.

image and a *peinture*; he also uses *peinture* for the motion "transmitted into our head"; and he even talks about this *peinture* passing through the arteries.[32] Clearly this is not a "picture" in Kepler's sense, or any sense, other than as a "representation." Descartes altogether ignored the distinction between real and virtual images. What mattered to him was the image in our eye, the appearance. He likewise rejected the Scholastic distinction between real and apparent colors, i.e., between the permanent colors of bodies and radiant colors like those in the rainbow or prism:

> And I cannot approve the distinction made by the philosophers when they say that there are some true colors, and others which are only false or apparent. For because the entire true nature of colors consists only in their appearance, it seems to me to be a contradiction to say that they are false, and that they appear.[33]

I would argue that as modern natural philosophers, Huygens, Gregory, Barrow, and Newton, considered the image in the eye as primary, and in this respect all images were the same. It was the job of the mathematician to describe the path that rays traverse until they arrive in the eye. It turned out that some sorts of rays diverge from a focus and others converge, but that was not for them a fundamental distinction. Huygens use of the term *visibilia* for both image and object shows that the principal object of study for the moderns was the appearance in the eye. The Jesuit mathematical philosophers were not Cartesians or modern philosophers and were, since Scheiner, much more concerned with the nature and reality of images, like Kepler himself. For them, unlike the modern mathematicians, it was a pressing problem of natural philosophy to understand the difference between an *imago* and *pictura*.

I cannot end my paper without commenting on one aspect of this history that seems to go against the grain of the conventional view, namely, the role of the eye in analyzing vision in early modern science. We are told that an eye with a perceiver was necessary for vision in medieval optics, whereas Kepler treated the eye as an optical instrument, "in fact as a dead eye," and introduced an image, the *pictura*, that really existed without any active powers but only a "dead" eye.[34] We have seen, however, that vision with a single eye that judged the place of the image played an essential role in the formation of the modern theory of imagery, so that the eye was not so quickly banished from the perception of images. While I readily admit that this is far from a medieval account of vision, it is not quite a modern analysis of vision by geometrical diagrams that contain only lenses and mirrors and object and image. Kepler explained vision by means of the *pictura* on the retina and assigned to judgment the role of projecting that *pictura* or image back

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[32] Descartes (1965), Discourse 6, p. 101; Descartes (1964-73), vol. 6, 130. In Discours 5 "Of the retinal images that form in the back of the eye," he uses image in the title and, in the first paragraph, for the image cast in a camera obscura. From thence he uses *peinture* just as Kepler about a dozen times until he returns to *image*. Antoni Malet (2005), 254, is simply mistaken when he writes that Descartes "discarded the word 'picture,' while calling pictures consistently images".

[33] Descartes (1965), Discourse 8, p. 338; Descartes (1964-73), vol. 6, 335.

[34] See Crombie (1967), and Smith (2005). Crombie's thesis is sensitively stated and some brief extracts from pp. 54-55 will make his position clearer. He explains that Kepler decided "to restrict the analysis of vision simply to discovering how the eye operates as an optical instrument like any other, in fact as a dead eye. [...] he demonstrated the physiological mechanism of the eye conceived, as far as the retina as a screen receiving images, as part of the same dead world as the physical light that entered it. He banished from this passive mechanism any active power to look at an object, and solved the optical problem of how it forms an image by a new geometrical construction [...]"

into the external world. For Kepler the place of the image was a psychological one. He largely abandoned mathematical theory here, but his successors tried to restore a mathematical theory for the place of the *imago*. Mersenne in defining an image in his *L'optique* introduced two kinds of image to resolve this dichotomy. The "interior or sensible" image is formed on the principal tunic of the eye, i.e., the retina. This is Kepler's *pictura*. The other sort of image, "which we will call exterior or apparent, is that which our fantasy represents to us some place outside either near or far from us, as if the object were in that place, from which it sends its rays to us to form the interior image, although that object is often far removed from this place."[35] Although Mersenne's terminology was not adopted, his exterior image would become the place of the virtual or real image as first proposed by Roberval a few pages later.

I will conclude with one final question. Why in mid-century did nearly everyone introduce an eye for image location, when Huygens did not need it? Since these images, i.e., virtual images, could *only* be perceived by an eye, they naturally utilized an eye to locate it. There were no luminous points to define it as with a *pictura*. Only after this concept of image location was developed did they recognize that it defined a virtual luminous point (focus) with rays emanating from it and that it could be treated exactly like a *pictura* or real image. Huygens leapt past this phase of analysis with an eye and directly recognized the existence of a virtual focus, even if he did not name it. This intermediate phase in the history of geometrical optics between Kepler and modern theory has been overlooked by historians.

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[35] Mersenne (1651), 98.

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"Res Aspectabilis Cujus Forma Luminis Beneficio per Foramen Transparet" – Simulachrum, Species, Forma, Imago: *What was Transported by Light through the Pinhole?*

Isabelle Pantin

In Kepler's *Optics*, at the end of the first chapter ("on the nature of light"), there is an appendix which recapitulates (and refutes) all Aristotle's theses in *De anima* II, 7: light is an incorporeal state of the medium, the activity of transparency,[1] involving no temporal process and no local movement (but only motion in the sense of qualitative change); color, the proper object of sight, produces, in the actually transparent medium, further qualitative change which affects the observer, and so on. These theses, Kepler says, are in complete contradiction with the principles of the *Optici* (Alhazen and Witelo), already expounded in chapter I – and this statement is in itself remarkable for, at the beginning of the seventeenth century, the Aristotelian and the 'perspectivist' conceptions of light and vision were usually presented as perfectly compatible (this is the case in Acquapendente's *De visione* and in Aguilonius's *Optica*). As a conclusion, Kepler invites the *Academici*, to refer to his description and explanation of the *camera obscura* in chapter II before attempting to refute his arguments. Indeed, he says, the *camera* has been the only thing that Aristotle lacked (*quæ sola Aristotelis defuit*, GW II, 46). Otherwise, probably, he would have conceived a different theory. Here, Kepler does not take into account the demonstration in the pseudo-Aristotelian *Problemata*.[2]

This remark has important implications. First, it confirms the logical construction and continuity of Kepler's book: chapter two (on the *camera obscura*, or, more exactly on the capacity of light to transmit and project forms and figures, "De figuratione lucis") is closely linked to chapter one (on the nature of light), as well as to the analysis of vision in chapter five. Moreover, it indicates that Kepler was not interested in the *camera obscura* for mere astronomical motives. These astronomical motives were of prime importance, as Straker has shown: Kepler eagerly wanted a precise and reliable instrument for the observation and measurement of eclipses, in order to obtain better evaluations of the distances and dimensions of the sun and the moon;[3] hence the necessity to explain why the image of the moon, during solar eclipses, appears significantly diminished on the screen. The great Tycho himself, too confident in the reliability of the *camera obscura*, had thus been led to stupendous error.[4] However, philosophical motives were also at stake.

Kepler certainly remembered that from the beginning (at least from Al Kindi's *De aspectibus*) pinhole images had been introduced in order to prove the rectilinear propagation of light, and the fact that rays and colours are not intermingled when they intersect.[5] However, he also knew that the *Optici* had failed in their description and analysis of the phenomenon: his own demonstration

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[1] Light actualizes the transparency that the medium possesses in potency.

[2] Pseudo-Aristotle, *Problemata* XV, 6: why a sunbeam, passing through a rectangular aperture give an image sensibly round.

[3] This was also a major preoccupation of his master, Michael Maestlin.

[4] Kepler. 1604. GW II, p. 48.

begins with a severe criticism of his predecessors's method when they had faced the problem of round images of circular bodies projected through angular apertures. Witelo and John Pecham are specially examined. Kepler probably did not know Roger Bacon's *Opus majus* and *De multiplicatione specierum*, never mentioned in the *Optics*.[6]

According to Kepler, the main cause of the failure is that the *Optici* themselves had been unfaithful to their own principles. Instead of following a purely geometrical method, that would have led them to the true causes of the phenomena observed on the screen, they had turned to indefinite and undemonstrated philosophical concepts. Witelo[7] had vaguely recalled the proposition that rays issuing from distant sources tend to become parallels,[8] and eventually taken refuge in the idea of the mysterious nature of light, where he had been rejoined by Pecham (whom Kepler calls "Pisanus" after Georg Hartmann, the editor of the *Perspectiva communis*).[9] Pecham was inexcusable because he had received hints of the real causes : the circularity of the distant body (the sun, in the case under examination), and the intersection of the rays.[10] However, Pecham's attempted demonstration had failed.[11] He had concluded that *per modum igitur radiositatis* (that is, via the geometrical method treating rays as straight lines) *impossibile est causam rotunditatis perfecte reperire*; and he had resorted to the reaffirmation of light's natural inclination towards circularity.[12]

In Kepler's eyes, the *camera obscura* offered one of these precious problems that proved the necessity and the fecundity of rigorous mathematical demonstration because they were neither too easy nor too difficult. It showed the disastrous effects of the habit of simultaneously relying on arguments of different orders, that had been the constant plague of optical theory. Moreover, the *camera*, as experimental apparatus, possessed exceptional demonstrative potentialities.

Traditional optics had always been centred on the problem of human vision and perception, and considered this vision to be an entirely intentional process.[13] In other words, the entire theory was characterised by its marked finalism. All that happened in the transparent media was described in the manner that best permitted to understand its principal result: the formation of images and concepts in the mind. The medieval theory of *species*, still predominant at the beginning of the seventeenth century, made possible to conceive continuous chains of analogous

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[5] The experiment of the candle placed before an aperture behind which is a screen is reported in the *De aspectibus* (translated by Gerard of Cremona in the twelfth century). In Alhazen's *Optica* (1572, I, 29, p. 17), this experiment becomes more complex: several candles are placed in different positions before the apertures, and their projected images prove perfectly distinct.

[6] Of course, the pseudo Aristotelian *Problemata* are also examined (GW II, p. 47). The authenticity of the work is not questioned.

[7] Witelo (1572), II, pr. 39: « Omne lumen per foramina angularia incidens rotundatur »

[8] *Ibidem*, II, 35: « Radii ab uno puncto luminosi corporis procedentes, secundum linearum longitudinem ad aequidistantiam sensibilem plus accedunt ».

[9] "Vitellio [...] voluit id accidere propter nescio quam radiorum æquidistantiam [...] At defectum hujus suæ demonstrationis ipse non dissimulat, prop. 35 *forte*, inquiens, *ad istud multum cooperatur proprietas radiorum*. In his versans ambiguitatibus, ostendit se causam veram, quæ ex altera demonstrationis ejus parte obscure colligitur, non intellexisse./ Hunc secutus Johannes Pisanus [...] ipse se in latebras arcanæ lucis naturæ cum Vitellione recipit [...]" Kepler. 1604, p. 46-47.

[10] *Ibidem*, p. 47.

[11] Lindberg (1968) thus explains the failure: the aperture Pecham had chosen was too large.

[12] Cf Pecham. 1542, b3r.

[13] See Smith. 1981, p. 568-589.

– if not similar – entities (the *species*) between the objects of the exterior world and the innermost chambers of the brain.

This theory,[14] fully developed in the work of Roger Bacon (ca 1214-1294), took its inspiration from two main sources, which were closely linked: the neo-platonic metaphysics of emanation, which was expressed especially in a conception of light, and the geometry and physics of optics which had been elaborated upon first by the Greeks, then the Arabs, before returning to the West in the thirteenth century. According to this conception, an infinite number of rectilinear rays spherically emanate from every point of everything in the universe carrying the powers of what they radiate from. Thus, natural forces are propagated until they find an appropriate receiver in which they can express themselves. The term *species* designates that which emanates; its meaning is "aspect", "image" or "form", as well as "likeness". The agents that produce *species* are many: substances and qualities (heat, cold, humidity, dryness, light, odour, taste and sound, all *sensibilia propria*).[15] Through the *species*, these agents seek to print their likeness on the receiver. In short, *species* are what allows natural agents to "multiply", although through a different sort of reproduction than that of physical generation, as it is carried out without material contact and by the simple activation of a certain potentiality already present in the receiver, and in the medium between agent and receiver.[16] The *species* are not transported but successively generated ("multiplied") in the medium, without discontinuity, but with a progressive attenuation.[17]

Kepler was not opposed to the *species* which play a crucial role in his conception of cosmic magnetism; but he saw that they gave ambiguity to optical theory, by being constantly used without discrimination. In his eyes, an impassable frontier existed between the domain of transparent or semi-transparent media, where light travelled according to the laws of geometry, and the dark regions of the body where sensations were elaborated under the law of *spiritus* which wandered among the humours. The *Optici* had been led to confusion because they had failed to see that they were only concerned with the first domain that did not extend beyond the "wall" of the retina.[18] In Acquapendente's *De visione* (Venice, Bolzetta, 1600), for example, several humours and membranes are simultaneously endowed with the optical properties of semi-transparent bodies, and with sensitive powers. As a consequence, it is impossible to determine the exact role of each of them in the process.[19]

This confusion was totally prejudicial. In fact, the *Optici* having no concern with sensation, would be better inspired to avoid the *species*, and content themselves with light and rays. In his *Optics*, Kepler employs the term *species* in the vague and common meaning of "image", "aspect", or "appearance", or when he refers to the propositions of Alhazen and Witelo. In his original demonstrations, he gives the word its full technical sense only in the cases where sensation is involved: especially that of remanent images.[20] For example, the user of the *camera obscura* must wait beforehand in penumbra, *quoad evanuerint species in clara diei luce spiritibus impressæ.*[21] In the *Dioptrice* the distinction is even clearer and more explicit. Its preface, that criticises Jean Pena's

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[14] See Lindberg. 1970; Lindberg. 1983; Lindberg. 1997; Spruit. 1995; Tachau. 1988; Tachau. 1997.

[15] Bacon, *De multiplicatione specierum* I, 2. In Lindberg. 1983, p. 32-41.

[16] *Ibidem* I, 3, p. 47-57.

[17] *Ibidem* I, 4.

[18] Kepler. 1604, GW II, p. 152: "Nam Opticorum armatura non procedit longius, quam ad hunc usque opacum parietem [...]".

[19] See notably III, 7, p. 100, 102; III, 8, p. 104.

De usu optices,[22] insists on the necessity of using appropriate terms: *expedit nos clarè loqui, nec aliud quam emissiones radiorum ex punctis lucentibus inculcare.*[23] And its conclusion is a description of the eye as an *instrumentum visorium*, traversed by rays of light. These rays, subject to intersection and refraction, eventually paint on the retina a *pictura* that afterwards becomes a *species immateriata.*[24]

Kepler's discriminative use of the term and notion of *species* was thus a means of avoiding confusion. The optical phenomena were to be treated with purely geometrical tools, in a spirit of objectivity. And that was easier when instruments, or technical apparatus, were considered, and not the human eye. The *camera obscura*, like the telescope some years later, could even help to view this human eye as a simple *instrumentum visorium.* It showed that light could picture images independently of sensation.

Kepler had two Jesuit followers who showed equal interest in optical apparatus and in the explanation of human vision: Franciscus Aguilonius and Christoph Scheiner. One can reasonably wonder what they had kept of this discriminative lesson, and in what measure it influenced their own manner of dealing with the *camera obscura.*

Apparently at least, Aguilonius put "vision" and "*camera obscura*" in quite different categories. The former is studied in the first four books of his *Optica,*[25] in the traditional 'concordist' manner that Kepler had sharply criticised. The only visible result of the aforesaid 'discriminative lesson' is that Aguilonius affirms that vision requires two principal organs, the one that receives the *species*, at the vertex of the 'visual pyramid' (it is called *centrum visus* and situated in the crystalline lens), and the one that perceives them: the *aranea tunica* which, in its posterior part, becomes the retina.[26] As one sees, the *species* are omnipresent, still provided with their characteristic Protean nature. For example, as they are spiritual, they can be both divisible, for they are based on material objects, and indivisible as representations, and because they end in a point at the centre of the eye.[27] Book II ("De radio optico") even confirms that luminous rays and spiritual *species* are regarded as almost equivalent. Optical rays are nothing else than fluxes of *species;*[28] more precisely, each *species* has its ray [...] that is to say, its pyramid.[29] Aguilonius never worries over verbal ambiguities or misleading synonymies: light carries representations of things that wear different

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[20] « Nam resident in visu *species* fortiorum colorum, post intuitum factum [...] Hæc *species* separabilis a præsentia rei visæ existens, non est in humoribus aut tunicis [...] : ergo in spiritibus et per hanc *impressionem specierum* in spiritus fit visio. Impressio vero ipsa non est optica, sed physica et admirabilis », Kepler. 1604, GW II, p. 152-3.

[21] *Ibidem*, p. 57 (II, 7).

[22] The *De usu optices* introduces Pena's translation of the *Optics* of Euclid (first edition, Paris, Wechel, 1557).

[23] Kepler. 1611, GW IV, p. 341.

[24] « Quæ igitur accidunt Instrumento <visorio> extra sedem sensus communis, ea per speciem immateriatam delapsam ab instrumento affecto seu picto, et traductam ad limina sensus communis illi sensui communi imprimuntur. Sed impressio hæc est occultæ rationis: nec tuto dici potest, speciem hanc intro ferri per meatus nervorum Opticorum, sese decussantium », *Ibidem*, p. 372.

[25] I. De organo, objecto, naturaque visus. II. De radio optico et horoptere. III. De communium objectorum cognitione. IV. De fallaciis aspectus.

[26] Aguilonius. 1613, I, 26-27, p. 26-27 ; see also I, 1, p. 3-6 (the anatomy of the human eye).

[27] « Quod de radiosa pyramide allatum fuit, id solum probat repræsentandi vi species indivisibiles esse. Quod ita est accipiendum, ut species, quæ ab objecto ad visum porriguntur, figuram pyramidis habere intelligantur, cujus quidem basis sit res ipsa oculo objecta, vertex autem puncto indivisibili terminetur. Hoc ergo punctum cum in centro visus existat », *Ibidem*, I, 43, p. 49.

[28] *Ibidem*, II, 1, p. 114.

names – images, forms, *simulachra*, *idola*, *species* or even *spectra* – *nihil interest, si modo id solum, quod rem repræsentat, intelligas.*[30]

These optical and philosophical principles are formulated in a complete theory, placed before the books that present their applications. The *camera obscura*, in particular, is somewhat unexpectedly relegated to the very last section of book V ("De luminoso et opaco"), as if its explanation could have shed no light on what precedes. As it happens, the first sections of book V deal with astronomical matters, notably the illumination of the moon and the problem of its spots, that provides an opportunity for mentioning Scheiner's recent observations of sunspots.[31] However, the *camera obscura* is not mentioned in this context, and figures only as a particular and separate question concerning light's pathway ("De trajectu lumine").

The section contains fifteen propositions (n° 85-99) dealing first with the form, dimensions, uniformity and intensity of illuminated spots projected from a point, or from a luminous body, through different apertures on screens situated at different distances and differently orientated. This prepares the resolution of the "Aristotelian problem" (in prop. 95-97), presented in a manner most probably influenced by Kepler. If Aguilonius had discovered the solution independently, as Ziggelaar[32] supposes, he would have found more easily the method expounded in Maurolico's *De photismi* (1611), because this method is more compatible with the 'geometry of the visual pyramid' to which Aguilonius was strongly attached. Maurolico figures a series of pyramids of which the base is on the luminous body, and the vertex on a point at the periphery of the aperture; by extension of the rays beyond the intersections, identical vertically-opposite pyramids are generated, that project on the screen innumerable inverted images of the base; but these images are so disposed that they transmit also the form of the aperture; hence the formation of a composite image that combines both forms.[33] In Kepler (followed by Aguilonius), the solution is equivalent but more conform to the true optical logic: infinite pyramids, issued from every point of the luminous body, project infinite images of the aperture; but these images are so disposed that they transmit also the form of the luminous body; the conclusion is identical.

The *camera obscura* proper is described in the last two propositions, that seem notably poor and almost insipid. The substantial part of the demonstration has been previously established, and it is sufficient to note that the image is inverted, that its luminous intensity is attenuated, and that its dimension depends on the distance of the screen.

The one interesting feature concerns the phrases. In almost the entire section, entitled "De trajectu lumine" as we have seen, Aguilonius effectively evokes the trajectory of light and rays. But as soon as the *camera obscura* appears, forms replace rays: *formæ externarum rerum, quæ solis splendor foris illustrat, in obscurum locum una cum lumine subeunt, objectaque charta, in ea velut propriis lineamentis expressæ conspiciuntur* (p. 451). Representation is at stake, therefore the discourse falls entirely under the rule of the *species*.

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[29] « [...] unius rei forma uno radio, et distinctarum rerum formæ distinctis radiis ad centrum visus perferuntur », *Ibidem*, II, 3, p. 115.

[30] « [...] non aliud quam rerum imaginem <lux> assumit, quam sive formam, sive simulachrum, sive idolum, sive speciem aut spectrum appelles, nihil interest, si modo id solum, quod rem repræsentat, intelligas », *Ibidem*, I, 69, p. 75.

[31] *Ibidem*, p. 421 A.

[32] Ziggelaar. 1983, p. 60.

[33] See Lindberg. 1984, p. 134-135.

Thus, in Aguilonius's eyes, the *camera obscura* was specifically an apparatus designed to capture forms, what Della Porta had already perfectly shown. The *camera* described in his *Magia naturalis*,[34] is, in some respects, a scientific instrument: it can serve as a model of the eye[35] and enables the observation of solar eclipses without ocular damage;[36] but it is, above all, a perfect theatre of marvels. According to Della Porta, it is easy to introduce in the chamber the moving simulacra of elephants, rhinoceroces and lions pursued by hunters,[37] and of atrocious fights – light throwing naked swords through the aperture to terrify the audience (*evaginati enses intro per foramen a lumine jaculantur, ut fere terrorem incutiant*).[38] Similar spectacles can even be realised during nocturnal feasts, by using torches and candles.[39] Moreover, it is possible to raise up ghost-like forms (*in cubiculi medio pendula videbitur imago cujusvis simulachri*), if some suspended cloth, invisible to the spectators, serves as a screen.[40]

Aguilonius never refers to the *Magia naturalis*, but in the section on colours, he condemns as sinful wizardry these very spectacles that delighted Della Porta. This occurs in a proposition establishing that the colours of the bodies soak themselves into the light emanating from these bodies, so that these colours, thus detached from the bodies, are transported, as if they were the said bodies' proper *hypostasis* (*ceu propria hypostasis decisos ab objectis vehit*, prop. I, 42). The first example of such fluxes (*exuviæ*) is taken from the *De natura rerum*. Aguilonius quotes the lines where Lucretius relates how coloured atoms, detached from the velum, fall on the spectators in the theatre and "infect" them.[41] From this theatre (and its fluxes of *species* and *simulacra*), Aguilonius comes to the next – the *camera obscura*, stressing the danger of this illusionist machine, in the hands of conjurers and pretended necromancers. These charlatans boast that they call up phantoms and demons, which is false; but it is true that the moving simulacrum of an accomplice, horribly attired, is "transfused" (*transfundi*) through the aperture fitted with a magnifying glass (as in Della Porta's descriptions).[42]

The *camera obscura* plays quite a different role in Scheiner's *Oculus* which carries out the project previously alluded to by Della Porta and approved by Kepler. In book III, Scheiner demonstrates the role of the retina by explaining the *camera*'s mode of operation. And this conclusive experiment has been prepared from the beginning of the book: in the chapters dealing with anatomical questions, the eye is already compared with a camera, carefully protected against light by the opacity of the uvea, choroids and sclera, so that the *camera oculi* is fitted for receiving the species.[43]

The choice of this mode of demonstration was obviously deliberate. Having borrowed from Kepler his principal innovations, Scheiner had perhaps wished to choose a different style, less mathematical and more experimental. But, above all, he was keenly concerned with the reliability of the *camera obscura* as an instrument of observation. By proving that it produced true images of

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[34] Della Porta. 1589. I have used the edition published in Hanover, 1619.
[35] Ed. cit., p. 547.
[36] *Ibidem*, p. 548.
[37] *Ibidem*, p. 547.
[38] *Ibidem*, p. 547.
[39] *Ibidem*, p. 548.
[40] *Ibidem*, p. 548.
[41] Aguilonius. 1613, p. 46.
[42] *Ibidem*, p. 47.
[43] Scheiner. 1619, p. 7.

the exterior world, he could obtain at least two valuable results. First he confirmed the soundness of the new theory of vision (that involved intersections and refractions of rays). And, conversely, he showed that the *camera obscura* was an eye, that is an instrument ideally suited for astronomical observation. I shall try to evoke briefly these points, that eventually make Scheiner's *Oculus* quite divergent from Kepler's *Optics*.

Scheiner clearly states that his first purpose is "to fix the seat of vision in retina". This is said in the title of the first part of book III (*Sedem visionis in Retina stabilit [...]*), and proudly repeated in chapter 6 of the same part: at last, thanks to the *camera*, the philosophers are able to observe, and almost "touch with their hands", the secrets of the eye which previously totally escaped them.[44] In chapter 26 of the same part (*Specierum erectarum applicatio ad oculum*), he develops the comparison of the eye with a *camera obscura*, in order to demonstrate how the images on the retina could be set upright.[45]

Thus, Scheiner had understood some essential points of the new Keplerian optics. He was quite familiar with its mode of demonstration, using cones that have their vertex on one point of the object, and their bases on the foramen,[46] even if he also employs Maurolico's vertically opposed pyramids, with their bases on the object and the projected image.[47] Occasionally, he even uses successively both schemas, and notes that they are equivalent (*seu quod idem est* [...]).[48] In the second (and last) part of book III (*De angulo visorio*) Scheiner goes so far as to admit that the *angulus visorius*, although indispensable, is nothing but a fiction.[49]

However, Scheiner was still attached to some traditional principles. For example, he has not completely got rid of Witelo's "radial pyramid", that suggests that the image passes through apertures as through a funnel;[50] and he still maintains that vision is achieved through the one principal ray, that has the power to impress the organ of sensation.[51]

This must be connected with his fidelity to the theory of *species*. In his eyes, light alone cannot project images. Thus, what is introduced in the camera is "with light, the true species of exterior things with their vivid colours".[52]

It is not gratuitous conservatism. As it rapidly appears, the *species* are the best guarantee of the reality of the images. In fact the question arises immediately after the description of the *camera*. Although the reliability of the instrument is attested by repeated experiments, it is necessary to ask whether the projected pictures are "something real? And if so, are they species? Or colour? Or pure light? Or the object itself?"[53]

The question is treated in due form, with the full development of *dubia* and responses, and the reality of the "apparitions" is eventually established.[54] They are not delusions produced by the

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[44] *Ibidem*, p. 137-138.

[45] *Ibidem*, L. III, part I, ch. 26 , p. 191-192.

[46] *Ibidem*, L. III, part 1, ch. 7, p. 140; L. III, part 1, ch. 9, p. 148.

[47] *Ibidem*, L. III, part 1, ch. 9, p. 147.

[48] L. III, part 1, ch. 22, p. 183-184.

[49] See especially ch. 3 (*Quid conferat anguli visorii inventio?*), p. 227.

[50] *Ibidem*, L. III, part 1, p. 134-135.

[51] *Ibidem*, L. II, part I, ch. 13, p. 73-74.

[52] *Ibidem*, L. III, part 1, ch. 2, p. 125. Cf p. 126.

[53] "[...] oriuntur nunc aliquot difficilia dubia: quorum primum est; An hæc phases verum quid & reale sit, An vero iis quæ in re non sunt, sed tantum apparent esse, sit adscribenda. Alterum, si reale quid est, quid sit? An species? An color? An mera lux? An ipsum objectum?", *Ibidem*, p. 128.

[54] "Picturam hanc inter ea, quibus res & veritas subsit, esse numerandam", *Ibidem*, III, part 1, ch. 3, p. 130.

imagination or a defect of vision, nor aerial spectres.[55] They are not pure light,[56] but something more substantial and more appropriate to sensation: they are *species*.[57] To perceive the object's *species* is almost to perceive the object itself.[58]

We see that one important result of Scheiner's demonstration is to confirm the existence of *species* ("*Discimus species visibilis dari.* In fact, what is painted on the screen is not nothing, but it is not itself the colour in the object, nor is it mere light"[59]) and their perfect conformity to the objects: they are divisible as the objects are, and each of their parts correspond to parts in the object (*Species in se divisibiles esse: et partem speciei partem objecti repræsentare*). In consequence, the astronomical observations realised with a *camera obscura*, are perhaps even more truthful than direct observations.[60]

Thus, Scheiner had read Kepler and understood him rather well, up to a certain point. But he certainly gave a biased interpretation of his ideas. This interpretation was linked to what I should call Scheiner's personal form of realism. To guarantee the truthfulness of representations, Scheiner still needed images that retained something of the substance of things. And pure light did not possess this something.

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[55] *Ibidem*, p. 130.

[56] *Ibidem*, L. III, part 1, ch. 4, p. 132.

[57] *Ibidem*, p. 132.

[58] "[...] veniendum est, ad dubitationem tertiam, & ostendendum Quomodo hoc experimentum fiat; ex eo enim cognito, modus fortassis aliquis invenietur, quo ostendatur in hoc casu rem ipsam, non speciem cerni.", *Ibidem*, p. 133.

[59] *Ibidem*, p. 137.

[60] *Ibidem*, L. III, part 1, ch. 4, p. 130. See also the experiment presented in III, part 1, ch. 8, p. 140 sqq.: if a Galilean telescope is adapted to the orifice the image of the sun (and of other illuminated objects) will be projected on the screen; with different apertures, the dimension of the solar disc remains the same, only the luminosity and colour varies etc.

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Clair & Distinct. Seventeenth-Century Conceptualizations of the Quality of Images

Fokko Jan Dijksterhuis

> I call a perception 'clear' when it is present and accessible to the attentive mind – just as we say we see something clearly when it is present to the eye's gaze and stimulates it with a sufficient degree of strength and accessibility. I call a perception 'distinct' if, as well as being clear, it is so sharply separated from all other perceptions that it contains within itself only what is clear.[1]

Descartes' concept of 'clear and distinct ideas' does not need an introduction here. Thanks to the goodness of God, we can be certain that the things we perceive clearly and distinctly are true. 'Clair et distinct' are visual metaphors and the visual context of the concept is clear from this definition. In *Principia* Descartes did not further discuss the optical meaning of clarity and distinctness. His very words do, however, raise questions: what is a sufficient degree of stimulation, and when is a perception sharply separated? Questions like these are the subject of this paper. When is an image clear and distinct and how does one know the degree of clarity and distinctness?

Distinct vision was standard topic in optics that Kepler put on a new track in his *Paralipomena* at the start of the seventeenth century. He problematized fuzziness in particular, and figured out how a pinhole image is exactly formed. The basic idea, which he then imposed upon mirrors, lenses and the eye, was that bundles of rays from point sources have to be brought into focus one way or another. This opened a line of sophisticated thinking on the conditions of the formation of distinct images, continued by the likes of Gregory and Barrow.[2]

Optics was a substantial element of Descartes' philosophy. He himself had high expectations of the possibilities of improving human perception by means of optical instruments.[3] (We may ask how 'clair et distinct' such telescopic images would be, how reliable human made pictures are in Descartes' view, but I will not embark on such philosophical issues.) In the course of the seventeenth century, the distinctness of images and vision was discussed in much detail, establishing a continuous line of investigation of authors reacting upon each other and elaborating theories further.

Clear vision on the other hand, did not develop into such a continuous line of investigation. This is remarkable, given that in Descartes' view clarity was even more basic than distinctness. Nevertheless, the topic was not studied systematically and did not become a pivotal issue in optics

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[1] Descartes [1647]. Part 1, paragraph 45. "J'appelle *claire* celle qui est présente et manifeste à un esprit attentif: de même que nous disons voir clairement les objets, lorsque, étant présents à nos yeux, ils agissent assez fort sur eux, et qu'ils sont disposés à les regarder; et distincte, celle qui est tellement précise et différente de toutes les autres, qu'elles ne comprend en soi que ce qui paraît manifestement à celui qui la considère comme il faut." Translation: Descartes [1984-1991] 1, 207-8. This is an addition to the original paragraph in Descartes [1644]: "Quid sit perceptio clara, quid distincta. Ita, dum quis magnum aliquem sentit dolorem, clarissima quidem in eo est ista perceptio doloris, sed non semper est distincta; vulgò enim homines illam confundunt cum obscuro suo judicio de naturâ ejus, quod putant esse in parte dolente simile sensui doloris, quem solum clarè percipiunt. Atque ita potest esse clara perceptio, quae non sit distincta; non autem ulla distincta, nisi sit clara."

[2] Shapiro [1990].

[3] Descartes [1637] *Dioptrique* discours septième; Ribe [1997].

or otherwise. Clarity turned up at irregular intervals in divergent contexts. A case in question is the law of illumination. Before Bouguer and Lambert various proposals had been made, but many of these quickly disappeared from the historical radar.

Clarity *is* a tricky subject. The images projected by Carsten Wirth's 'camera' raise questions like why the colours in a camera obscura image appear so much more saturated than in our 'natural' views of the world. Several factors have been brought up: the nature of the lenses used, or of the mirrors; the diffusing qualities of the projecting screen; the fact that the normal glare is missing; and even the physiology of perception to the point of the difference between the way rods and cones operate in perceiving a picture. It might be the case that viewing a picture in a dark room simply alters our perception and activates different modes of perception, but the conclusion was that it is an extremely complicated matter.

All these aspects of clarity turned up in the seventeenth century as well, various people taking various lines of approach. Some considered illumination – or intensity – of light itself, like Kepler. Others looked at the nature of luminous objects, the effects of the path of light, the properties of vision, and so on. Likewise, as regards the lack of clarity of images, some emphasized the nature of light propagating, others the effects of the intervening medium, and still others the defects of the eyes, etc.

Clarity is and was a diffuse concept with diverse aspects. And these aspects were discussed in the seventeenth century, in various ways and in various problem context and often in a rather ad hoc manner. This makes 'clarity' a fascinating topic for discussing the conceptualisation of images. In this paper, I will not offer a (full) inventory of seventeenth-century ideas on clear images. Rather, I want to show the disparity of ideas and the way specific problem contexts shaped ideas of clarity, and in particular the role played by optical instruments.

Descartes' pair 'clair et distinct' raises its own difficulties. Whereas the meaning of 'distinct' is pretty univocal, 'clair' is a rather ambiguous term. In Latin, French, as well as English, it implies brightness as well as distinctness, thus being tied up with the other half of the pair. Allthough I focus in this paper on discussions of the amount of light, I will use 'clear' rather that 'bright' to maintain contemporary language.

This paper offers a few examples of the divergent manners the clarity of images was discussed by various kinds of seventeenth-century students of light and its effects. My main goal is to show the diversity of approaches and the way they were embedded in particular problem matters: natural philosophy, astronomy, physiology, instrumentation, painting. I will not try to be exhaustive in any way, leaving a more comprehensive treatment of seventeenth-century discussions of the quality of images for a later occasion.[4]

Artistic Prelude

Artists may not have been too concerned about the true nature of light or perception, but rather about truthfull representations of the world. As they painted they developed ideas about the clarity of images, in particular the effects of relative contrasts. An analysis of sixteenth- and seventeenth-century painting may reveal what ideas they developed, but goes beyond the scope of this paper,

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[4] I will not, for example discuss, optics writers like Beeckman, Barrow, Molyneux, Cherubin, or tests of the powers of perceptions in 'paragone' and the Hooke-Hevelius debate.

being confined to written sources. A glimpse of artistic conceptions of clarity is given by Samuel van Hoogstraten, a pupil of Rembrandt who wrote a comprehensive expositon of painting *Introduction to the (higher) school of painting, or the visible world*. The *Visible World* explained the art of conceiving and executing a picture. It was not so much aimed at instructing (future) painters – although Hoogstraten definitely had these in mind – but teaching lovers of art to judge the quality of a painting.

In the seventh book of the *Visible World*, Hoogstraten discussed the effects of illumination. The relative clarity ('klaerheit') of pictural objects was his primary interest, considering for example the light of a white cloud opposite the sun.[5] He tried to explain the order of clarity of various objects by proposing the sun's light to be hundred, its illuminating light ten, shadows in the open five, bright lights in a room four, and so on to dark holes being zero.[6] Hoogstraten was of the opinion that painters need only have phenomenological understanding of these things, but he had explained his gradation somewhat by comparing the lights casts over various distances in a shadowplay. The amount of light depended on the number of rays per area as was easily understood by comparing the shadows cast by objects at various distances from a light source.[7] A painter, however, should primarily be concerned with producing well composed and visually attractive pictures, as Hoogstraten explained in the next book of the *Visible World*. He should therefor refrain from making cacophonies of light and dark, and depict the elements of his painting relatively bright rather than naturally.[8]

Kepler, Aguilón and the Nature of Light

Allegedly, Kepler discovered the law of illumination. *Paralopemina*, chapter 1, proposition 9: the intensity of light is inversely proportional to the distance to its source.[9] One may wonder what is 'true' about Keplers law, given that it was a purely geometrical deduction from his concept of the nature of light. Light according to Kepler, is a surface expanding spherically from a point-source and thus "the ratio that holds between spherical surfaces, a larger to a smaller, in which the source of light is as a center, is the same as the ratio of strength or density of the rays of light in the smaller to that in the more spacious spherical surface: that is, inversely."[10] Kepler was of course following the perspectivist tradition of the multiplication of species, albeit interpreting the mathematics of light propagation in a physical way.

Keplers 'intuition' was followed by many in the seventeenth century. Mersenne, Huygens, to name only two, considered the amount of light to be inversely proportional to the distance to its source. Yet, as was the case with Kepler, the 'law' of illumination was hardly more than an aside, an obvious consequence of theory that wasn't further investigated. After all, it left a lot of questions open as it only regarded the spreading of light in space. Nothing was said about the effect of distance covered (by a single ray) or of the medium traversed.

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[5] Hoogstraten [1678] 258.

[6] Hoogstraten [1678] 267.

[7] Hoogstraten [1678] 261.

[8] Hoogstraten [1678] 306-308.

[9] Ariotti [1976] 334-336.

[10] Kepler [1604] 10; translation: Kepler [2000] 22.

Quite soon, Kepler was criticized by Aguilón. In the *Opticorum* (1613), he raised conceptual issues and introduced a different means of investigation. Aguilón too had a geometrical conception of (the propagation of) light – staying much closer to perspectivist tradition – but he gave the diffusion of light in space further thought and he added empirical leads obtained by means of a instrument.[11] The instrument is in one of the famous vignettes Rubens made for the *Opticorum.*

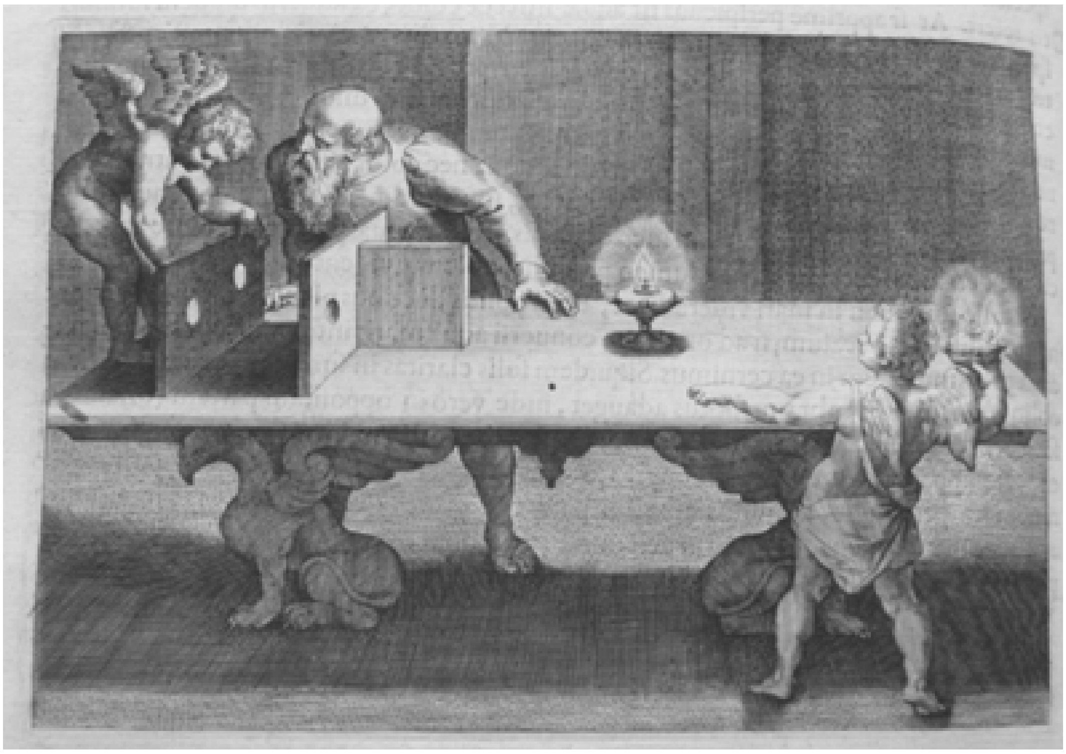

Figure: Aquilón's instrumental analysis of the intensity of light, as depicted by Rubens.

According to Aguilón the intensity of light does not diminish because it is spread out, but because it looses power while traversing through space. To substantiate his point, he erected a vertical board with two holes in front of a second vertical board. (prop. 6) Two light sources separated by a wall project bright spots on the second board. In the Rubens illustration a lamp with two wicks – and thus twice as strong – is placed at twice the distance of a single wick lamp. On the second board two equally bright spots appear, suggesting that intensity decreases proportionally with distance. Rubens' illustration does not accord with Aguilón's explanation, however. The text clearly states that the double light projects a brighter spot. Aguilón went on to determine the distance at which both lamps should be placed to produce equally bright spots. He then argued that the intensity decreased exponentially. Maybe Rubens did not agree with Aguilón's conclusions and simply drew what was correct in his view. Ziggelaar points out that the theoretical and empirical results are not fully consistent, partly because Aguilón did not distinguish absorption and spreading.[12]

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[11] Aguilón [1613] Book V, propositions 4-15.

Despite the popularity of the *Opticorum*, Aguilón's theory of light intensity was not adapted very much.[13] In particular mathematicians followed Kepler, if intensity was of interest at all. Although Aguilón's object of study was, like Kepler's, the nature of light, with his empirical investigation he introduced an element of perception. He did not raise the question whether and how we *perceive* lights with different intensity, but the perception of equal brightness was the basis of his empirical conclusions. After Kepler, perception and physics of light were gradually separated in the seventeenth century (to be brought together again in the nineteenth century).

Powers of the Eye

Besides being a philosophical theme, perception was the object of medical studies. Among these the *Ophthalmographia* (1632, 1648, 1659) of Plempius stands out. He not only introduced Kepler's theory of (retinal) image formation in ophthalmology, but with it a largely instrument infused approach to the analysis of the eye and its defects.[14] Plempius is known as a collaborator of Descartes, in the ocular dissections modelled after Scheiner's *Oculus*. Doctors had held on to Galen's concept of the visual ray until the seventeenth century and did not know perspectivist literature. Plempius' project was therefor even more fundamental than merely introducing a particular mathematical theory of vision into medical literature, he sought to link up mathematical and medical traditions.

In the pathological part of *Ophthalmographia*, Plempius discussed the effects of light and darkness on vision.[15] Comparing the eye with the camera obscura, he argued that the pupil should be properly widened to let in exactly enough light. Too much would overshine the image, too little would make it too faint to perceive. In a healthy eye the pupil automatically adapts to the surrounding amount of light, albeit somewhat slow when coming outdoors from a dark room. (People with bulging eyes see worse because more disturbing surrounding light can enter the eye.) In his discussion of day- and night-blindness, the difference between Plempius and other doctors is most clearly. Whereas it was traditionally argued with day-blindness the strong daylight dissipates the subtle visual spirits, Plempius said that the pupil was just too wide.[16] He argued, in the 'curationes', that a cure was difficult – except when dilatation was caused by living conditions like imprisonement – and warned for the customary diets and evacuations.[17]

With his detailed discussion of the subtleties of human vision, Plempius draws attention to the empirical problems of evaluating clarity of images. He did not discuss the nature of light and its relation to the perception of images. Doctors had a lot of knowledge of the nature and the conduct of the eye. They particularly understood that the eye is a flexible and highly adaptive instrument. It is an active instrument that establishes a full view of the world that turnes out to be very difficult to reproduce instrumentally. Moreover, they probably realized that the eye might not be a reliable instrument for judging the quality of images in any objective way. However, medical tracts were

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[12] Ziggelaar [1983] 88-89. 'Absorption' seems to be quite a misleading term in this context.

[13] Dechâles used Aguilón's instrument, albeit in another way. Dechâles [1674] 460. I will not discuss investigations of intensity in the context of the nature of light by Mersenne, Boulliau and the like.

[14] Vanagt [2006] 38-39.

[15] Plempius [1632] 166-167.

[16] Plempius [1632] 171.

[17] Plempius [1632] 224.

little read outside medical circles and others might highly overestimate the eye's capacities for comparing different intensities, let alone to determine absolute intensity. An important insight of Bouguer would be, a century later, that the eye may serve only reliably as a null-indicator.[18]

Instrumental Clarity

With Kepler, Aguilón on the one hand, and Plempius on the other, the topic of clarity has been reviewed in its physical and its physiological aspects. The perception of clear pictures and the clarity of light as it propagates from its source were largely detached topics. This even goes for the contribution of clarity to the production of distinct images. One place where these various aspects came together was the issue of telescopic images.

Quite some knowledge on the clarity of images developed along with the development of optical instruments in the seventeenth century. Galileo put aperture stops on his objective lenses to improve the images produced, and later on Huygens found out that putting a ring in the focal plane would even improve images more. This is interesting because it meant blocking a large part of the light, which appears to be crucial to forming clear images, actually enhances the quality of an image. It is an example of an instrumental way of finding things out. As a historian one can try to reconstruct such insights by studying artefacts – in the same way paintings are a source of knowledge – but seventeenth-century optical instruments are rare. We can also recourse to writings on instruments. I pick out Huygens, for he gave the most searching mathematical analysis of the quality of telescopic images.

Huygens' main problem was how large the opening of a telescope could be made to produce optimal images. A large opening increasing the clarity of the image but at the same time reduces its distinctness. In other words: clair et distinct are inverse proportional. The question then is, what exact proportion? In 1666, Huygens discussed the topic in detail.[19] His exposition is part of a series of dioptrical propositions related to spherical aberration, that formed the heart of the problem in his view: if the opening of a lens is widened, rays farther from the axis will pass; but these are refracted further from the focus, thus increasing the fuzziness of image points. Huygens knew the exact proportions between the shape of lenses, their focal distances, and spherical aberration. He could therefor derive exactly the effects of a particular configuration of lenses on the quality of images. So he did.

Huygens derived a measure for the fuzziness of an images – 'cercle d'aberration' – and showed that the objective lens was mainly responsible for it.[20] As to the clarity of images, he claimed that an image cast through a pinhole half the diameter of the pupil will be four times less clear (as only a quarter of the rays seen with the naked eye pass through).[21] Huygens did not determine the quality of images produced by a telescope directly, but approached the problem pragmatically. The starting-point of his analysis was a telescope that produced good images. The question then came down to determining how to adjust it while maintaining the quality of the image. I will not

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[18] Ariotti [1976] 333-334.

[19] In 1653, in his first version of his 'Dioptrica', he had briefly discussed the resulting clarity of a projected image of the sun. Huygens [1888-1950] 13, 250-253.

[20] Huygens [1888-1950] 13, 338-341.

[21] Huygens [1888-1950] 13, 332-335.

give the details at this occasion. Huygens concluded with a table listing focal distances of the lenses, the opening of the objective and the magnification of telescopes.[22]

Together with the whole analysis of spherical aberration, these propositions were discarded by Huygens when he found out about the nature of chromatic aberration from Newton.[23] In the 1680s, he returned to the topic. He followed the same line of reasoning, starting with a satisfactory telescope, analyzing the effects of adjusting it, and deriving a new proposition relating the opening of the objective lenses, the focal distance of the ocular, magnitude, distinctness and clarity of the image.[24] The analysis was further refined, adding new details. This time Huygens took chromatic aberration into account and he added some interesting new angles, for example where he linked the effective opening of the telescope to the diameter of the pupil.[25] The main difference with his earlier accounts was, however, the numerous qualifying remarks on his mathematical results that displayed the practical knowledge of optical instruments he had accumulated. Repeatedly, he adjusted his conclusions on the basis of experiential knowledge.

Most interesting in this new account is, however, the switch Huygens made subsequently. He considered what to do when a telescope fitted to observe Saturn was turned to the Moon.[26] Claiming that each point of the Moon was a hundred times brighter than a point of Saturn (being ten times closer to the Sun), he calculated the sufficient opening of the adjusted telescope, only to add: "but in reality it is completely different."[27] Huygens then explained that the adjusted telescope would have such a small opening that the pencils of rays projected on the eye became very small and the "distinct contour of the images disappears by an unknown cause, inherent in the natural constitution of the eye"[28] He gave an absolute limit and added that this could be verified by viewing objects through a lamina with a corresponding foramen. (He added that too small an opening of the telescope also rendered the faults in the lenses visible and thus disturbing. When viewing Venus – 225 times brighter – the results would be even more extreme, and Huygens said that a blackened glass to prevent blinding was the solution.)

In this way Huygens in his analysis of the quality of telescopic images included physiological aspects. He had partaken in dissections of eyes and elaborated a mathematical theory of the eye, so he was knowledgable in these matters.[29] Interesting for us, is the way he conceptualized the quality of images in terms of the instrument producing them. Distinctness and clarity, he defined in terms of the number of rays and the width of a pencil leaving the telescope. An important result of his analyses was the coherence of distinctness and clarity. Huygens did not systematically

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[22] Huygens [1888-1950] 13, 350-353.

[23] Dijksterhuis [2004] 83-92.

[24] Huygens [1888-1950] 13, 500-505.

[25] Assumed that clarity is determined by the number of rays passing through a system. Not validated directly. He added an experimentally found insight – as he phrased it: doubling the focal distance of the ocular quadruples the clarity. Huygens [1888-1950] 13, 504-505.

[26] Huygens [1888-1950] 13, 504-509.

[27] Huygens [1888-1950] 13, 507. "at reipsa secus accidit." Huygens, like many others, assumed that all planets are equally bright of themselves.

[28] Huygens [1888-1950] 13, 507. "Quod si duplum ejus sive diameter totus sit intra 1/5 vel 1/6 linea [0,4 mm], hoc est, minor quam 1/60 vel 1/72 pollicis deperit illa imaginum circumscriptio, ob causam in oculi naturali constitutione latentem, sive ea in choroide aut retina quaerenda sit, sive in ipsis oculi humoribus."

[29] Huygens [1888-1950] 13, 128-135; 790-802 (theory of eye); 787-790 (dissections).

elaborate the various ideas he put forward in this rich analysis. Ultimately, he was interested in getting to know his instruments, not the nature of perception.[30]

Distant Stars

Huygens did not, of course, have an absolute measure of clarity, or intensity of light, and it seems he was rather naïve regarding the possibilities of evaluating intensity. In *Kosmotheoros* (1698), he argued how the distance of Sirius could be determined by evaluating its brightness compared to the Sun. The argument was originally from the same time as the analysis of telescopic images discussed above and in a way Huygens just reversed it.[31] He proposed to stop the light from the sun by a pinhole until the spot was just as bright as Sirius: 1/27664th part of the Sun's disc. And thus Sirius would be at 27664 times the distance to the Sun. Huygens did not explain how he could compare the brightness of Sirius observed at night with the pinhole of Sunlight at daytime. Bouguer would readily point out the fundamental weakness in the argument, besides raising doubts over the eye's capability of judging (relative) intensities.[32] In the original exposition, he had compared the Sun's brightness with the Moon's, and then Sirius with the Moon.[33]

Huygens leads us to a new context in which clarity was considered: astronomy. This was the context in which Bouguer worked, more specifically the issue of the absorption of light in the atmosphere. In the course of the seventeenth century the intensity of light in relationship with astronomical observations had been popped up in a variety of ways. In a letter to Galileo, Castelli, recalling a discussion over the reciprocal illumination of Earth and Moon, formulated a relationship between size, strength and distance of a light source.[34] The origin of the statement is, however, unclear and neither Castelli nor Galileo seems to have continued on the issue. Which makes it an ad hoc statement, illustrative of the point I am making in this paper. The theme of secondary light on which Castelli wrote, originally came from artists and had been 'scientificized' by Galileo.[35]

The same goes for the contribution of Geminiano Montanari, half a century later. In an effort to determine the size and distance of a spectacular meteor over Bologna on March 31th, 1676, he

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[30] In *Traité de la Lumière*, (Huygens [1690]) Huygens made an a priori claim that the intensity of light wavelets is too small for them to be perceived, and that light is only percieved where they assemble in a wavefront.

[31] The 'pensées meslées' are dated 1686, Huygens [1888-1950] 21, 349. The comparison is in the 15th 'thought' (Huygens [1888-1950] 21, 352). In 1694 he elaborated the idea (Huygens [1888-1950] 21, 833-834), and included a brief exposition in book 2 of *Kosmotheoros* (Huygens [1698]; Huygens [1888-1950] 21, 814-817).

[32] Bouguer [1760] 46. "Mais outre que ce savant Mathématicien ne mettoit peut-être pas alors toute la distinction nécessaire entre les forces absolues des lumieres & leurs intensités, il n'est que trop certain que nous ne pouvons juger immédiatement de la vivacité de deux sensations, que lorsqu'elles nous affectent dans le même instant."

[33] Huygens [1888-1950] 21, 352.

[34] Galilei [1964-1966] 16, 122 (letter 2975). "Se saranno due lumi, ineguali in specie et in grandezza, illuminanti la medesima sorte di ogetti in distanze ineguali, l'illuminazione assoluta del primo all'illuminazione assoluta del secondo haverà la proporzione composta del lume in specie del primo al lume in specie del 2°, della grandezza della superficie del primo alla grandezza della superficie del 2°, e della proporzione duplicata della lontananza del 2° dall'ogetto illuminato alla lontananza del primo dall'ogetto da lui illuminato".

[35] Reeves [1997] 91-137 in particular.

elaborated a insightfull exposition of the intensity of light. He related that he had experimented with reading printed type by the light of varying candles at varying distances – a set-up not unlike the paragone in which telescopes were compared – and concluded that the number of candles is the square of the distance. Noting that the meteor's light had made visible tiny twigs, and considering its distance, he argued that it equalled 22,5 billion candles.[36] In this way, Montanari restated Kepler's law of illumination, while substantiating it experimentally. But this achievement too fell off the radar.[37]

Conclusion

At the end of the seventeenth century, the issue of clarity was still a dispersed affair of all kinds of writers making – often rather ad hoc – claims from a variety of points of view. It would not be brought to the point of a systematic, continuous study until halfway the eighteenth century. The examples I have given show that clarity was a multifaceted issue, with aspects of physics, mathematics, instrumentation, physiology, and so on. And this may precisely be the reason clarity was not picked up in seventeenth-century optics. In particular the coherence of physical and physiological aspects of perception would not be (re)established a century later. Distinctness could be studied in a purely mathematical way much easier, and therefor was a regular theme in seventeenth-century optics.

Returning to Descartes, and the importance clarity and distinctness had in his philosophy, we may say that the optical conditions for a perception to be reliable had yet to be established. Huygens went very far in mapping the subtleties playing a part in the establishment of clear and distinct images, and he did so in analyzing the way instruments produce images. In this context he did not fail to pass sharp criticism on Descartes' claims of the possibilities of improving natural perception by means of instruments.[38] Descartes expected that new instruments would make planets visible in equal detail as the earth. Huygens countered:

> Thus I find that, when one content oneself with a quarter of the original clarity, the opening of the outer lens will surpass the diameter of the earth, if one requires that the objects situated on Jupiter appear to us as they are found at a distance of 40 feet. It follows that here is another thing over which one cannot triumph by industrious hands.[39]

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[36] Ariotti [1976] 338-339.

[37] Beeckman too, in his Journal around 1630, considered intensity of light in an astronomical context, instructing a surveyor to measure the distance over which a light source is visible.

[38] Huygens [1888-1950] 13, 450-451. Versus *Dioptrique*, seventh discourse, ip 155-160. In the first draft of his 'Dioptrica' of 1653, Huygens had already mounted his critique: Huygens [1888-1950] 13, 224-229.

[39] Huygens [1888-1950] 13, 451. "Nam, licat jam quarta parte hujus claritatis contenti simus, invenio tamen aperturam illam lentis exteriorem Terrae diametro majorem esse debere, si res in Jove tanquam 40 pedibus distantes spectandas praebere postulet. Ut appareat aliud quam manuum industriam hic requiri."

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PART III

LENSES AND MIRRORS

The Optical Quality of Seventeenth-Century Lenses

Giuseppe Molesini

1. INTRODUCTION

The seventeenth century had been a period of extraordinary development for the art of lens making. [Bedini 1966] At the beginning of the century, lenses were almost regarded as curiosities, and just used for spectacles and magnifiers; at the end, lenses had become high-technology items, used to create prestigious instruments for the observation of natural phenomena and for the exploration of the universe. The quality of glass had been improved, lens figuring and polishing had been perfected, and the basic laws of image formation had been understood.

The history of the early developments of optics is documented by the lenses and the optical instruments that have survived to our times. In the course of recent years, a number of such lenses and instruments now housed in museums, universities and institutes has been extensively studied. In particular, telescopes and telescope optics have been carefully inspected, and documentary information has been organised in annotated catalogues. [Baiada, Bònoli and Braccesi 1995; Van Helden 1999] Also, examinations with state-of-the-art optical testing equipment have been carried out, and various accounts have been reported. [Greco, Molesini and Quercioli 1992 and 1993; Miniati, Van Helden, Greco and Molesini 2002; Bònoli, Miniati, Greco and Molesini 2002; Molesini 2004] Here the major outcomes are reviewed, with examples of tests performed on lenses of particular significance. A discussion on the possible use of simple lenses as camera obscura objectives is also given.

2. GENERAL REMARKS

Lenses are obtained after grinding and polishing a glass disc to spherical shape on both sides. In principle, the lens surfaces could also be non-spherical; the sphere has though the advantage that it is generated more easily in the optical shop, as the result of uniform wear between the glass disc and the lapping tool. In addition, while a lens with aspherical surfaces could perform very well for a particular position of a point source in the field of view, the image degrades quite rapidly and may become too blurred even at relatively small field angles. Conversely, a lens with spherical surfaces is far less critical with respect to the working conditions, and represents a good compromise between image quality and field coverage. As a matter of fact, lens surfaces have been made of spherical shape up to our times, and aspherics are only used in modern special applications. Although not entirely justified by image quality criteria, departures of a lens surface from a sphere are generally considered as defects.

To a first-order approximation, the most significant quantity associated to a lens is its focal length f. The latter depends on the refractive index n of the glass, and on a geometric shape factor given by the radii of curvature R_1, R_2 of the lens surfaces (the lens thickness plays a minor role). The focal length locates the point where light rays from a far source are concurring ("*punctum concursus*" [Kepler 1611], now the "focus"), and besides it acts as a scaling factor for the image size.

Converging lenses ($f > 0$) are thicker at the centre than at the edge; diverging lenses ($f < 0$) are thicker at the edge. In seventeenth century, the use of diverging lenses was almost exclusively restricted to correction of nearsightedness (myopia), and to oculars in galilean telescopes. Here we will consider only converging lenses, that can produce real images of the scene, i.e., images that can be cast on a screen. To such a task, the lens shape can be various: plano-convex, bi-convex or meniscus; the actual shape only affects the lens performance at higher-order approximation. Early telescope objectives used by Galileo were plano-convex, and then also bi-convex. [Sagredo 1615] The focal length was typically in the range 0.5 ÷ 2.0 metres (or 2.0 ÷ 0.5 dioptres of optical power). After Galileo, lenses of longer focal length came into use, in the attempt of reaching higher magnification. For spectacle-makers, such lenses would have been about the limit of usefulness for far-sighted viewers. It is understood that new, special workshop tools and polishing procedures had to be developed to comply with focal length requirements of telescope construction. In addition, while for spectacle applications the lenses had to be good only on the size of a few millimetres (the diameter of the eye's pupil), in the case of objectives the quality requirements extended over the whole aperture.

As to the aperture itself, the optical parameter conventionally accounting for it is the so-called f-number *f/N*, that for simple lenses with the stop at the lens is the ratio between the focal length and the diameter of the clear aperture. Such a parameter increases as the lens diameter stops down, approaching conditions named "paraxial", where only rays very close to the axis pass through the lens and proceed forming the image. Under paraxial conditions, lens surface defects are little affecting the image quality; the light intensity I at the image plane is though very low, as it scales according to $I \sim (f/N)^{-2}$. On telescope objectives of seventeenth century, f-numbers of the order of *f/40* and larger have been measured. For camera obscura applications, values of the order of f/10 and smaller would be desirable.

Previous studies showed that the most renowned artisans of seventeenth century were capable of producing telescope objectives practically perfect for their use, or "diffraction limited". As to technological capabilities related to fairly short focal length and small f-number, however, one has to refer to a different class of optical components, such as the outfit lenses making up erectors in terrestrial telescopes, and oculars. In the following paragraph, examples of both telescope objectives and outfit lenses will be presented.

3. OPTICAL TEST RESULTS

Optical components of seventeenth century have been examined in the laboratory, using standard methods currently adopted for quality assessment. In particular, interferometric tests with phase-shift techniques have been performed, obtaining accurate information on surface shape (departures from the best fitting sphere) and optical path difference introduced in a transmitted wave front. [Greivenkamp and Bruning 1992] Other lens parameters, such as radii of curvature and focal length, have been measured with conventional laboratory procedures.

3.1. Telescope Objectives of Torricelli

To demonstrate the optical quality of telescope objectives, an example of Torricelli's lenses is selected. Evangelista Torricelli (1608-1647) moved to Florence in 1641, and assisted Galileo during the last three months of his life. In 1642 he started polishing lenses, reaching full mastery of optical shop practices and making significant advances in the field. Torricelli also studied the polishing process from the point of view of theory, formulating the basic principles of spherical surface generation. His know-how and working techniques were kept secret, [Galluzzi 1976] although other artisans soon achieved a comparable level of professional ability.

Figure 1: Telescope objective of E. Torricelli in Naples (Courtesy of Museo di Fisica, University of Naples "Federico II").

Actual diameter	11.1 cm
Useful diameter	9.2 cm
Axial thickness	5.0 mm
Front surface	convex, radius (306 ± 3) cm
Back surface	plane
Focal length	(6.0 ± 0.1) m
f-number	*f*/65
Glass refractive index	1.52 ± 0.01

Table 1: Optical specifications of Torricelli's objective in Naples. [Greco and Molesini 1994; Paternoster, Rinzivillo and Schettino 1996].

Examples of Torricelli's lenses are on display at the *Istituto e Museo di Storia della Scienza* (IMSS), Florence. Another Torricelli's lens is housed at the *Museo di Fisica,* University of Naples "Federico II". The latter lens (Fig. 1) was accidentally found in a shelf of the physics laboratory by Gilberto Govi (1826-1889) in an undefined date before 1886, and recognised because of an inscription that says "Vang.ta Torricelli fece in Fiorenza per comand.to di S. A. S.ma" (Evangelista Torricelli made in Florence by order of His Very Serene Highness). [Govi 1886] The lens data are presented in Table 1. [Greco and Molesini 1994; Paternoster, Rinzivillo and Schettino 1996] The shape is plano-convex, with peak-to-valley (*P-V*) departure from nominal shape within 1.3 μm for the plane, and 0.76 μm for the convex surface. Such a departure is quite small; although it is not completely negligible, its effect on the expected lens performance falls below the image degradation caused by chromatic aberration. For demonstrative purposes, in Fig. 2 the map of the departure of the convex surface from the best fitting sphere is presented.

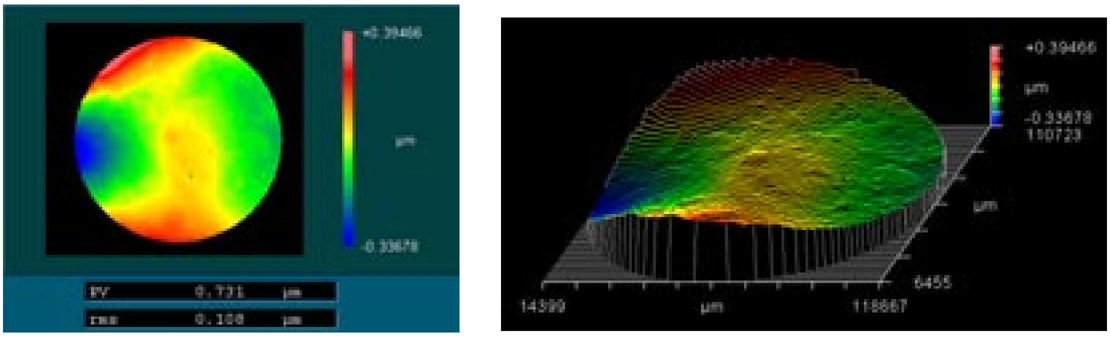

Figure 2: Surface topography (departure from best sphere) of the convex surface of Torricelli's objective; the diameter represented is approximately 7 cm.

The focal length of the above lens is quite long, and the f-number is accordingly high. This reflects the trend of the time, when magnification was sought in the first place: concepts such as diffraction and resolution related to the wave nature of light had still to come. It appears that Torricelli was certainly able to control the surface shape during the polishing process; the basic workshop operations (probably not the secrets, however) are described by Torricelli himself in a letter to a correspondent in Rome. [Torricelli 1642]

In fact, at the beginning of the seventeenth century the optical fabrication technology was at an almost rudimentary level. In the absence of workshop techniques that could guarantee the quality of the end result, Galileo used to purchase great quantities of lenses, and then to choose the best performing ones. The efficiency of the process was though quite poor: a letter of 1616 relates that of some 300 objectives made by one of the best artisans in Venice, 22 were selected, but only three passed, and even these were not deemed perfect. [Sagredo 1616] The demand for lenses of improved quality and in great quantities, however, soon resulted in technological advancements: in 1644, two years after the death of Galileo, Torricelli reported having produced two good objectives out of six polished in eight days of work. [Torricelli 1644]

It is likely that, at the end of the polishing process, a lens should have had to be discarded because of poor optical performance due to causes then unknown. Apart from the shape of the surfaces, a hidden problem that affected lens making was about glass homogeneity. In fact, the example selected of Torricelli's lens is a witness of defective glass quality. In Fig. 3, the interferogram of the lens in transmission is presented; the inconvenience is revealed by the saw-toothed profile of the fringes. The reconstructed map in Fig. 4 shows evidence of a corresponding ripple imparted to the wave front. While probably this lens could not be used as a telescope objective, it is though impressive for the regularity of its surfaces, and for its size. Torricelli signed it, as an artist would sign his masterpieces.

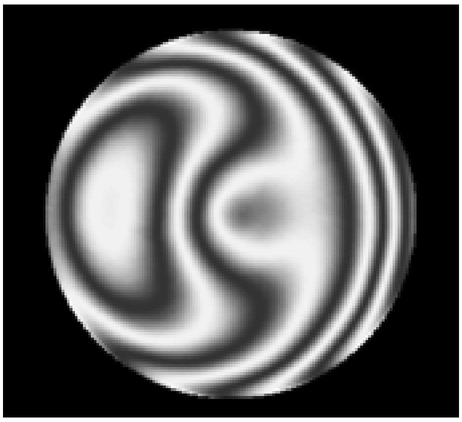

Figure 3: Interferogram of Torricelli's objective in Naples, analysed in transmission.

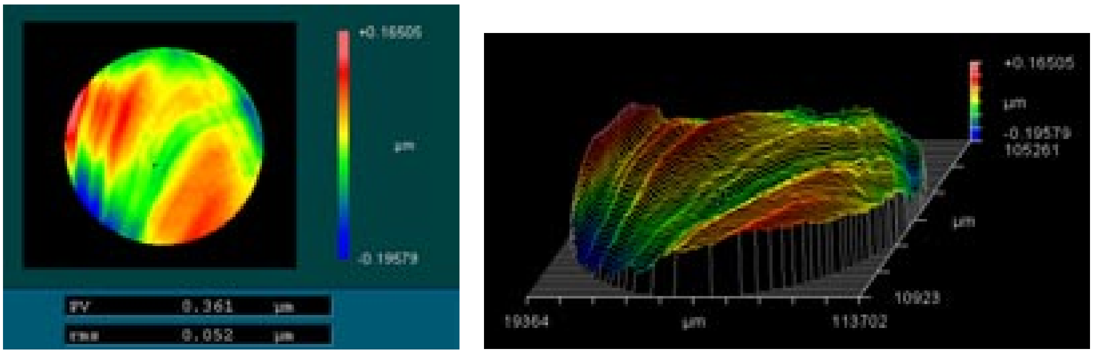

Figure 4: Transmitted wave front topography (departure from best sphere) of Torricelli's objective.

3.2 Erector and Ocular Lenses of Campani

Giuseppe Campani (1635-1715) worked in Rome, where he started producing optical instruments in 1662. Having made a name of himself as a telescope maker of excellence, he developed optical devices and system instruments that greatly contributed to the progress of optical and astronomical sciences in the second half of the seventeenth century and beyond. Campani used to work alone in his shop, not disclosing his glass polishing practices but to his daughter(s). His production constitutes a top reference for the state of the art in lens making at his time.

Campani's telescopes were usually conceived as system instruments, with a high quality objective, and a choice of attachments (erector, oculars) to vary the configuration and the magnification. Here the quality of the outfit lenses used within such attachments will be discussed.

A number of Campani's instruments still survive; the one here selected for presentation is inventory no. 2551 at IMSS (Fig. 5). The telescope is made from eight draw tubes, with an inner erector tube. The latter (Fig. 6) is a unit of its own, and can be removed to pass from terrestrial to astronomical configuration; in its layout, the erector consists of two lenses of slightly different focal lengths f_1, f_2, separated by a distance $f_1 + f_2$. In particular, one erector's lens was extracted from its mounting and examined in detail. The relevant data are reported in Table 2. The lens is of the equi-convex type; the f-number is as small as *f*/2.4. The surfaces are fairly regular, with peak-to-valley departure from best fitting sphere of 0.27 μm and 0.19 μm for the two surfaces, respectively. Such a quality would be considered very good even for today's standards. As an example, in Fig. 7 the map of the departure of one of such surfaces from the best fitting sphere is presented.

Figure 5: Campani's telescope, inventory no. 2551, at IMSS in Florence: optical layout to scale.

Marginal rays are in red. The first lens to the left is the objective. To the right is the compound eyepiece, made of a group of three lenses; the first two lenses constitute the erector, the last one the ocular.

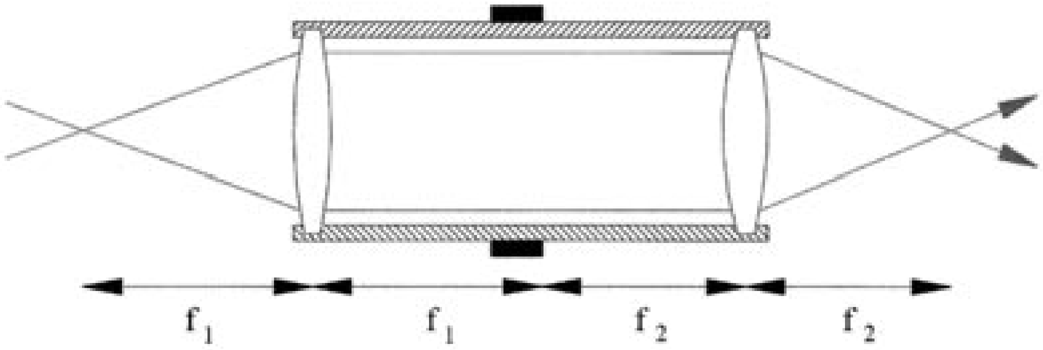

Figure 6: Schematic of the erector belonging to Campani's telescope, inventory no. 2551, at IMSS.

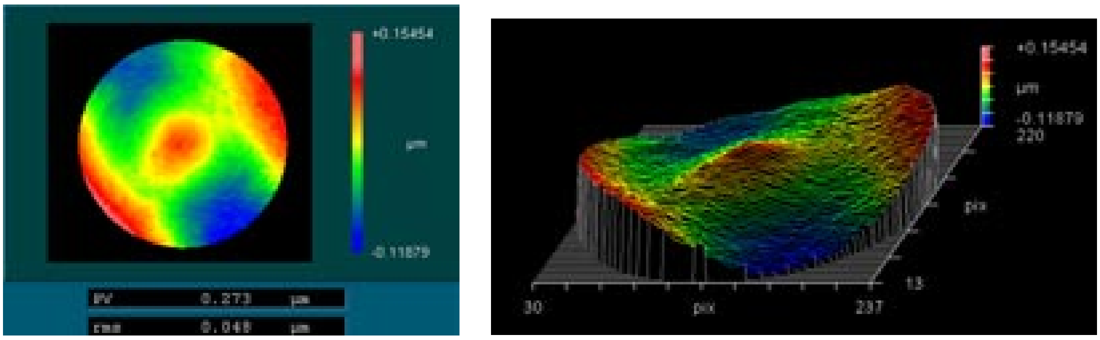

Figure 7: Surface topography (departure from best sphere) of a convex surface of Campani's erector.

Diameter	29 mm
Front surface	convex, radius (76.0 ± 0.5) mm
Back surface	convex, radius (76.0 ± 0.5) mm
Focal length	(68.9 ± 0.1) mm
f-number	*f*/2.4
Glass refractive index	1.55 ± 0.03

Table 2: Optical specifications of Campani's erector lens selected for presentation.

Other outfit lenses made by Campani have also been examined, all resulting in a comparable quality of the polished surfaces. The remaining shape features that are perceived on the lens surfaces may be related to optical workshop practices, such as the geometry of the support by which the lens was glued to the handle used during the polishing process.

Overall, it appears that lenses of very good optical quality could be fabricated in seventeenth century. Such lenses were in use within telescope systems; as to the camera obscura, however, it has to be discussed whether such an utmost quality was really necessary.

4. OPTICAL LAYOUT OF A CAMERA OBSCURA

To understand the quality requirements for a simple lens to be used within a camera obscura, a typical layout has been simulated with an optical design program. [CODE V, Optical Research Associates, Pasadena, California] The layout specifications are taken from a real camera housed at the IMSS; the values of the parameters used are only approximate, since the camera could not be disassembled for test and inspection. A schematic drawing is presented in Fig. 8. The camera includes a flat mirror that redirects light 90 to the lens axis. The image is formed on a ground glass acting as a screen.

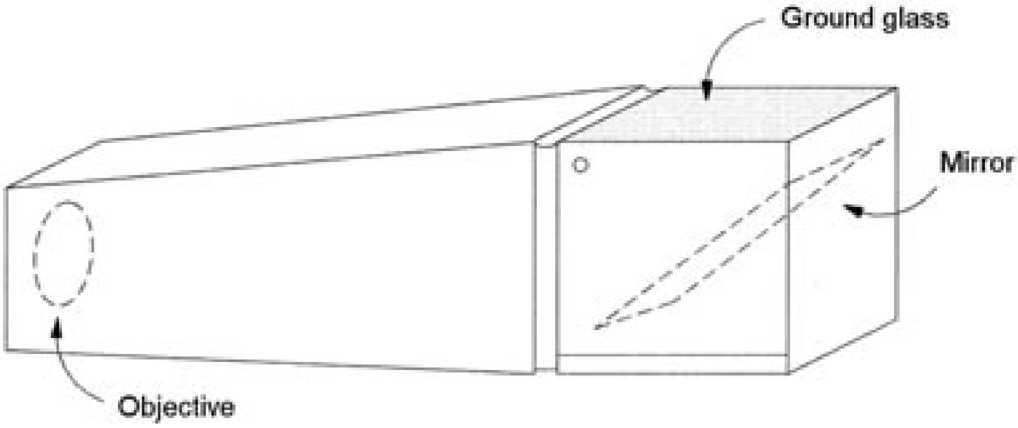

Figure 8: Schematic drawing of a camera obscura with objective, folding mirror and ground glass.

Lens diameter	70 mm
Front surface	convex, radius 700 mm
Back surface	convex, radius 700 mm
Axial thickness	6.0 mm
Focal length	676 mm
f-number	*f*/9.7
Glass refractive index	1.5185 at the wave length of 550 mm

Table 3: Optical specifications of the camera obscura simulated by computer.

From the point of view of geometrical optics, the plane mirror only varies the direction of the axis, and is generally neglected in ray tracing. The camera specifications that have been used in the simulation are listed in Table 3. In practice, the system is made of an equi-convex lens of 676 mm focal length, f-number *f*/ 9.7, image format 18x18 cm^2; the stop is at the lens. It is assumed that the lens surfaces are perfectly spherical. The system is a very classical one, and is usually studied in terms of Seidel aberrations. [Welford 1986]

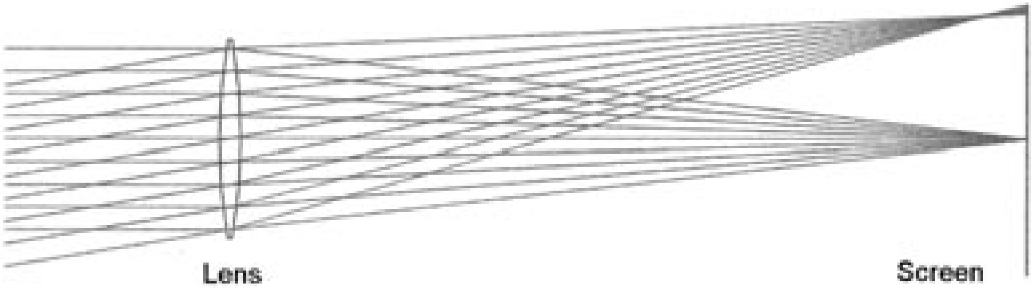

Figure 9: Meridian ray tracing (qualitative) at 0° and 7.5° field angles for the camera obscura specified in Table 3.

Ray tracing by computer simulation is presented in Fig. 9 (qualitative). Meridian ray bundles at 0° and 7.5° field angles are drawn; given the lens focal length, the latter field angle corresponds to a corner point of the 18x18 cm^2 image format, while the former field corresponds to the centre. In Fig. 10 the ray intercept at the image plane ("spot diagram") is shown, encoded in red, green and blue colours for the reference wavelengths 600 nm, 550 nm, and 500 nm, respectively; the spot diagram for field angles 0°, 2.5° 5° and 7.5° is given, also varying the screen position in steps of 4 mm about the central image location. As it clearly appears, the system is affected by field curvature, i.e., the best image lays on a curved surface instead of a flat screen. As a consequence, if the screen position is located so that the image is sharp at the centre, it will be somewhat out of focus at the edge, and vice versa.

In addition to field curvature, further aberrations are appearing. Spherical aberration, coma and astigmatism tend to enlarge and deform the spot diagram, so that the image is blurred; distortion instead is absent, due to the fact the stop is at the lens. Axial and lateral colour produce axial and lateral shift of the image spot according to wave length. All such problems, and more due to light intensity requirements, had later to be afforded and dealt with by early photography. [Kingslake 1989]

Besides, a major difference with respect to other instruments such as the telescope is that in the camera obscura the eyepiece is missing, and the image produced by the objective is directly looked at by the naked eye. As it is known, the limiting resolution of the human eye at the near point (conventionally, at a distance of 25 cm) is approximately 0.1 mm, so that a spot diagram smaller that that size would not be necessary (under ideal conditions, a diffraction limited focusing system working at *f*/10, wave length 550 nm, would produce a light spot of about 0.01 mm in diameter). A further problem affecting the image quality in a camera obscura is though given by the ground glass where the image is projected. Such a glass is necessary to be able of viewing the image all over the format, but it degrades the image quality in terms of contrast due to light scattering and diffusion within the glass itself. [Goldberg 1992]

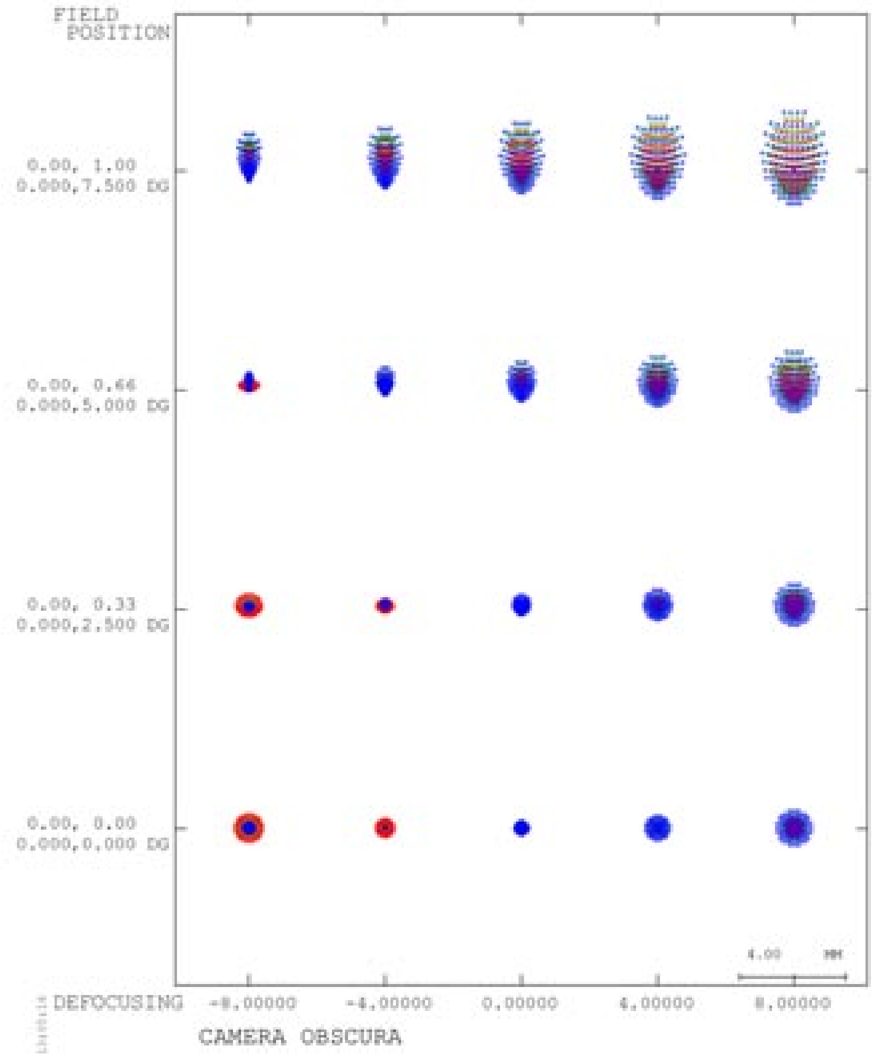

Figure 10: Spot diagram at 0°, 2.5°, 5° and 7.5° field angles, wavelengths 600 nm (red), 550 nm (green), 500 nm (blue). The effect of defocusing in steps of 4 mm is presented.

As a last consideration, it is noted that the scheme discussed above assumes that the object scene is on a geometric plane in front of the lens. Such an assumption is often not realistic. Usually the scene is instead on different planes from the lens, so calling for considerations on the "depth of field" that can be viewed in focus, while the fore and rear scene are increasingly out of focus. This phenomenon is intrinsic to image formation, and cannot be overcome even if aberrations were absent. As a consequence, one has to accept that a scene extending in depth, viewed through the camera obscura, is in some parts out of focus, and it requires scanning to put all the parts subsequently in focus.

5. CONCLUSIONS

In the light of the above considerations, it appears that the imaging in a camera obscura made of a simple lens is subjected to a number of tradeoffs that include the lens f-number, the field of view, the depth of the scene to be observed, and more. The lens quality in terms of surface regularity is certainly important, as well as the shape factor and the glass homogeneity, but the tolerances on the lens parameters are indeed less tight than in the case of telescope optics, where the imaging requirements are pushed to the limits, although on a quite narrow field of view. In the case of telescope optics, the artisans of seventeenth century proved capable of reaching their goal, producing lenses of utmost quality, as revealed by tests carried out on the instruments inspected.

In the case of the camera obscura, unfortunately it was not possible to carry out tests in the laboratory to study the quality of the lenses used at the time. It is though understood that, if the need for lenses of high quality would have been determined, in seventeenth century the technology for producing them was available. However, the analysis briefly presented shows that a simple lens, even if it were optically perfect as to its shape and glass quality, could not be free of basic imaging defects that show up under the conditions of use within the camera obscura; other problems not depending on the lens, such as the screen diffusion, are also affecting the image quality.

It is argued that, also considering the skill of the artisans of the time in optimising various devices that were produced, a sort of natural engineering process might have occurred, setting up by trial and error a suitable tolerance budget that would let to obtain the best overall performance under the given conditions. In this philosophy, since the use of perfect lenses could not improve the image quality beyond some limits, and besides it would result in a significant economical effort, one is not expected to find camera obscura objectives made of perfect lenses, but of lenses of performing quality for the particular application.

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The Camera Obscura and the Availibility of Seventeenth Century Optics – Some Notes and an Account of a Test

Tiemen Cocquyt

I. INTRODUCTION

Ever since the telescope and the microscope made a significant change to our world view in the seventeenth century, the origins and the rapid development of these devices have been the subject of ongoing study. During the nineteenth century, each nation paid particular attention to the role that their ancestors had played in these developments. Consequently, the material artefacts of such progress found their ways to collections and museums. In more recent times, theories and conceptions of optics were prominent in the discussion of seventeenth-century optics. In the last decades however, more focus has been put on the study and interpretation of preserved material heritage of these traditions, and it is understood that polishing and grinding techniques have played a prominent role in the astronomical breakthroughs of the seventeenth century[1]. Furthermore, interferometric measurements have recently shown that seventeenth-century lens makers were able to grind their lenses to a degree of precision that can be considered perfect for the telescopic application they had in mind.[2] Also, some production characteristics of individual lens makers were uncovered that supports us in getting a better understanding of seventeenth-century lens production as a whole.[3]

In this paper, I am attempting to apply our current knowledge of seventeenth-century optics to a projection device like the camera obscura. I will argue that in past discussions about lens quality, the function of the lens has often been self-evident. When discussing the role of optics in an interdisciplinary framework, one should not forget to take the actual application of the optics into account.

Quality differences among seventeenth-century lenses are further discussed, and, by looking at some general tendencies in the seventeenth-century instrument workshop culture, a suggestion is made for an economical model of lens availability in this century.

In the second part of this paper, an experiment is described where preserved seventeenth-century heritage – albeit from a different tradition – was employed to gain more insight in how lens quality affects projected images. Therefore, conclusions from this paper should be interpreted as instrumental. They serve to distinguish extravagant claims about early projection devices from historically more probable scenarios.

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[1] Albert van Helden, "The Telescope in the Seventeenth Century." *Isis* 65/1 (1974), pp. 38-58.

[2] Giuseppe Molesini, "The Telescopes of Seventeenth-Century Italy." *Optics & Photonics News*, June 2003, pp. 34-39; see also the article of Giuseppe Molesini in this volume.

[3] Ibid.

II. Seventeenth-century Lenses: Application and Availability

When considering the forms, qualities and quantities that lenses were generally available in from the seventeenth century onward, the image we get is rather fragmented. Spectacles were introduced in the late thirteenth century, and their availability spread quickly.[4] With the introduction of the telescope, lenses with longer focal lengths witnessed a steady development in the seventeenth century.[5] Still, the diameters of such telescope lenses did not increase much. For demonstrations in optics, lenses with larger diameters were commercially available in the eighteenth century, but short focal lengths were most appropriate for such purposes. On the other hand, high-quality telescope object lenses with large diameters were only available from the turn of the nineteenth century onward.[6]

The selectivity given with collections of museums adds further to this fragmented image. In collections of optical devices of the past, astronomical lenses prevail. Recently, interferometric measurements of preserved lenses from the seventeenth-century astronomical tradition have convincingly shown the superiority of the lenses that were available in this period.[7] As such products can be considered ‘masterpieces’ of the lens-making craft, they often found their way to collections and museums where they can still be admired. Thus, it is not that surprising that the lenses preserved in present days’ collections are representative for the higher quality part of the lens-making craft only.

Furthermore, another aspect of the diverging preservation possibilities of lenses is the symbolic value that astronomical object lenses gained from the object under investigation: the heavens and the celestial objects they made visible. In certain cases, preserved object lenses have become the symbols of a specific astronomical discovery.

On the other hand, no seventeenth-century lenses from an application other than observational astronomy or microscopy seem to be preserved in any collection. There are, however, preserved spectacles that were manufactured in and before the seventeenth century. Still, in terms of function and availability, it is difficult to consider them as masterpieces of the optical craftsmanship in their time of manufacture. All over Europe, spectacles were commonly available products by the turn of the seventeenth century.[8]

History of observational astronomy and history of microscopy have traditionally been written as distinct chapters. This is very evident, since there is hardly any point where both traditions overlap, and those rare intertwinements are only to be found in the early decades of the seventeenth century, when both materialisations were still prototypes based on one and the same principle. Yet, when examining the instrumental parts of both traditions in parallel chronology, some interesting aspects come to the surface.

For example, when discussing the persons associated with the ‘workshop culture’, several names come forward in these seemingly distinct, yet close traditions: names such as Galileo,

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[4] Albert van Helden, “The Invention of the Telescope.” *Transactions of the American Philosophical Society* 67/4 (1977), p. 10.

[5] Albert van Helden, “The Telescope in the Seventeenth Century,” l.c., p. 46.

[6] See, for example, Henry C. King, *The History of the Telescope*. New York (Dover Publications) 1955, pp. 176-205.

[7] See Giuseppe Molesini, “The Telescopes of Seventeenth-Century Italy,” l.c.

[8] Albert van Helden, “The Invention of the Telescope,” l.c., pp. 10-11.

Drebbel, Huygens, Campani, and Hartsoeker appear in both the instrumental history of astronomy and that of microscopy. In the period before societies of learned men institutionalised experimentation, natural philosophers taking up the production of their devices themselves were not uncommon. When specialised craftsmanship was required, the scientist was generally still in close contact with the craftsman. Only around the turn of the eighteenth century did the (philosophical) instrument making craft professionalize.[9]

When evaluating the chronology in which designation and professionalization can be discerned, it appears that changes in the optical instrument making community were manifest a generation earlier than was the case for philosophical instruments. Air-pumps were not widely spread in the late seventeenth century, nor were barometers or other instruments where natural phenomena were 'actively' produced. In contrast, microscopes and spyglasses already had an established market long before. We thus see that observational astronomy and microscopy occupy an interesting place in seventeenth-century science, when considering the dynamics between theory and practice but also with respect to the professional establishment of an instrument makers community.

At the time the telescope was devised, it is likely that the focal lengths of spectacles ranged from 30 to 50 centimetres.[10] Longer focal lengths would hardly have been worth the effort, since the corresponding eye defect to correct for decreases quickly with higher focal lengths. Furthermore, producing low-curvature spherical lens surfaces was precisely the difficulty that had to be overcome in the early development of the telescope.

If we have a look at lenses with a focal distance of one metre or more, we see that such lenses are preserved dating from a rather early stage of the seventeenth century already. But, in this period, such lenses were unique products of advanced craftsmanship. They must have been extremely uncommon; such lenses were top notch technology. Only from about 1640 do we see focal distances of several metres. This is in agreement with the astronomical telescope coming into widespread use; from here on the breakthroughs in observational astronomy can generally be expressed in terms of increasing focal distance.[11] Of course the preserved object lenses dating from after the 1640's are products of superior craftsmanship as well, but it seems likely that lenses with - for this time - moderate focal distances were somewhat easier to manufacture.

While focal length and surface quality were decisive for astronomical discoveries, glass quality was also an important aspect of lens-making throughout the seventeenth century.[12] An illustration of such quality differences over time can clearly be seen when inspecting the first lens Christiaan Huygens made observations with in 1655. This object lens (other parts of the telescope have not been preserved) is now kept in the Utrecht University Museum, and it is the oldest lens known to be ground by Huygens. In the last decades of the nineteenth century, the quality of this lens also puzzled the Utrecht professor of astronomy J.A.C. Oudemans, and for the purpose of

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[9] Deborah Warner, "What is a Scientific Instrument, When did it Become one, and Why?" *British Journal for the History of Science* 23 (1990), pp. 83-93. See also: Albert van Helden, "The Birth of the Modern Scientific Instrument, 1550-1700." In: J. G. Burke (ed.), *The Uses of Science in the Age of Newton*, Berkeley (University of California Press) 1983, pp. 63-65.

[10] Albert van Helden, "The Invention of the Telescope," l.c., p. 11.

[11] Albert van Helden, "The Telescope in the Seventeenth Century," l.c., p. 46.

[12] Giuseppe Molesini, "The Telescopes of Seventeenth-Century Italy," l.c.; Anne C. van Helden and Rob H. van Gent, "The Lens Production by Christiaan and Constantijn Huygens." *Annals of Science* 56 (1999), pp. 69-79.

comparison he inquired the Prague observatory for the loan of an object lens with a corresponding focal length, made by Giuseppe Campani around 1680. This lens still resides in Utrecht these days, and it is as instructive as then to put both artefacts next to each other for visual inspection. While the Campani lens is free of striae or soot and as good as free of bubbles (only very close examination gives something away), the Huygens lens is more yellowish in colour and contains relatively larger bubbles and soot particles. Also, traces of the polishing process can be found, which is not the case with the Campani lens.

Still, Huygens gave the acquisition of glass serious consideration, as is attested by his correspondence.[13] The increase in glass quality can clearly be seen when inspecting the Huygens legacy in chronological order, especially in the first years of lens production.

Figure 1: Telescopic object lenses by Christiaan Huygens (1655) and Giuseppe Campani (ca. 1680). Photo courtesy of the Utrecht University Museum.

Quality limitations did not, however, prevent Huygens from making successful observations soon. The discovery of the brightest moon and the ring surrounding Saturn in 1655, was made with the first lens known to be ground by Huygens. It seems that observational success was determined by the subtle balance between technological improvements and limitations.

But perhaps it is more interesting to look at the general tendency that can be found when examining preserved seventeenth-century lenses. One can think of an average maximum focal length that could be obtained in corresponding periods of the seventeenth century. If we imagine a graph, plotting the focal length against year of manufacture for each preserved lens, this average maximum would manifest itself in a rising curve passing through the higher part of the distribution of the lenses. Lenses situated close to this curve were top notch technology, while lenses below this curve are likely to have caused – to some extent – less difficulties in the

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[13] Ibid., pp. 72-75.

production process. That is, I make the assumption that lenses became products of technology, and that at a certain point there were 'economical' lenses as derivatives of top class lenses in terms of manufacturing precision. In the seventeenth century, manufacturing precision was essential for making good low-curvature lens surfaces; for lenses with moderate focal lengths these criteria could be relaxed.

To sum up: Throughout the sixteenth century, the main application of lenses as spectacles limited their focal lengths to about 50 centimetres. In the second decade of the seventeenth century however, the newly devised telescope led to a new application for lenses, and a small-scale specialisation in the lens making craft. Lenses with focal lengths of one to two metres *were* produced in the 1620's and the 1630's, but they were top class precision components. From the 1640's onward, attainable focal length increased significantly. To the extent that the economic model I suggested before holds, lenses with focal lengths of one to two metres would have been easier to manufacture by this time.

What, then, can we say about late-sixteenth-century and seventeenth-century camera obscuras, or other projection devices, and their availability? First, it is clear that camera obscura construction, in particular its projection distance,[14] will have obeyed the limitations of then available lenses.[15] Second, given a certain camera obscura configuration, there is an optimal range of focal lengths. Thus, contrary to the (astronomical) telescope, where there is virtually no limit to usable focal length of the object glass, camera obscuras with focal lengths of several metres would be impractical in terms of image size, and image dimness.

Considering furthermore the problem of 'high tech' versus economy lenses, it seems obvious that none of the preserved astronomical object lenses in any collection will have witnessed an usage in a camera obscura. Although both focal distance and surface quality were very decisive for observational success, this was not the case when applied in a camera obscura. As I argued in the case of Huygens, there was a subtle balance between technological limitations and improvements which decided on new telescopical discoveries. To our current knowledge, the *Admovere* lens was the first lens Huygens ground, and its glass quality can be described as characteristic for its particular time and geographical region. Yet, it must have been 'better' than the object lenses before, since it enabled him to observe Saturn above the threshold of resolution which was determinative for making new discoveries.[16] But, the telescope is a compound optical instrument

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[14] In this discussion of camera-obscura projections, rather than on the box device with glass projection screen that came into use at the end of the seventeenth century, I focus on a setup where the observer is situated between the lens and the projected image.

[15] In order to have an overview of preserved seventeenth-century lenses and their focal lengths, a compilation of data in several catalogues and publications was used. A vast selection of Italian telescopes and lenses preserved at the IMSS, Florence, can be found in: Albert van Helden, *Catalogue of Early Telescopes*, Florence (Giunti) 1999. For detailed measurements and discussion of several of these lenses see: Mara Miniati, Albert van Helden, Vincenzo Greco and Giuseppe Molesini, "Seventeenth-century telescope optics of Torricelli, Divini, and Campani." *Applied Optics* 41/4 (2002), pp. 644-647; Vincenzo Greco, Giuseppe Molesini, Franco Quercioli, "Telescopes of Galileo." *Applied Optics* 32/31 (1993), pp. 6219-6226. An overview of preserved telescopes dating from the first half of the seventeenth century can be found in: Rolf Willach, "The Development of Telescope Optics in the Middle of the Seventeenth Century." *Annals of Science* 58 (2001), 381-398. For object lenses manufactured outside Italy, the Huygens collection offers a good illustration; see: Anne C. van Helden and Rob H. van Gent, "The Lens Production by Christiaan and Constantijn Huygens," l.c., pp. 69-79.

with high magnification – hence the importance of the object lens - whereas the camera obscura employs a single convex lens working at low magnification.

Were simple spectacle lenses, then, sufficient for making a camera obscura? Certainly not. First, the range of focal lengths that spectacles were available in was too short for camera obscuras discussed here. It is, second, important to note the differences in image formation between spectacles and telescopes. In the case of spectacles, the eye, looking through the lens in a certain direction, makes use of only a small part of the lens surface, and the eye's power to accommodate ensures that the object stays in focus when looking in another direction where the lens has a relative asphericity. In the case of a telescope's object lens, however, the entire lens surface contributes to image formation, and the asphericity of the object lens as a whole becomes important.[17] In the case of the camera obscura, its single lens also makes use of every part of its surface for producing an image. That is, a camera obscura with a half-covered lens is still a camera obscura. Therefore asphericity, inhomogeneities, and bubbles do matter in this application, and a camera obscura requires a higher standard of lens quality compared to spectacles. In practice however, requirements can be relaxed given its low magnification, and lenses as good as the astronomical object lenses were certainly not necessary for making a good camera obscura.[18]

Taking all of these aspects in consideration, one might still wonder how good camera obscura lenses had to be for giving an acceptable image, and this is where the preserved heritage proves to be very useful again.

III. An Unhistorical Reconstruction Experiment

In order to examine such questions, recently I was fortunate to cooperate with Carsten Wirth (MPIWG, Berlin) in a reconstruction experiment at the Utrecht University Museum. The motive for this experiment was that, since no seventeenth-century camera obscuras survive, knowledge about their properties and capabilities is missing as well. Furthermore, a diversity of opinions was known to exist about the implications of seventeenth-century lens quality for this purpose. Therefore, a range of lenses dating from this period was selected for setting up a reconstruction.

After first examination, no lenses were found to be 'perfectly' suitable for what was initially hoped for: a camera obscura with a projection distance of one to two metres, preferably with relatively large diameter lenses. None such lenses were preserved in the Utrecht collection, therefore, a selection of best approaching lenses was made. This selection consisted of seventeenth-century lenses with relatively small apertures and focal distances of c. three metres. By consequence, projected images were destined to be considerably dim. From a test setup employing a twentieth-century singlet lens with comparable properties, this expected limitation was indeed observed. Therefore, the obscured 'camera' was darkened to the extreme. In addition,

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[16] True, as a seventeenth-century scientist Huygens was "a man who had all the manual dexterity of a Galileo and the theoretical interest in optics of a Kepler" (A. van Helden, "The Telescope in the Seventeenth Century," l.c., p. 48.), but he can not be accredited for being a fanatic astronomical observer. See: Anne C. van Helden and Rob H. van Gent, l.c., p. 69 and further.

[17] Max von Rohr, "Die Brille", in Siegfried Czapski, Otto Eppenstein (eds.), *Grundzüge der Theorie der Optischen Instrumente*, Leipzig (Johann Ambrosius Barth) 1924, pp. 419-420.; Rolf Willach, *The Development of Lens Grinding and Polishing Techniques in the First Half of the 17th Century*. Lecture at the XIX International Scientific Instrument Symposium, Oxford, 2000.

[18] For a firm, quantitative treatment, see the contribution of Giuseppe Molesini in this volume.

respecting several minutes of accommodation to the darkness proved to clear up the images significantly.

Figure 2: Projection of a skeleton cast by the Huygens lens UM Li 38 during experiments conducted by Carsten Wirth and Thiemen Coquyt in the Utrecht University Museum in 2006.

From this, it can be concluded that the ratio of projection distance to aperture soon shows practical limits in the camera obscura. The setup that was used, ranging from f/30 as far as f/100, was only directly usable in the lower limit; above that the previously mentioned accommodation had to be applied. Conversely, accommodation might have been an employed practice when large projections needed to be obtained in the period under investigation.

Next, the modern lens was interchanged with a historical lens. The lens in question is an astronomical object lens, manufactured by E. D. Bevere in 1709. Although the production date is slightly late for our investigation of seventeenth-century optics, the glass quality of this lens, which contains relatively large bubbles, does remind one of the century under investigation. A similar conclusion can be found in the article describing the discovery of this lens, by the Utrecht professor Harting.[19]

Interchangement with this lens showed a diminution of quality compared to the modern lens. Still, the image was highly acceptable, i.e. not deformed. Rather, the projection had lost some of its focus, but only on a close-up level (after interchangement we had refocused, of course). When evaluating the entire image, one can say that the image was poor in brilliance compared to the modern lens.

Subsequently, the images of two other lenses were examined. One was the lens *Admovere* by Christiaan Huygens, and the other the Campani lens. As was stated before, none of these lenses originally had any usage other than serving as a telescope object lens. Therefore, it may seem odd to use particularly these lenses for a camera obscura application. However, there were specific motives for this. Both lenses have a focal distance of ca. three metres, which is rather short for preserved seventeenth-century lenses. Moreover, while focal distance and clear aperture are comparable for both lenses, each one represents a well-documented period in the history of lens production, and is therefore more representative than 'anonymous' lenses. Thirdly, both lenses have been evaluated and compared in detail on their astronomical merits since they both reside in Utrecht,[20] and without this the conclusions of this experiment would have been far less significant.

Briefly, the conclusions from the late nineteenth-century telescopic comparison of these lenses state that the Campani lens was better than the Huygens lens. This was concluded on two grounds: a terrestrial comparison with a test object on 330 metres distance, which made quantitative conclusions possible, and a reconstruction test with the lenses mounted in the optical path of the Steinheil telescope of the Utrecht Observatory, pointed at several celestial objects.

In the figure below, the observed resolving power of both lenses at full aperture is graphically shown. Although the curves are interpolated from four data points only, starting at a magnification of 54, one can see that the differences in resolving power are most apparent at higher powers. Nevertheless, it should be noted that the typical magnification of the earliest Huygens telescopes was about 50 times, and his most important discoveries were done at a power lower than 100. Campani's telescopes, being later in date, also had quite modest magnifications for their time.[21] This optimal behaviour is also attested by the graphs. Therefore, the data at higher

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[19] Pieter Harting, "Oude optische werktuigen, toegeschreven aan Zacharias Janssen, en eene beroemde lens van Christiaan Huygens teruggevonden." *Album der Natuur* 1867, pp. 273-274.

[20] J. H. Klein, "Eine Prüfung alter Fernrohrobjektive von Huygens und Campani." *Sirius* 23 (1899), pp. 277-280.

magnifications should rather be regarded as additional measurements. And, this taken into account, performance of both object lenses is less different than one would think.

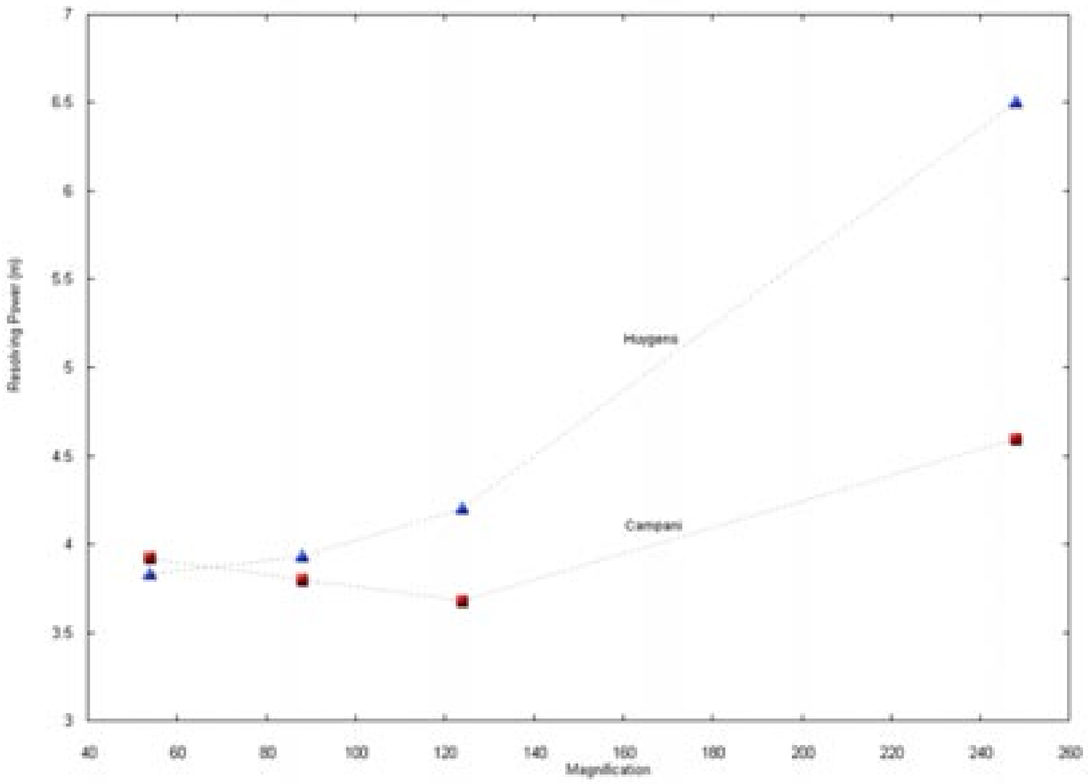

Figure 3: Resolving power of the Huygens and Campani object lenses at different magnifications, as measured by A.A. Nijland at the end of the nineteenth century, and published by J. H. Klein. The resolving power is expressed in metres, and related to a test setup at 330 metres distance.

However, telescopes can best be tested at night, and the second part of Klein's article is fully devoted to this. In the introduction we can read *"Wie zu sehen, ist C[ampani] dem H[uygens] überlegen, aber nicht gar so viel. Viel grösser jedoch wird der Unterschied zwischen C und H für Sterne."*[22] Although conclusions differ for each individual celestial object, there are some tendencies. Generally, observations through the Huygens lens better show dim objects,[23] but are systematically less sharp than those with the Campani lens.

How would this translate to projected camera obscura images? Naturally, no fringes of chromatism were observed in our test. Interchanging the Bevere lens with the Huygens lens showed a slight image improvement. This was best attested by the contrastive details of our test object, which clearly showed more sharpness. And, by substituting the Huygens lens with the

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[21] Albert van Helden, "The Telescope in the Seventeenth Century," l.c., pp. 46-47. For a discussion of the selectable magnifications in Campani's telescopes, see Giuseppe Molesini, "The Telescopes of Seventeenth-Century Italy," l.c., p. 38.

[22] J. H. Klein, l.c., p. 278.

[23] The article mentions a free aperture of only 49 mm for the Campani lens, while for the Huygens lens the full aperture of 52 mm was used.

Campani lens, sharpness was improved even more, up to an image which resembled the result of a modern singlet lens. Therefore, in our camera obscura application and over a century later, we can agree with Hugo Schröder's remark that the Campani lens' quality is comparable to a modern singlet lens.

But just *how much* did sharpness improve when substituting lenses? As I stated before, differences were subtle, but could be discerned when examining the projected image in detail. However, the images of all three lenses we examined was surprisingly acceptable. At a later point, when we tried to match the photographs that were made of the projection screen with their specific lenses, the recorded time of the picture actually was the only information that could assure us of the correct match – this probably explains sufficiently just how subtle the differences were.

Therefore one is inclined to say that, regarding the 'complete picture', all three lenses were equally suitable for projection purposes. Only in a detailed view, close to the projection screen, differences could be discerned. Generally, these differences manifested themselves in a sensory experience of 'brilliance'. Given that differences in resolving power between these lenses will never be macroscopically visible at such magnification, this impression of brilliance, although seemingly subjective, is in agreement with the optical properties of the lenses. That is, in an optical system working close to the diffraction limit, such as a telescope, lens regularity as well as aberrations determine resolving power, and this in turn has decisive consequences for the usefulness of the image. In low magnification applications such as a camera obscura, resolving power will unabatedly be dependent on lens quality and configuration, albeit that resolving power is not the main criterion of the instrument's quality. All images will be useful, but some might be received better on – observationally - less obvious or quantifiable grounds.

In case one would like to quantify these differences, certain test objects containing line patterns would have to be developed, together with a magnifying device to measure the resolution in their projection. At that point, interferograms of the lenses under test would also be sensible for quantification purposes. Indeed, this method would be far more elaborate than direct observation. Furthermore, one would miss out on the experience of observing impressively colourful images in an obscured room – this should not be underestimated.

Conclusions from the experiment

Although we have not been able to offer a quantitative comparison of the tested lenses in a camera obscura setup, the experiment did give us insight in the influence of lens quality on projected image quality. To begin with, it was clear that images from *preserved* seventeenth-century lenses are remarkably acceptable, even from notoriously mediocre ones. Furthermore, quality improvement can be observed with increasing lens quality. Yet, while for astronomical applications this improvement is dramatically decisive on the chances for discovery, the differences in a camera obscura application are substantially more subtle, and on first inspection only discernable in 'brilliance' or sharpness of selected details.

Also, it was seen that aperture limitations rapidly affect usability of the lens. We have been working at, or perhaps slightly beyond, the limit of usable f-number. Accommodation was necessary for making the details in the image visible. However, since our aperture circumstances were rather unfortunate, depth of field was surprisingly good (over 3 metres). From this, it is clear that there is sufficient room for a range of compromises between image dimness and depth of field. It should be noted that arguments concerning depth of field have been used in analyses of fifteenth-century paintings, allegedly produced with the help of a camera obscura.[24] Therefore, we believe that our experiment sheds new light on this discussion. Still, the discussion in this paper is focussed on seventeenth century optics. It can be concluded that lens quality is not a sufficient argument for refuting the application of the camera obscura in this period.

IV. General Conclusions

In this article, I have investigated how our current knowledge of seventeenth-century optics can shed more light on the use of the camera obscura in this century, a topic on which not much detailed information, nor any material heritage is available. When studying the application of lenses in observational astronomy and microscopy, certain patterns come to the surface. For example, one sees how the presence of such applications initiated a demand for lenses with specific properties, but also how this demand could only be met in agreement with technological capabilities in lens grinding. Also, one can observe how the origins of an optical instrument making community lay in peripheral activities taken up locally both by craftsmen and natural philosophers, and how this practice professionalised throughout the seventeenth century.

In order to use this information for understanding camera obscura practice, I have assumed that the camera obscura is a product of lens making technology. Furthermore, I have assumed that professionalisation of the craft led to the availability of 'economical' lenses as derivatives of top class lenses, by relaxing the manufacturing criteria (precise low curvature surfaces). Given these conditions, it becomes clear how important focal length is for concluding something decisive about camera obscura practice. But, when we reason focal length to be about one metre, we can certainly conclude that general availability of such lenses varied substantially throughout the seventeenth century. That is, more specific statements both about period and focal length would foster the discussion about seventeenth-century camera obscuras.

Still, such treatment leaves us with two new questions: where, in the continuous range between 'top notch science' and more common 'secondary application', do we want to situate the camera obscura? And consequently: how does image formation in this application depend on lens quality? In order to answer such questions, an experiment was devised. In this experiment, a selection of preserved seventeenth-century lenses was used in a camera obscura setup. Although this experiment is by all means unhistorical – the lenses used are artefacts from a different tradition – it should be remarked that such an experimental approach was missing in the camera obscura debate up till now. The experiment showed that images produced by preserved seventeenth-century lenses are remarkably acceptable. Moreover, it was observed that image quality was improved with increasing lens quality, although this could only be discerned on close examination. Hence, quality criteria for lenses in camera obscura applications are marginal compared to their importance for observational astronomy, in which case they are decisive for observational success and discovery. As such, the conclusions of the experiment are in agreement with optical simulations of a camera obscura.[25]

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[24] David Hockney and Charles M. Falco, "Optics at the Dawn of the Renaissance." *Technical Digest of the Optical Society of America*, 87th Annual Meeting (OSA 2003).

In addition, the experiment showed the importance of lens diameter on projection. Given that, unlike focal length, lens diameter remained a limiting factor throughout seventeenth-century lens application, certain restrictions on the optical configuration of the camera obscura apply. Yet, while small lens apertures and thus high f-numbers constrain image brightness, they are also advantageous for the depth of field. The experiment suggested that, if the 'camera' is sufficiently obscured and one takes the time to accommodate, good compromises between image brightness and depth of field can be obtained.

To conclude, while this paper does not lead to strict consequences for the proposed scenarios about the camera obscura in the seventeenth century, it does make clear that lens quality is not a sufficient argument for refuting its application. Moreover, it serves as an instrument to test such scenarios in confronting them with the material heritage of seventeenth-century optics and our knowledge about its context of usage and manufacture.

Acknowledgements

I would like to thank Klaus Staubermann, Carsten Wirth and Sven Dupré for the valuable discussions and for involving me in this research project. Also, I would like to thank Albert van Helden for the many discussions about seventeenth-century optics in the past time.

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[25] See the article of Giuseppe Molesini in this volume.

Comments on 17th-Century Lenses and Projection

Klaus Staubermann

Abstract:

Various attempts have been made to understand the role of the camera obscura in Renaissance painting. This study tries to understand the actual practice necessary to produce the image. Based on original artifacts as well as reconstructions I will first explore the functioning and making of the device, especially that of the lenses. From there I will illuminate the practice required to project and control the image. In order to comprehend historic practice I will draw on comparions from astronomical lenses and especially magic lantern projections. I will try to show how historic observers could rely on their optical instruments and media and thereby were able to come to a judgement on what they saw and what they wanted to see. I will conclude that not the quality of the projected image but first of all the observer's visual judgement was at the very center of camera obscura practice.

1) I will argue this comment by taking the museum curator's stance. I will start from an article presented by my colleague, the Harvard curator Sara Schechner, at the Hockney workshop in Ghent in 2003.[1] Sara Schechner has studied the quality of still existing early mirrors (Hockney claims to have used "a simple shaving mirror") and argued that no mirror could have produced an image of sufficient quality.[2] She concludes in her presentation: 'always get the facts right' – a strong reminder for any study on historic material culture and practices.

2) What I will do here is to look at seventeenth lenses instead of mirrors. This is for various reasons. One is a reference to an Isaac Newton statement by the twentieth century optician and director of the Hilger workshop, F. Twyman: In his book "Prism and Lens Making" he refers to Newton in that late seventh- and early eighteenth-century mirrors were five time worse in producing images than lenses.[3]

3) Lenses normally come into being in three steps: by glass making, cutting/grinding and polishing. Historic glass making has has been studied by various historians and archaeologists. Also, from the sixteenth century onwards it has been well documented, for example by works such as Agricola's "De Re Metallica".[4]

4) Cutting, grinding and polishing lenses are all closely related. Early lenses were often casted into disks already. As the historian of optics Rolf Riekher has pointed out, it was

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[1] Sara Schechner, "Between Knowing and Doing – Mirrors and their Imperfections in the Renaissance", *Early Science and Medicine*, X, 2 (2005), 137-162.

[2] David Hockney, *Secret Knowledge* (London 2001), 74.

[3] F. Twyman, *Prism and Lens Making* (London 1952), 16.

[4] Georg Agricola, *De Re Metallica Libri XII* (Wiesbaden 2003).

the grinding of the lenses that decided over the final result. Polishing improved the lens but it could not save a badly cut or ground lens.[5]

5) Further, since only the center of the lens produced a decent image (sphaerical chromatism was known but not understood yet) the margins of the lens were usually covered by an aperture stop.
   Also, from a bunch of lenses produced only a few were considered suitable and chosen for observations and, as Catherines Wilson writes in her work on early microscopy, carefully compared and selected beforehand.[6]

6) Usually, two kinds of seventeenth century lenses are found in museum collections: spectacle lenses and astronomical lenses. This can be explained by the association of spectacles with famous individuals and of telescopes with famous discoveries. Seventeenth-century camera obscura lenses are mainly absent from collections, perhaps because they were not considered worth being collected.

7) It is worthwhile projecting images with early spectacle lenses. Although the lens quality is often limited and the field of vision not homogenous, the image is sharp and of good contrast.[7]

8) Astronomical lenses from the seventeenth century, such as the famous Huygens or Campani lenses, are of much better quality but also of great focal length. However, they are also suited for projection. Carsten Wirth has told us more about this during this workshop.[8]

9) Let me now come to the camera obscura. As I have pointed out earlier, and others before me, the number of existing seventeenth century camera obscura lenses is very limited. Also, as Martin Kemp has stated in his earlier work, not much is known about their use in terms of historic records.[9]

10) This might also explain why scholars interested in the reconstrution of camera obscura have often limited themselves to modern lenses, such as Philip Steadman or the camera obscura research group of Jena University.[10] Possible imperfections of lenses and how to overcome them were not at the center of investigation of such reconstruction projects.

11) Filippo Camerota in an earlier publication on “Painting and Topography” has pointed at the poor quality of lenses that made it difficult to achieve decent images. Optics

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[5] Personal communication. See also Rolf Riekher, *Fernrohre und ihre Meister* (Berlin 1990).

[6] Catherine Wilson, *The Invisible World* (Princeton 1995).

[7] Experiments with historic lenses were carried out at the Utrecht University Museum with kind support of the Max-Planck Institute for the History of Science.

[8] See the contribution of Carsten Wirth in this volume.

[9] Martin Kemp, *The Science of Art* (New Haven), 193-196.

[10] Philip Steadman, *Vermeer’s Camera* (Oxford 2001).

historian Rolf Willach in his studies on the development of telescopes in the seventeenh century has pointed to similar limitations.[11]

12) However, Willach has also pointed out that especially aerial telescopes in the seventeenth century produced “good images”. This has been confirmed by the historian of astronomy Felix Luehning, who has reconstructed such an aerial telescope lately.

13) As we have heard from Carsten Wirth, reducing the diameter of a lens, also by means of an aperture stop, or producing images with lenses of great focal length (and thereby reducing the effect of spherical and chromatic aberration) can still produce a good – although faint – projected image.

14) During the camera obscura reconstruction project of the Jena research group – an eighteenth century camera but equipped with a small lens – it became clear that the human eye, if given sufficient time, can well adjust to such a faint image.

15) I argue that in the seventeenth century lenses were available that were suited to produce images required for a camera obscura – even if such lenses cannot be found or are not documented. I will now try to understand how the spectator would deal with such an image. I will refer to a different optical device, the *magic lantern*, here for comparison.

16) The use of the magic lantern in the seventeenth century is well documented. The German Jesuit priest Anasthasius Kircher projected images with what he called a ‘lantern’ in Rome in the 1640s. The first reported lecture based on projected images dates from 1653/54 when the Jesuit A. Tacquet showed painted transparent pictures of a journey from China to the Netherlands undertaken by a fellow member of his order, Martin Martini. By 1659 the device had been refined to its most definitive features by the Dutch scholar Christiaan Huygens. By 1672 the ‘laterna magica’ was produced in large numbers in Northern Europe. Ten years later the lantern was already being used for the study of microscopic objects which could be enlarged and observed on a screen. Around 1700 lantern images were widely used in lectures on national and biblical themes as well as natural history and mathematics.[12]

17) From early surviving lanterns, for example in museums in Kassel or Leiden, we can assume that the quality and properties of their lenses can be considered similar to that of other lenses of their time.

18) It is worthwhile asking what effect the projected image had on the spectator. To all what we know the lantern image of the seventeenth century was convincing and had a strong impact on those who were exposed to it.

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[11] Filippo Camerota, “Looking for an Artifical Eye: On the Borderline between Painting and Topography”, *Early Science and Medicine*, X, 2 (2005), 263-285. Rolf Willach, “The Development of Telescope Optics in the Middle of the Seventeenth Century”, *Annals of Science*, LVIII (2001), 381-398.

[12] See for example Ernst Hrabalek, *Laterna Magica* (Muenchen 1985).

19) For the effect of projected image, three factors are important to be considered: belief, trust, and judgement. This is what I will look at now.

20) Antoni Malet in his treatise on “The Telescope as an optical instrument” has argued that in the seventeenth century nature-like images were not necessarily considered “better”. And, furthermore, that awareness existed that painters’ vision was subjective.[13]

21) Equally interestingly, Patrick Trevor-Roper in his book “The World Through Blunted Sight” has described different historic painting attitudes due to visual maladies. He points out that the process of perception and painting was often relativistic but that the result was not necessarily considered to be poor – often on the contrary.[14]

22) From my own experience with historic magic lanterns I can argue that the quality of the image might be poor but that the combination of projection techniques and will to believe what is to be seen can create a convincing image.

23) Martin Kemp in his work “The Science of Art” has described an artist’s practice with a camera obscura in detail. Kemp tells us that the the process was a dynamic one, “a controlled series of aesthetic choices at every stage”.

24) As Carsten Wirth has shown in his replication work, the process of image manipulation, choice of lenses and focussing – although with modern lenses – forms the basis of the optical projection process. This insight is supported by the historian of art Svetlana Alpers, who in her seminal book “The Art of Describing” on reality and realism in seventeenth-century Dutch painting, has strengthend that such manipulation was only possible if the spectator had established trust in his instruments first.[15]

25) Besides belief in what was to be seen and trust in the instrument judgement was a crucial prerequisite. Erna Fiorentini, in a Max Planck preprint titled “Instrument des Urteils”, instrument of judgement, has argued that in the case of the camera lucida the drawing process is not one of copying but of translation. Essential element of this process is the conscious control of instrument and eye. Fiorentini argues further that such visual control requires both the perception and judgement of the observer.[16]

26) What can be argued for the camera lucida and the observer interacting with it can also be applied to early magic lantern projection: working with image projection does require to reduce an image to its technically controllable features first, a method different from plain representation of images. This way the reduced image is easier to control and allows more secure judgement. Successful performance gave projectionists confidence in their own abilities and formed the basis of their judgement.

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[13] Antoni Malet, “Early Conceptualizations of the Telescope as an Optical Instrument”, in *Early Science and Medicine*, X, 2 (2005), 237-262.

[14] Patrick Trevor-Roper, *The World Through Blunted Sight* (London 1997).

[15] Sevtlana Alpers, *The Art of Describing* (London 1989), chapter two.

[16] Erna Fiorentini, *Instrument des Urteils*, Max-Planck preprint 295 (Berlin 2004).

27) Hence, it was not the question of whether an image was real or simlpy realistic that mattered to the observer but whether the image was convincing within the required demands and limitations. This argument is canvassed by media historians and for several periods. The historian Terry Castle in her work on historic magic lantern projections has concluded that the images were convincing and were often mistaken for real. Furthermore, Jonathan Crary has argued that the technisation of images, though for a much later period, led to a demand for more 'vivid' images and more refined techniques. Crary's observer was not only aware of the fact that the images were not real but also knew the techniques how to create them. Finally, the media historian Tom Gunning has claimed that it was actually the dialectics of realistic images and imagery realism which shaped the senses of the observer. Refining this dialectic technique allowed the observer's vision to be controlled and in return helped to establish trust and to shape judgement.[17]

28) In conclusion: what I wanted to demonstrate in my brief comment was twofold:

   – Although we do not find many seventeenth century historic camera obscura lenses today we can assume that appropriate lenses existed and that they enabled the production of images suitable for 'drawing from nature'. The existence of astronomical lenses and the well documented use of the magic lantern in the seventeenth century support this claim strongly.

   – From the magic lantern as well as other later optical projection devices we deduct that what mattered as much as the quality of the produced image was the control of the projected image. Crucial factors of this process were the belief in the appearance of the image, trust both in the device and in the ability to manipulate the image, and judgement while controlling the image, the instrument, and the eye.

29) Thank you!

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[17] Terry Castle, "Phantasmagoria", *Critical Inquiry*, XV (1988), 39. John Crary, *Techniques of the Observer* (Cambridge, Mass., 1990), 132. Tom Gunning, "Aesthetics of Astonishment", in Linda Williams (Ed.), *Viewing Positions* (New Brunswick 1994), 116.

PART IV

PAINTING

The Camera Obscura as a Model of a New Concept of Mimesis in Seventeenth-Century Painting

Carsten Wirth

I. INTRODUCTION

In this article I do not wish to discuss the question as to *whether* artists of the seventeenth century actually implemented the camera obscura in a painting process or not. Rather, I will investigate *how* concrete contemporary applications of this instrument might have looked, what problems were associated with it and what such an application would mean for the creative process, practically and conceptually.

From the very first instances where the camera obscura was mentioned in the literature of the sixteenth century, the image projected by the lens of this instrument has been associated with an artistic application for drawing or painting.[1] There is no argument among today's historians that the optical camera obscura,[2] which emerged in the final third of the sixteenth century, exerted an influence of some kind on the aesthetics of a number of pictures of the seventeenth century. Yet how a practical and conceptual application of the camera obscura might have looked in concrete terms is still unclear today. For a painter like myself, however, the possibility that the optical camera obscura could have been an integral component of a process of painting is so relevant that I would like to investigate in detail how this instrument could have been applied in the practice of painting, and which creative-aesthetic concepts would have been prerequisites for such an application and would have influenced it as well. These questions are closely linked to each other. Only by reconstructing the concrete way the instrument functioned is it possible to judge whether it served as a mere aid or as an integral component of a creative process.

In the discourse to date, the camera obscura generally is relegated to the role of an aid. There appears to be broad agreement that the application of the camera obscura served primarily to master those tasks which were subsumed by Rennaissance artists under the many-faceted concept of *disegno*. Thus the camera obscura is brought into line with instruments of perspective and drawing that had been utilized since the fifteenth century to obtain the coordinates and lines for a perspectivistic construction. The elements of construction gained in this manner flowed into a process of composition in which the artist, proceeding from the *invenzione*, used the line of the *disegno* to define the proportions and composition of shapes, so that these then – in a clearly separated procedural step – could be worked over with *colore*.[3] An unambiguous definition of the

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[1] G. Cardano: *De subtilitate*, Nuremberg 1550; Giovanni Batista della Porta: *Magia Naturalis*, 1st ed. (4 vols) Naples 1558, 2nd ed. (20 vols) 1589; D. Barbaro: *La Pratica della Perspettiva*, Venice 1568; Giovanni Battista Benedetti: *Diversarum Speculationem Mathematicarum et Physicarum Liber*, Turin 1585.

[2] In the following the camera obscura with a lens will be referred to as the "optical camera obscura", in accordance with the contribution of N. Wenczel in this volume.

[3] According to Vasari, *disegno* designates both an initial sketch of ideas and the complexly arranged, elaborate construction of *perspettiva*.

shape by the “immaterial” line was regarded as a prerequisite for the successful utilization of the broadly differentiated spectrum of the material color.

From the perspective of this concept of *disegno*, the role of the camera obscura must appear problematic: Those tasks which the trained Renaissance master accomplished through analytical spirit and the mastery of geometry were, so runs the assumption, fulfilled by the naturally generated projection of the camera obscura without any effort by the artist. The projected image is equally accessible to the untrained, non-inspired amateur, who need only transcribe this image to appropriate *disegno*. The result is therefore no longer based on *invenzione*. As a consequence, declaring that a painter used the camera obscura challenges his accomplishment as an artist and the status of the artwork he produced.

Yet assuming that the camera was restricted to *disegno* tasks implies that the optical camera obscura was utilized for a purpose that had been defined and mastered before the advent of this instrument. It also presumes that there was no problem in attributing the actual image projected by the camera to the theoretical Renaissance concept of “image.” It further implies that those optical properties of the camera’s optic that did not correspond to the traditional concept of image, or which could not be explained in terms of this concept, were classified as optical errors and corrected accordingly. However, this approach completely excludes the possibility – suggested by contemporary descriptions – that the image projected in the camera obscura was perceived as something exotically different and novel, something that challenged the Renaissance concept of the image and the conventions of representation.

> It is impossible to express its beauty in words. The art of painting is dead, for this is life itself, or something higher, if we could find a word for it.[4]

When Constantijn Huygens, a connoisseur of the arts as well as of the sciences of the age, wrote these lines about image projection by the optical camera obscura in 1622, this instrument has already been around for over 50 years. The conceptual critique of painting seems astonishingly modern, imparting the impression of the enduring effect of the novel aesthetics of the camera’s image projection, which must have appealed to contemporary painters as well.

There are no descriptions from the early seventeenth century that document an artistic use of the camera obscura. For this reason it is customary to fall back on the first written sources (Barbaro, Benedetti, della Porta) of the sixteenth century[5] to provide evidence of the introduction of the camera as a *drawing* instrument. Yet it is not surprising that mathematicians like Barbaro, and even Cigoli, who was not only a painter and author, but also a theoretician, regarded camera projection primarily under the aspects of *disegno* and *perspettiva*. Della Porta’s concrete instructions for direct painting using the camera, on the other side, is generally ignored.

> If you cannot draw a picture of a man or anything else, draw it by this means; If you can but onely make the colours. This is an Art worth learning. [...] one that is skill’d in painting must lay on colour where they [*the projections*] are in the Table, and shall describe the manner of the countenance; so the Image being removed, the Picture will remain on the Table [...][6]

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[4] Constantijn Huygens, Letters 1622.
[5] See note [1].
[6] Della Porta: *Magia naturalis*, b. XVII, 6.

The premature restriction of its use to certain camera models and techniques, and the presupposition that it functions as an aid for *disegno* tasks, also have to do with the fact that no single apparatus has been preserved from the first century of the optical camera obscura's existence. Thus attempts at reconstructing seventeenth-century camera models and their application have usually resorted to camera models from the eighteenth century.[7] These are typically tent-type or box-type cameras,[8] which generally were designed to perform only certain, specific tasks: They project a small image, usually used for landscape drawings and architectural drafts (as created by *vedutisti* like Canaletto[9]). These models are extrapolated backward to the seventeenth century, by way of subtracting the technical progress achieved in the interim as regards the quality of lenses and mirrors. The dilemma is obvious: On the one hand, the performance of these technically inferior models must remain unsatisfactory; on the other, the eighteenth-century instrument, from which the reconstruction starts, was designed for a specific task, which is unconsciously assigned to the hypothetical seventeenth-century apparatus by this reconstruction. In this way, a certain course of development is presumed for the instrument and its application (from the sixteenth into the eighteenth century), although the evidence for this course is anything but sufficient.

The phenomenon of the *optical* camera obscura, which was described for the first time by Cardano in 1550, defied categorization as an instrument with standardized design and established application until around 1670, remaining a variable and experimental design. Thus I would see the artists of this time as anything but passive users of an already existing device made available to them by an external party. Rather, they would have manipulated the (natural) phenomenon of image projection in a dark space by means of the lens, a diaphragm and mirrors according to the intention inspired by the projection.[10]

Conceiving of the camera obscura as nothing other than an expedient instrument in the manner described above does not do justice to the visual experience of the viewer in the camera obscura. What makes the camera obscura so special compared to other optical instruments is its direct correspondence to the human eye, which it emulates. It places the viewer in the eye itself, letting him look at the retina. The viewer is offered a vision of where and how seeing takes place: The camera obscura portrays the optical process of vision, making it a conscious experience so it can be studied by observation. Like today's perception theoriests, Kepler became aware that the interface of perception lies here, where light becomes sensation. The retina is replaced by the canvas. Within the camera this is the workplace of the painter, who has shifted his task from a *retroactive reproduction* of nature to the *evocation* of its manifestations.

The camera separates the painter from his motif, excluding the surroundings and functioning as a perceptual filter. Incident light is selected (aperture), concentrated (lens) and investigated

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[7] Steadman's reconstruction is an important exception to this practice. P. Steadman: *Vermeer's Camera*, Oxford 2001.

[8] For a classification of the various types of camera obscuras, see Norma Wenczel's contribution to this volume.

[9] Van Vitelli is an early example of the late 17th century. Like Thomas Sandby later in the 18th century, he obviously added data of single projections to create a wider panoramic view.)

[10] The first descriptions of the camera with a lens as a boot-type camera are best regarded as small optical laboratories, in which the components lens, aperture, mirror and projection screen were arranged experimentally for the purpose of testing or elaborating an application. Such variable camera models were determined by the special demands of the application.

through manipulation (movement of the focus). The eye of the painter is located within another, artificial eye, a *studiolo* of visual perception. Astonishing phenomena can be established in the camera obscura, as objects of a motif are rendered differently in the projection than they are perceived through direct observation. The manifestation of things seen through the "*oculus artificialis*," the artificial eye of the camera, is quite different from the direct perception of the human eye, which is perceived to be the natural, "actual" state. When a motif is selected or set up this changed "sight" also influences the choice of colors, contrast values, the selection of objects, the placement of light, etc. – everything is evaluated and selected in terms of its effect in the projection. The set is designed according to criteria determined by the camera. The view through the camera thus changes the way artistic criteria are defined. The motif becomes a set, a stage with props (among which sometimes even dolls are decorated[11]), which is manipulated in order to evoke certain effects in the projection.

The camera changes not only the appearance of the motif, but also the motif itself. The point of departure for the process of painting is no longer reality, but rather a projected reality. The projection becomes the motif – a metamorphic image composed of the individual images seen in the camera. The camera stands for a shift from a naturalistic realism to a representation of reality in which the process of seeing is conceived as a part of the things themselves. That's why I understand the *camera obscura as a model of a new concept of mimesis* in the art of the seventeenth century. The focus shifts away from the question as to *what* is protrayed (*historia*), toward the question of *how* something is portrayed (*maniera*). Interpreting the form of what is seen becomes more important than narration.

An application of the camera obscura in which a direct projection on the canvas is used for painting would allow the artist to grapple with the form of representation in this manner, and may have been realized by artists in the seventeenth century. Thus I do not proceed from the assumption that the use of the camera was restricted to *disegno* tasks, although there were certainly always applications of this kind as well, but rather I am interested specifically in a " painterly application" of the camera. That is, an application of the projection of the camera that serves not only to locate points and lines, but to modulate light values: The picture is painted in the camera itself, in a procedure to be discussed in greater detail below. The paint modulation according to the projection on the canvas offers an interpretation of the projected light structures, which are subject to constant modification during the painting process – these modulations of color do not establish a congruent correlation like the traced line. What I am interested in here is thus a process of painting using both, the motif and the projection.

In this process the painting gradually grows through the projection of the image, which coalesces with what was painted to compose a hybrid image of projection and paint, until these cancel each other out by superimposition. This is not a process of reproducing the image, but rather makes it possible to integrate the projection into the painting process. Painting directly in the camera obscura is thus a condition for an artistic process that integrates phenomena of projection in the production of the work of art.

This thesis entails a number of technical and practical requirements, which I do not simply postulate, but have developed and tried out in practice on the basis of several specially designed

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[11] See the letter of G. Terborch the Elder to his son G. Terborch the Younger, in Wheelock: *Gerard Terborch*, New Haven and London 2004, p.188-189.

camera prototypes. The most important of these requirements must be mentioned in this introduction, even though they cannot be portrayed concretely until the discussions below:

1. Orientation of the projection

For the camera obscura model I proceed from the assumption that an upright and not laterally reversed projection is required for an artistic application. This orientation of the projection allows the painter in the camera to create a direct analogy between the projection of the motif and his direct view of the motif. After my experiments with the camera, I see the foundation for an artistic application in alternating comparisons between the projection, the painted picture and the motif.[12]

2. W3 camera model

As none of the camera obscura models discussed to date yields a corrected projection on a *vertical* canvas,[13] I will introduce along with my thesis the model W3 which I specially developed to fulfill all of the requirements described: W3 projects an *upright* and *not laterally reversed* image on a *vertical, opaque* projection screen (see figure 1 in Part II). Through the vertical position of the projection there is no limitation to the image-size or the size of the projection. Furthermore, this model allows coordinated refocusing. This problem of coordinating several focus settings of a camera obscura optic to project a coherent image of a space with correct perspective had not yet been solved systematically.

3. Refocusing

Refocusing becomes necessary because the objective of the camera is not capable of creating sufficient depth of field throughout all areas of the motif. In opposition to conventional argumentation, this is not due to the inferior optics of the seventeenth century. As experiments show, with such a large projection size in the camera, refocusing is required even with a modern, corrected triplet objective.[14] As I will demonstrate on the basis of examples, the W3 camera model offers special possibilities for controlled refocusing even on larger canvases and projections.

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[12] All early descriptions of the camera obscura with a lens always mention the correction of the projected image using mirrors. Barbaro, Benedetti, della Porta, and nearly every author offer suggestions for how to turn the picture around, especially when the projection is to be used for drawing or painting. In opposition to various suggestions that consider a camera model with an upside-down projection, contemporary sources clearly regard a vertical inversion of the image as an obstacle for artistic exploitation. Of course, this is not the case for projections that serve merely to determine individual coordinates, for rendering perspective, for instance.

[13] See the contribution of Norma Wenczel to this volume.

[14] Experiments were conducted with three Liesegang Meganast Triplets: 1.) f = 1000mm / aperture c.180mm, F = 5,6; 2.) f = 800mm / aperture ca. 180mm, F = 4,5; 3.) f = 600mm / aperture ca. 180mm, F= 3,8.

4. Objective Lens

Thanks to the possibility of refocusing, the limits of material technology and errors in portrayal to which the optic of the camera obscura is subject as well as the main problem identified, limited depth of field, lose their categorical significance. The most important criteria that then emerge are brightness and the size of projection, which place certain demands on the objective.

In previous reconstruction experiments, attempts were made to approximate the possible level of optics of a camera obscura in the seventeenth century by drawing on the documented standard for telescope lenses in the glass technology of the period. This is problematic, not least because the telescope lenses of the seventeenth century are impracticable for the luminosity required by the camera obscura due to their limited diameter.[15] Due to this fixation on measured, solid glass lenses ground to the highest precision, that is, on "high-tech" objectives unattainable by the average artist, the possibilities of an experimentally applicable "low-tech" optic have yet to be considered.

5. Water lens

An important component of my thesis and instrument in my experiments is the water lens or fluid lens, a "low-tech" optic I manufacture myself. For the first time, I would like to propose this type of lens as an optic for the camera obscura of the seventeenth century. The standard of contemporary hollow glass technology involved in producing such lenses would mean entirely different technical conditions for the quality of projection in the camera obscura. For instance, water lenses could be constructed with diameters that allowed very bright projections. Furthermore, the simplicity and availability of the technology make it possible to handle this optic empirically and experimentally, allowing its further optimization and adaptation to individual demands. The water lens, a glass filled with water, was accessible also to less privileged contemporary painters.

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In what follows, I would like to argue for the plausibility of my thesis by describing how I developed and examined them with the means at my disposal as a painter. The camera model used for my experiments originates from the ongoing development of prototypes I am constantly modifying for my own art work. Inspiration and ideas for these come in part from examination of exemplary artworks of the seventeenth century. Because I do not want to separate technical and practical issues from artistic and conceptual ones, I will reconstruct examples of procedures for working with the camera.

After a brief explanation of my camera model W 3 based on the prototype I used and the optic used with it (II), I will describe two models of working using the example of two different seventeenth-century painters, whose work is well studied and documented, namely Johannes Vermeer (III) and Diego Velázquez (IV).

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[15] Small lens diameters are described as a problem by all authors of camera obscura reconstructions.

While I presume that both artists used the camera obscura (in different ways) to create pictures, this question is not the object of my argumentation and experimental investigations, as I emphasized at the outset. For before this question can be answered, answers to more concrete questions must be found: questions of the optic, the painting technique, the method of application, and ultimately also the question of the artistic conception of the artwork itself. In this context I believe the question as to "how" to be more seminal than the question of "whether." For in the end the results of my reconstructions may also serve to clarify criteria for judging those paths of argumentation that reach other conclusions.

My method thus consists in reconstructing a scenario that permits the experimental investigation of an application of the camera obscura in the art of painting. The objective is not the reconstruction of a historical instrument or a picture (I do not try to reproduce any Vermeers), but rather the reconstruction of a methodology that allows assertions about an artistic concept. Just as the painters used the camera to approach a motif, so I use this instrument here to approach a concept of these paintings. For this I consciously selected pictures by painters whose depicted pictorial space can be compared, through reconstruction, with the actual space of the motif. The hypothetically reconstructed application of the camera obscura in the painting process must then hold its ground within these narrow requirements.

II. MY CAMERA MODEL

1. W3

With the W3 I am introducing a new camera obscura model. It is distinguished by the advantage that it can project an image upright and true to side on a *vertical*, opaque surface – canvas projection (**CP**). By employing two independent projection screens – **CP** and reference projection (**RP**) – , W3 opens up a spectrum of options for focusing in a coordinate manner.

Figure 1 shows the camera W3 along with the projection of the motive – the head of a person – on the two projection screens. It is a boot-type camera obscura: The motive is in an adjacent room (behind the black curtain), and the light enters the darkened room through the lens and the diaphragm. The position of the unit consisting of lens, diaphragm, and mirrors can be changed vertically along the blue line labeled ***b*** (figure 1b).

If mirror **M1** is pivoted off the **X-axis** (figure 1a), the light proceeds straightly from the aperture to the opposite vertical screen, the reference projection (**RP**), producing an image that is upside-down and reversed left-to-right – the classic camera obscura projection. Since no light-absorbing reflection of mirrors is involved, this projection is the brightest possible and particular apt for increasing the depth of field by reducing the aperture.

Apart from the screen **RP**, all components of W3 – lens, diaphragm, mirrors, and **CP** – are mounted on a dolly that is movable (on tracks) back and forth along the **X-axis** (that is, along the blue line ***a*** on figure 1b). By moving the dolly, a refocusing of the lens is accomplished. Such a refocusing means a change of the object-distance (distance between object and lens) as well as, for the (unmoved) **RP**, a change of the image-distance (distance between lens and projection screen).

If mirror **M1** is pivoted into the **X-axis**, the light is reflected by an angle of 90 degrees into the plane of the **Y-axis** (figure 1a) where, through further reflections by mirrors **M2** and **M3**, it is projected onto **CP**, producing an image that is correctly oriented – neither upside-down nor reversed left-to-right. A special advantage of W3 consists in the image-distance for the **CP** that remains unchanged by such a refocusing. This allows the projections on **CP** to be adjusted, which change in size through refocusing, according to the reference projection on **RP** (in null position). The steps of this refocusing process will be described in detail below in part III 13 to 15.

Adjustments of the focus for **CP** can be accomplished in various ways:

1) By moving **CP** along the blue line ***c*** (figure 1b).

2) By moving the mirror unit **M2/M3** along the blue line ***d*** (figure 1b) – a rise of 100 mm magnifies the image-distance by a factor of 2.

3) Naturally, refocusing is also possible by moving the lens along the blue line ***f*** (figure 1b). However, this move changes the setting of the focus for **RP** as well.

All of these adjustment options can be combined. The fewer components of the camera are moved when refocusing, the easier and more precisely can previous focus settings be reinstalled. In adjustment option 1), the position of the lens remains unchanged. In adjustment option 2), the position of lens *and* **CP** remains unchanged – a significant advantage if one wants to shift from one projection screen to the other by just pivoting mirror **M1**.

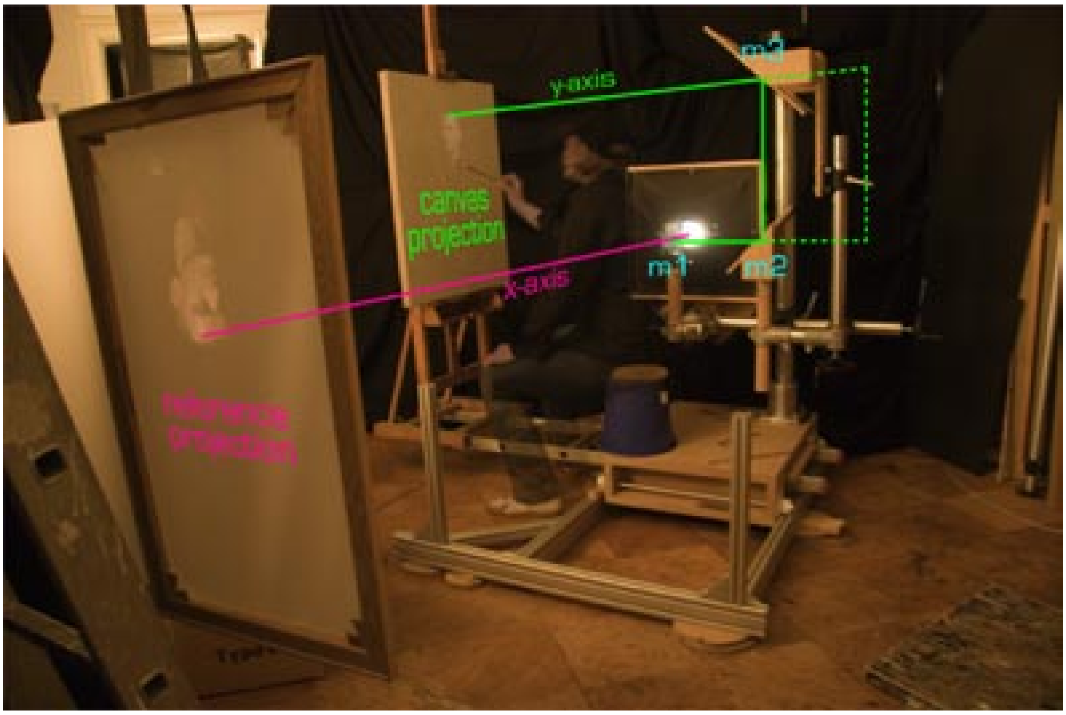


Figure1a: The Camera Model W3 – The paths of the light rays for the two projection screens.

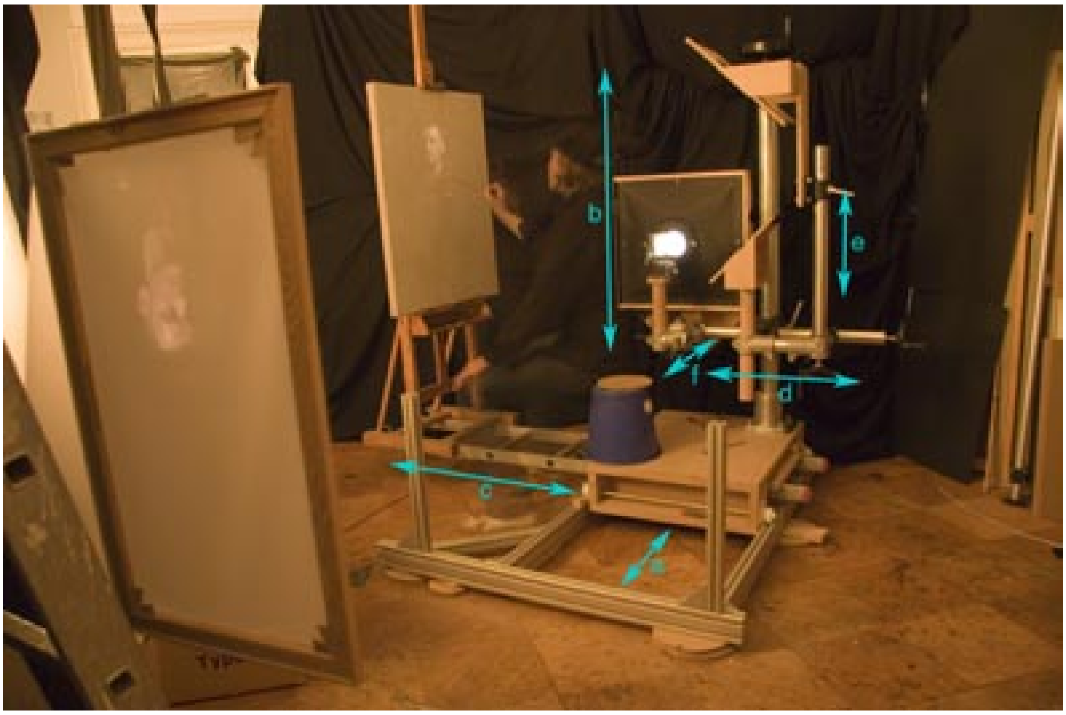
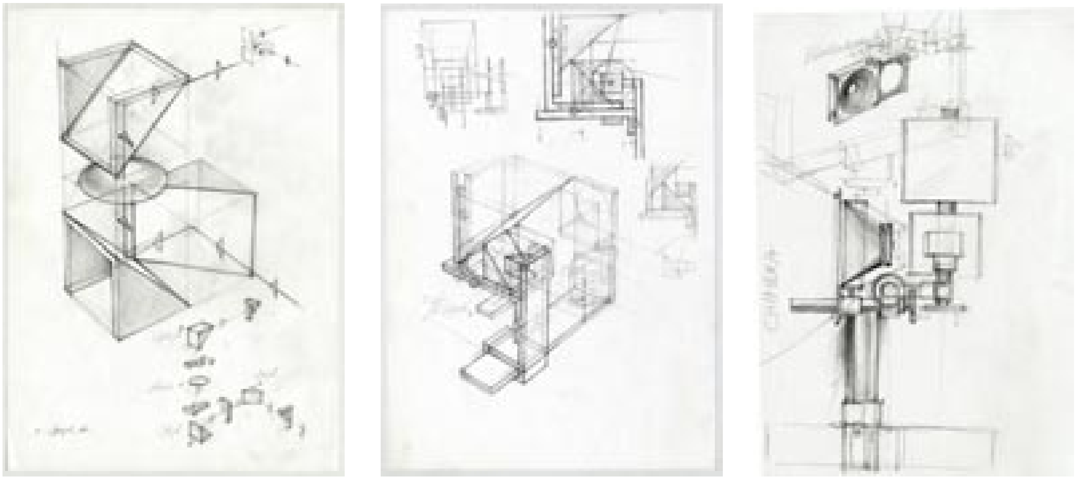


Figure 1b: The Camera Model W3 – The blue lines indicate the possibilities of moving the different parts and units of W3.



Figures 1c – e: The Camera Model W3
c: Modifications of the projection by a lens and three mirrors in W3, including (below) a demonstration of the image inversions indicated by the capital letter F.
d: First sketch for an improved arrangement of mirrors with optimized sizes and moving possibilities in W3.
e: Design sketch of the mounting of the optic unit (lens, diaphragm, mirrors) of W3.

2. Optic

The initial question when attempting to “reconstruct” a historic camera obscura is which lenses were available to an artist in the seventeenth century for such an instrument. No lenses from the seventeenth century have survived that can be clearly attributed to application in a camera obscura. The few lenses from the seventeenth century that can be dated with any certainty are telescope lenses by renowned lens grinders who signed their products. The few survivng examples represent the standard of contemporary “high-tech” optics. However, the lenses for the camera obscura-applications discussed below demand different qualities than those of the typical telescope lenses.[16] While the purpose of a telescope is to enlarge the direct view of an object in infinite distance, the function of a camera obscura optic is to project the image of a relatively close object on any projection surface (but many times larger than the image projected on the retina of the telescope viewer), and to make this projection relatively large and as bright as possible.[17] Therefore the lens in the camera should be as “bright” as possible, that is, have as large a diameter as possible and a corresponding aperture ratio to allow the generation of a large, bright projection. So quite naturally, already in the earliest reports, larger lenses are specified explicitly as ideal for

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[16] When the lens technology of the early seventeenth century is assessed, the first telescope lenses are often referred to as standard. A comparison of a contemporary camera obscura lens with the technology of astronomical instruments is inappropriate, because it does not take into consideration the different demands of the two optical systems. The mere fact that the optical camera obscura is significantly older than the telescope makes clear that there can be no meaningful comparison between the optical standards to which telescope manufacturers aspired and the optic implemented in the camera obscura.

[17] Of course, projections were also generated using telescopes whose eyepieces had been removed. But when the camera is applied not for purposes of astronomy, landscape panoramas or miniatures, but rather, as in the case of the selected examples, for the projection of relatively close objects in a certain image size, its diameter and aperture ratio must be different than those of the contemporary telescope lenses.

the camera obscura.[18] As late as the second half of the seventeenth century, Hooke recommends using as a lens a " *[...] Glass, which the larger it is the better, because of several Tryals that may be made with it, which cannot be made with a smaller [one].*"[19]

It was not so much the technology of lens grinding, which was still fairly undeveloped at the beginning of the seventeenth century, but rather the limitations of glass technology that presented a problem with regard to producing an objective for a camera obscura with a significantly large diameter. Defects in the glass or an irregularity in grounding have devastating effects in astronomic optics. In contrast, the image of the projection in a camera obscura is fairly insensitive to such faults. Many of the defects that are disturbing in a telescope optic are barely – or not at all – perceptible in the projecting optic of the camera. An unbiased viewer with no concept of a perfect optic might even admire the multiple optical effects in the image of the projection rather than judging them to be a disturbance: From this perspective the *Seidel aberrations* are light phenomena that can be of interest to the painter, "beautiful" defects, so to speak. The identification of "optical imaging defects" is anachronistic for the early seventeenth century. After all, around 1600 there was still no such thing as "aberrations."[20] A number of the quite visible effects, like the points of focal distortion caused by astigmatism, for instance, are worked into paintings as forms of a new aesthetic.[21] Others, like the spherical aberration occurring in any uncorrected single-lens objective, can be easily modified by using diaphragms and refocusing.

However, it is not the diameter of the lens alone that is crucial here. The size and brightness of the projection are dependent on two interacting factors, namely focal distance and diameter. The most important indicator of the relationship between these factors is the aperture ratio defined by the f-number: f/N.[22] The greater the focal length, the larger the scale of the projection. For large projections, however, a correspondingly large amount of light is needed as well, that is, a large aperture. A lens with a large aperture and a small focal length generates a bright, small projection. With the correct balance of these values, when a large focal length is combined with a large aperture, even large projections can be sufficiently bright for the camera. The correct ratio of these

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[18] See for example W. Bourne , *A Treatise on the properties and qualities of glasses for optical purposes, according to the making, polishing and grinding of them* (c. 1585) , in Van Helden, *The Invention of the Telescope*, Philadelphia 1977, p. 33: "… to make a glasse for perspective … [it] maybe rounde, and bear a foote in diameter; as fine and white Vennys Glasse. And the larger, the better …" This "glasse" belongs to an instrument for surveying, made up of a lens and a concave mirror, which often is seen as a forerunner of the telescope since Bournes desciption is interpreted in the sense that the observer sees a virtual mirror-image and not an image projection like in the camera obscura.-J. Kepler recalls having seen in Dresden a camera obscura with a lens of one foot in Diameter (330mm) in J. Kepler, *Paralipomena*, (1604). In the *Dissertatio cum Nuncio Sidero* (1609) he states that he has projected the image of the moon onto a screen placed at a distance of no less than 12 feet (about 4m) from a lens of large size. (See F. Camerota in *Early Science and Medicine,* Vol.X No.2 (2005).

[19] R. Hooke: *Posthumous works*, 1705, sect. V, under 6. from June 1681, p. 119.

[20] Kepler's analysis of the varying image sizes of the diameter of the moon, which ultimately contributed to the understanding of the optical path of light in the camera obscura, refers to an image phenomenon, but does not describe optical image defects like Seidel aberrations.

[21] Seidel aberrations have different effects for a camera than for a telescope. While effects like coma and chromatic aberrations are decisive in astronomy, but are barely noticeable in the camera, spherical aberration is the most disturbing error with respect to image projection in the camera obscura, an error, however, which can be compensated for even by primitive diaphragms. – On lens quality in the seventeenth century, see Molesini in this volume.

[22] See the contribution of G. Molesini in this volume.

proportionalities depends on the task at hand: Thus the projection of, for example, a landscape takes place under different conditions than a projection for a portrait.

Because the focus usually can be set to infinity in a landscape or cityscape, the depth of field does not present a problem. The focal length can be relatively small for a drawing of a panorama, for instance, resulting in a wide-angle setting (as in landscape photography). The small scale of the illustration allows many objects to appear in the central area of the focus. The topographical drawings of the eighteenth century are thus not terribly demanding in terms of projection technology.[23] For a life-size projection of a person, however (for a portrait, for instance), a practical focal length would lie between 800 and 1000 mm (because of the size of the projection and the distances between the the model, the camera and the canvas).

The conditions in the camera can be demonstrated for the example case of a life-size image for a portrait, yielding the following proportional relationship: If the object on one side of the lens and the projection surface on the other are both placed at a distance of the double focal length from the lens, a life-size image will be generated. For the focal length of 1 m I used, this means that the subject of the portrait sits 2m away from the camera, while the canvas must also be located 2 m from the interior of the lens.[24] The projection size of a lens with such a long focal length demands a correspondingly great amount of light in order to generate enough brightness in the image. A large aperture is thus a *conditio sine qua non*. The diameter should be large enough for the objective to achieve an aperture ratio of around 1:3, which can be stopped down to increase the depth of field.

The shape of the lens is another important parameter, for different shapes of lenses have different imaging characteristics. The shapes of lenses interesting for us here are biconvex and plano-convex.[25] In experiments, biconvex lenses showed a stronger focusing on a centered area, while plano-convex lenses distribute the light more equally, and when the planar side is directed toward the object, distort least throughout the entire field of the projection. A possible consequence would be to use biconvex lenses for portraits, and plano-convex lenses for the perspective of rooms.

This conclusion yields the following optimum lens shapes: For the example of a life-size projection, the suitable optic would thus be a plano-convex (for perspective) or biconvex lens (for portraits) with a diameter of 330mm and a focal length of approximately 1000 mm (aperture ratio of approx. 1:3). The size of such lenses would correspond to earlier descriptions of large lenses by such authors as Bourne and Kepler.[26] From what is known today lenses of this size could hardly have been produced using the solid glass technology of around 1600.[27]

If optics with a diameter of a “foote” (approx. 300 mm) diameter, as described by Kepler and Bourne, truly existed around 1600, we must assume that they were quite different from the “high-tech” optics of astronomy used in the telescope. That means, we must assume that they originated

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[23] A lens with a focal length of 450 mm and a diameter of 100 mm, i.e., an aperture ratio of 1:4,5, is very well suited here. The projection covers a medium-sized sketch pad.

[24] This example also demonstrates the advantages of W3 - in a tent camera, the only other model that projects “correctly,” this arrangement is not practicable due to the long distances between lens and projection plane.

[25] Positive meniscus lenses described as the optimum single lenses later, e.g. by Wollaston, are out of the question historically.

[26] See note [18].

in a "low-tech" optics, developed earlier than or parallel to that of spectacles and telescope lenses. What might such a "low-tech" optic for the camera have looked like?

A "low-tech" optic would had to have been distinguished by a relatively simple and thus easily accessible technology that allowed the empirical optimization of projection processes. The possibility of *trying out* this optic to achieve an ideal imaging performance for the camera would be especially important. These conditions are fulfilled by the water lens.

Even before light is investigated with ground glasses, the experimental arrangements using liquids, that is, transparent media that occur in nature, are what are used to study the phenomenon of the refraction of light when it enters a medium of other density.[28] So in the early fourteenth century for example Theoderich von Freiberg demonstrates the reflection and refraction of light in the water drops of the rainbow using a glass sphere filled with water. [29] Later on water filled glass containers obtain an important exemplary role for the human eye or for its individual components. In addition to a geometric theory of optics, there also exists an experimental optics, whose tools are the water lens and later the camera obscura.

In many treatises about optics, the glass filled with water is mentioned as a substitute for crystal or glass lenses. In his expanded edition of the *Magia naturalis* of 1589, in which the camera obscura is described with its "small lenticular (convex) Crystal glass to the hole," Giovanni Battista Della Porta, too, points out the possibility of replacing a crystalline lens with a glass filled with water:

> ... in the place of this we may use a vial full of water. But the most violent of them all, is with, A Crystal Sphere, or portion of it.
>
> And if a sphere be wanting, we may supply it with a vial full of water, that is round and of glass, set against the sun. If you set behind it any combustible matter, that is friendly to the fire, so soon as the rays unite about the supersicies, it forthwith kindles fire to the wonder of the spectators. When they see fire raised from water, that is extreme cold, so will the portions of spheres, as spectacles, lenticulars, and such like, which we spoke of already. [30].

This casts a new light on the oft-bemoaned lack of historical lenses appropriate for use in a camera obscura. In the place of solid glass lenses, water lenses – vessels of hollow glass filled with water – were also usable as optic for the camera obscura.

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[27] Beyond the problem of grinding techniques, the manufacture of the glass itself would have presented the greatest problem. The material technology challenge consists in the size of a grindable glass blank. Correspondingly large panes of glass suitable for grinding may have exhibited considerable irregularities, making them unserviceable for astronomy, but would have been of a quality sufficient for camera obscura-objectives. It would not have been possible to grind a lense of this size on the grinding lathe in use at the time.

[28] In her standard work Mary Luella Trowbridge concludes: : „*At a very early time the lens for no doubt grew out of observations made on glass globes and burning glasses.*" Philological Studies in Ancient Glass, Urbana1930. See the literature on optics from Euclid, to Ptolemy, all the way to al Haitam, R. Bacon, and Witelo.

[29] Boyer writes: "… *but until the thought occured to Theoderich, no one had hit upon the brilliantly ingenious idea of bringing the rainbow into the laboratory through the simple expedient of envisaging the globe of water as a magnified raindrop*" in Carl B. Boyer: "The Theory of the Rainbow: Medieval Triumph and Failure", *Isis,* Vol. 49, No.4 (1958), pp. 381ff.

[30] Della Porta: *Magia naturalis*, b.XVII, 19.

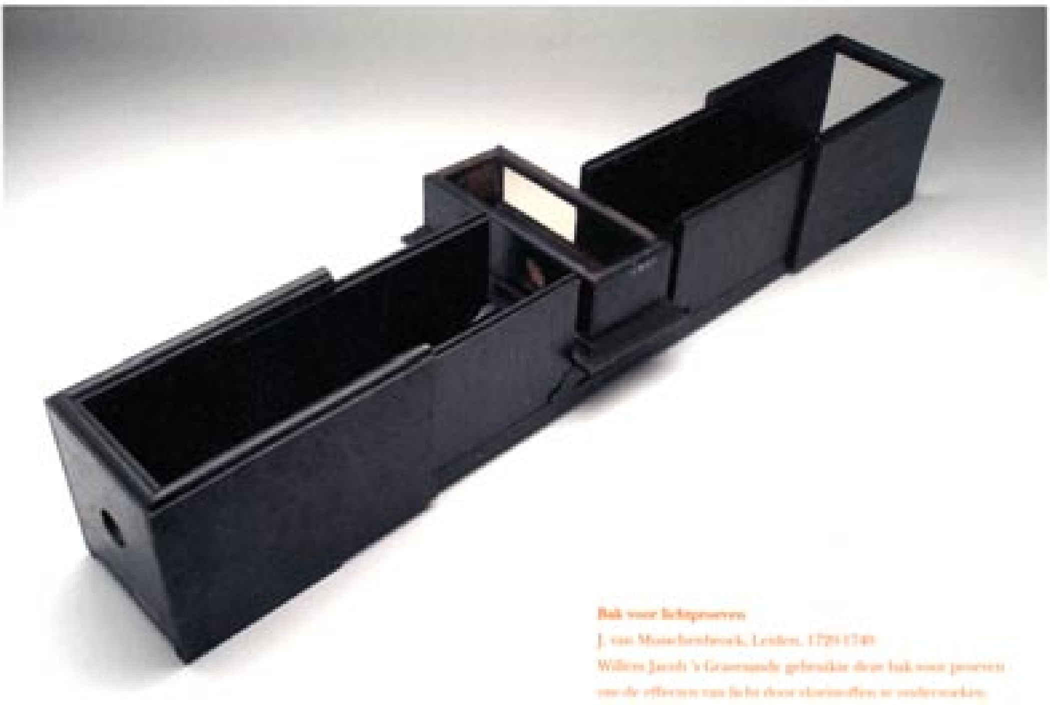

Figure 2a: Water Lenses I – "Optical bench" made by J. van Musschenbroek (c. 1720-30) the flexible structure of which allows the intervals and positions of different liquid lenses to be varied and combined in order to study their effects. The shape of the glasses and the hollow volume to be filled are variable.

Figure 2b: Water Lenses I – Simple water lenses in the 17th century could have looked like these ones that consist of convex plate glasses made of hollow glass and flat sheets of glass, stuck with putty into wooden frames or boxes.

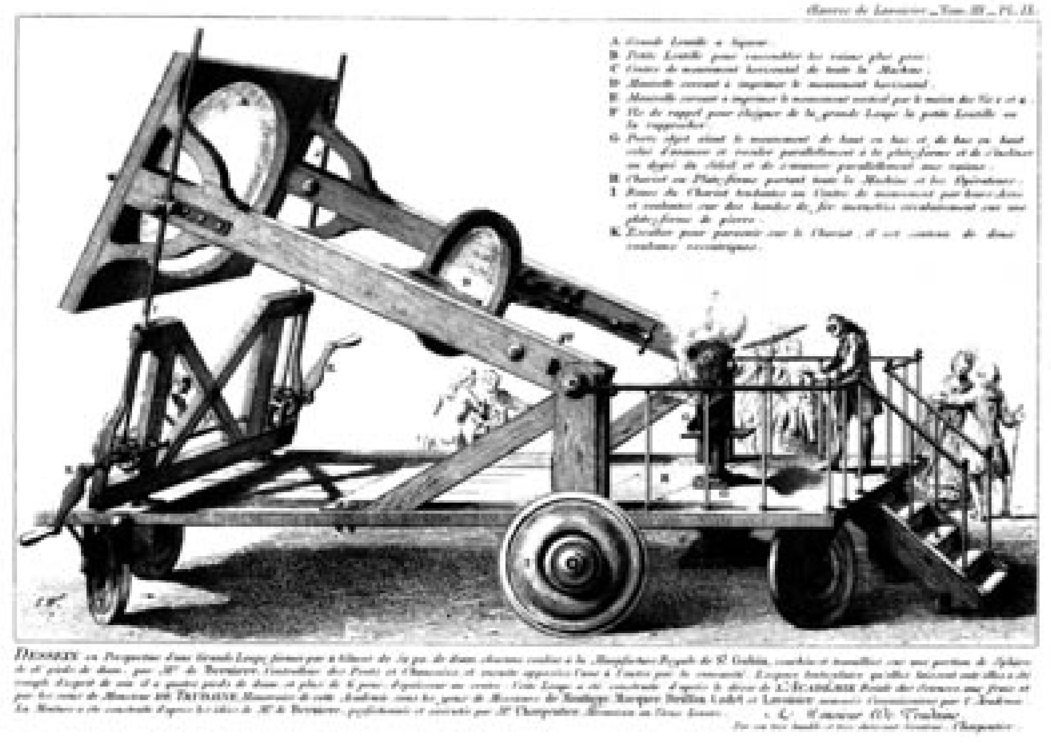

Figure 2c: Water Lenses I – Water lens comissioned by Trudaine and manufactured by Bernier and Carpentier (late 18th century). The lens which was used as a solar burning glass, measured c. 130 cm in diameter and consisted of two glass spheres filled with water or spirit.

The greatest technological advantage of the water lens consists in the fact that it can be manufactured of thin hollow glass. Almost all of the glass production in the sixteenth and early seventeenth century consisted of hollow glass, which had achieved a very high standard. As the numerous examples of preserved vessels and depictions of convex mirrors show, hollow glass was manufactured in the form required here. The hollow glass of the water lens does not have to be ground; rather, its spheric form determines the radius of curvature of the lens's shape.

A glass bowl filled with water already constitutes a plano-convex lens, whose horizontal water surface represents a perfectly level optical surface. However, if the lens is to be used in an upright position, it must be closed as a vessel. Thus for the flat side of a plano-convex lens a glass plate is needed, for instance, a ground and polished plate of cristallo, a nearly colorless and particularly clear and homogenous soda glass, that was manufactured for Venetian mirrors since the mid-sixteenth century. Because of its planity, Venetian plate glass, ground exactly level on both sides, is the ideal component for the flat side of the plano-convex water lens. [31]

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[31] Through (two-sided) grinding followed by polishing on iron tables, even at this time it was possible to achieve high planity of plates of glass made from cylinders rolled out in the stretch oven. The Milan scientist Hieronymus Sirturus mentions this technique in: *Telescopium Sive Ars Perfeciendi Novum*, 1618; see also Rolf Willach, "The Development of Telescope Optics in the Middle of the Seventeenth Century", *Annals of Science* 58 (2001), p.385; Inge Keil: *Augustutanus Opticus*, 2000, p.233; see also the contribution of G. Molesini in this volume.

The usual method of manufacturing convex bowls involved cutting circle-shaped segments from spherical glass balloons. These inflated balloons originated on the blowtube and could be manufactured at considerable sizes. If such a spherical shape is generated exclusively by the interior pressure of the air blown into it, there is no material distortion through contact, and (for homogenous materials) a nearly perfect sphere is formed. The surface of the thin-walled glass is extremely smooth and even, especially when it is freely suspended during fire-polishing. This glass globe for the convex spheres of the lens were also supposed to be manufactured of *cristallo*, as tiny air bubbles are the only irregularity contained in this material.

The diameter or radius of curvature of the cut-out globe segment is limited by the size of the glass balloon.[32] To manufacture even larger glass spheres with a greater radius of curvature (flat belly, large focal length), it was also possible to use hollow glass plates, which were manufactured using the cylinder method: Plates laid onto a metal ring, direct from the stretch oven before cooling, sag under the material's own weight and form a spherical shape. The tolerances in the thickness of the glass are insignificant in this process, as the glass sags evenly.

No large spheres are required for the plano-convex water lens I use. What is important is the radius of curvature of the segment, such that relatively small bowls can be manufactured, barely larger than the maximum aperture of the diaphragm.

Figures 3a – b: Water Lenses II
a: Self-manufactured spheres of plexi-glass which form the convex side of a water lens.
b: Self-manufactured plano-convex water lens. Diameter: c. 380 mm, focal length: c.1100 mm.

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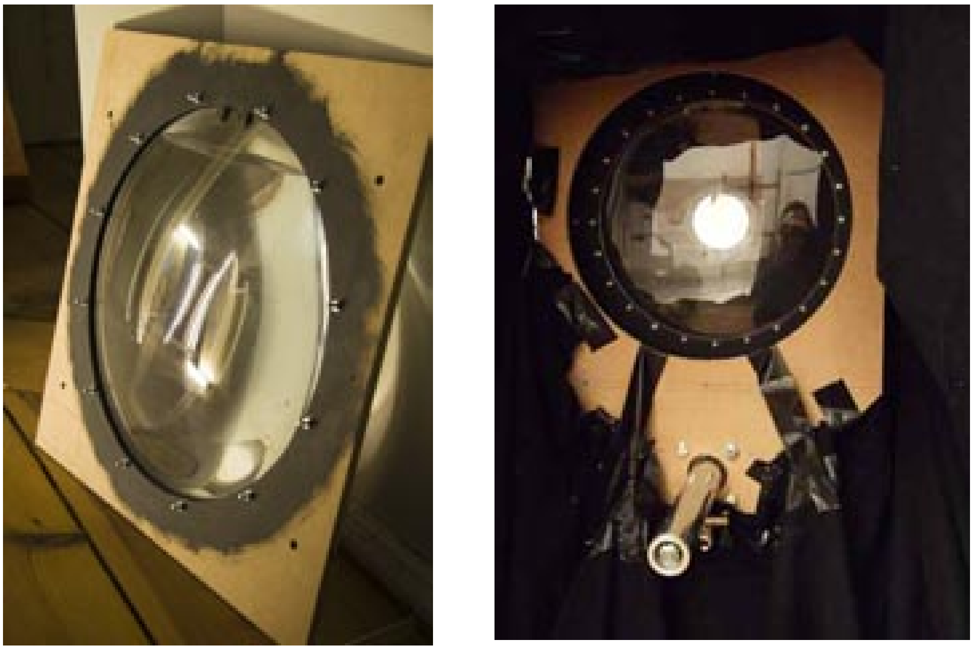
[32] The balloon becomes distorted when the weight of the glass becomes too heavy.



Figures 3c – d: Water Lenses II
c: Self-manufactured bi-convex water lens. Diameter: c. 380 mm, focal length: c. 550 mm.
d: The lens mounted on camera W3, seen from outside the camera. Through the opening of the fairly closed diaphragm light is seen from inside of the camera.

The water lens I built is composed of a flat and a convex-shaped Plexiglas disk, with the space between these plates filled with distilled water (of which the refraction index is approx.1.33,[33] and thus less than the index of the historical glass used for telescope lenses, which was approx. 1.5[34]). The spherical shape of the convex disc was achieved through thermoforming as described above for glass plates, that is, by placing a heated Plexiglas disk on a ring. As described above, the heated material sags into a spherical shape – with a bit of experience, this process can be controlled fairly well. The actual shape of the lens corresponds to depictions of large convex mirrors, like the ones seen in paintings of the sixteenth and seventeenth centuries. This similarity might raise questions as to how actually depictions of such devices in historical paintings should be interpreted. The iconographic connotation of the mirror in art historical terms and the technologically ambiguous notion both of *mirror* and *lens* in the 17th century leave some room for interpretation here.

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[33] In experiments the lens was filled with various liquids like poppy oil, alcohol and diverse distillates, in order to investigate the effects of the various refraction indexes.

[34] Approximate refractive index of the glass of Huygens' lenses. Anne C. van Helden and Rob H. van Gent, *The Huygens Collection*, Museum Boerhaave, Leiden 1995.

Figure 4: Historical Mirror – Caravaggio: *The Conversion of the Magdalene*, 100 cm x 134,5 cm, Detroit Institute of Arts.

For the plane mirrors used in the camera, the idea was to proceed from the standard that we find depicted in the paintings of this period.[35] If we suppose that Venetian mirrors were used to manufacture the tilted mirror of the camera obscura, the the reflecting surface can be regarded as optically correct within an acceptable range of tolerance.[36] The high absorption of light by the mirror was probably the greater problem here, resulting in a dimmer projection. However, experiments with filtering films on the mirror surface demonstrated that a high-contrast image is reflected astonishingly well despite strong absorption. Polished metal mirrors may have been of lower quality, with regard to both the planity and the degree of reflection.

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[35] The Dutch painters prove to be very reliable as far as the depiction of the true scale and materials of inventory is concerned. Types of mirrors like the ones that appear in the paintings of Gerard Terborch (or in France in paintings of Georges de la Tours), for instance, appear in the European painting of the seventeenth century so frequently that it cannot be presumed that they did not exist in this form and quality. – Depictions of mirror images in which coincidental reflections of fragments of an object can be seen from unusual perspectives bear witness to a new, objectivated view of optical phenomena as to an important aesthetic innovation. The coincidental picture of a fragment, a section of a picture without iconographic meaning, appears for the first time in these pictures in the frames of those mirrors which previously had shown the well-proportioned ideal countenances of figures like Venus or Narcissus.

[36] Schechner's assessment of flat glass mirrors of the sixteenth century is not relevant here. S.Schechner: "Between Knowing and Doing: Mirrors and their Imperfections in the Renaissance", *Early Science and Medicine* Vol.X, No.2, 2005

III. PAINTING WITH THE CAMERA OBSCURA – VERMEER

Ultimately, actually painting with the camera obscura prototype is the only method to check whether the theoretical presumptions made here are correct. For this reason I will now describe the reconstruction of two hypothetical applications of the camera, thereby taking the liberty to name them after two representatives of seventeenth-century painting, namely Vermeer and Velazquez. My concern here is to elucidate the various results of my experiments on the basis of two opposing types of painter and their very different ways of working, in order to clarify a number of points regarding the possible historical applications of the camera.

As regards the selected example paintings I proceed from the assumptions that the painters applied the camera obscura within a concrete location, and that the perspective of this location can be inferred in their pictures. Establishing a connection between the laws of optics and an artistically effective procedure is the challenge involved in these hypothetical attempts of a reconstruction. As I mentioned above, what I am concerned with here is not individual indications of an employment of a camera obscura by Vermeer or Velazquez. Rather, the reconstructions are supposed to make visible a method of painting that illuminates the relationship between image projection and the artwork and thus an artistic conception.

Of all the seventeenth-century painters, one could hardly find two oeuvres more different at first glance than that of Vermeer and Velázquez. The latter, born at the beginning of the century, after classical, Italian-oriented training, became the "*Pintor del Rey*," the court painter, whose contracted work consisted in producing portraits and historical paintings that glorify the Habsburg dynasty in life-size poses of royalty. The former worked in the second half of the century as a citizen of a liberated country , the Protestant Netherlands, and became a *Gildenmeister* who depicted the privacy of "modern life," everyday living without posture, mostly in small interiors, in an innovatively intimate way. Beyond this categorization, however, certain mutual roots can be recognized from a historical distance, which can be identified as *Carravaggesque* in the widest sense. Velázquez's early *bodegones* (kitchen still lifes) stand for a Hispanicized Caravaggism; in Vermeer's early works like the *Procuress,* or *Christ in the House of Martha and Mary*, the influence of Utrecht Caravaggism (whose leading exponents were Baburen and Honthorst) leaves its mark. Both painters worked in an environment that allowed innovative impulses from the sciences to affect art – Velázquez, in the scientific ambient of the Sevillan circles of his teacher Pacheco[37] (and later, through corresponding contacts at Court); Vermeer, in the vivid ambient of Delft, where there was much experimentation with the connections between architecture, perspective and optics, leading to the development of such special forms as Hoogstraaten's peep boxes and Fabritius' panorama painting[38]. Vermeer's acquaintance with informed intellectuals like Van Leeuwenhoek, de Moncony, the de Gehyns and others, whatever the nature of these relationships might have been, is documented. The point of departure of my investigation into both painters' use of the camera obscura has less to do with aspects of art history, however, than with the characteristics of their painting based on their pictures.

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[37] D. Davies and E. Harris: *Velázquez in Seville*, Edinburgh 1996.

[38] For a portrayal of that environment, see Walter Liedtke et al.: "*Vermeer and the Delft School*", New Haven 2001.

In the "Vermeerian" procedure the optical qualities of a camera obscura projection are apparently treated with extreme consequence and made a subject of the painting. Vermeer's pictures investigate the "manifestations of light" through painting, subtly, all the way to the abstraction of details, while at the same time aspiring to the perspectivist coherence of a complex spatial situation. His pictures can be reconstructed on the basis of the coordinated application and consequent implementation of camera obscura projection. This perspectivistically coherent treatment of space clearly distinguishes him from the Caravaggists. In carravaggistic paintings single fragments can readily be identified as translations of camera obscura-projections, that are collaged together to form a coherent scene or narrative motif.

After a variety of experiments with the camera obscura it can be established that Vermeer's depictions of complex interiors can never correspond to one *single* projection by a historical camera obscura optic. This is also confirmed by the results of other authors who performed optical experiments to reconstruct Vermeer's camera.[39] If his pictures actually were produced using a camera obscura, this process involved a specially developed, complexmethod that allowed him to manipulate projected images to achieve the intended results.[40] Thus multiple projections must have been used to produce a painting, by combining the desired qualities of each single one of them. Accordingly, the search for a working model of a "camera obscura a la Vermeer" does not mean seeking a mirror-image correspondence between *one* camera projection and the painted picture, but rather for a method that unifies different aspects of various projections in the process of painting to manufacture one picture.

The following describes step-by-step a hypothetical application of the camera obscura as Vermeer may have used itand as I tested it experimentally. The experimentalreconstruction of this method of painting is thus based on a feed back from the technique of painting. The criteria of this method led to a result in which even projections that previously had been assessed as unusable are assigned a function within a combined working method.

1. Setting up the camera obscura

Initially the lens can be moved freely by hand in order to select the desired projection of the motif on the back wall. After the position of the lens is determined, the camera is then installed such that a projected image of the selected motif can best be brought into focus.

2. The reference projection (RP)

The projection on the back wall will be designated as the "reference projection" in what follows. It shows the brightest and most precise image we receive in the camera, as it is not weakened or distorted by any tilted mirrors.[41] Therefore this projection is particularly suitable for stooping

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[39] For experimental reconstructions of a historical camera obscura, see C. Seymour, "Dark Chamber and Light filled Room: Vermeer and the Camera Obscura", *Art Bulletin* 46 (1964), pp.423-31. ; D.A. Fink, "Vermeers Use of the Camera Obscura: A Comparativ Study", *Art Bulletin* 53 (1971), pp.493-505, Allan A. Mills, "Vermeer and the camera obscura: Some practical considerations", *Leonardo*, Vol. 31, No. 3 (1998), pp. 213-218. The most thorough study on Vermeer's use of the camera obscura is by Philip Steadman: *Vermeer's Camera*, 2001.

[40] The above mentionedauthors described the optical problems of historical objectives in experiments.

down by the use of a diaphragm in order to obtain as sharp an image as possible. The focus of the projection is set in such a way that further stopping down can extend the depth of field evenly to the foreground and the background. In order to increase the depth of field and, in the ideal case, to "sharpen" all objects of the motif, the aperture of the diaphragm is reduced to the minimum. Such extreme dimming makes the projection correspondingly darker, a circumstance that is acceptable for the reference projection and presents no effective impediment for its future use, as long as the "drawing" of the objects can be recognized clearly in the darker projection.[42]

Since the image is portrayed upside down and laterally transposed, the projection can not be used for painting directly (see above).[43] The task of the reference projection is to deliver a proportionally uniform scale for as many objects as possible in the currently defined perspective. What is aspired to here is thus not brightness and luminance of color, but rather as general as possible a definition for drawing of all important objects. In its black, nuanced precision, the extremely dimmed image resembles the reflection of a *Claude glass.*

3. The lens position (null position) and the back wall

The position of the lens selected for the reference projection is designated below as the "null position." The position of the lens that corresponds to the standpoint of the observer, and the position of the projection surface, must be marked. This ensures that the lens, which is later aligned for refocusing through movements along the optical axis X, can be returned precisely to the marked null position in order to get the same reference projection. From this moment on the back wall remains stationary, should it not be a fixed wall of the room, as the case of Vermeer suggests.

The thus configured projection is the matrix for the picture motif, the master plan for all further procedural steps and camera movements. Its function is comparable with that of a reference star in astronomic observations, which serves as a constant point of reference for orientation and as a standard for measurements.

4. Markings

At the start the format of the future picture can be selected and sketched in within the dimensions of the reference projection – the "frame." The bearer of the image, the canvas, is chosen in the corresponding size.

At this stage the first markings can be performed. In addition to marked positions on the mechanism of the camera (null position), it is above all the markings on the projection plane of the RP that make it possible to return to the original position after a refocusing movement.

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[41] This factor carries special weight in consideration of the historical quality of the mirrors. However, as stated above, I do not share the assessment that this quality was entirely insufficient.

[42] It must be noted that one's eyes get used to the darkness when they remain in the camera obscura for longer periods. Eyes thus sensitized can easily recognize a dark, but sharp image. See A. Mills, note[39], pp. 215, 216.

[43] The correctly orientated portrayal of objects like maps, globes, books and paintings in Vermeer's pictures has consequences for the selection of camera obscura procedures that may be considered.

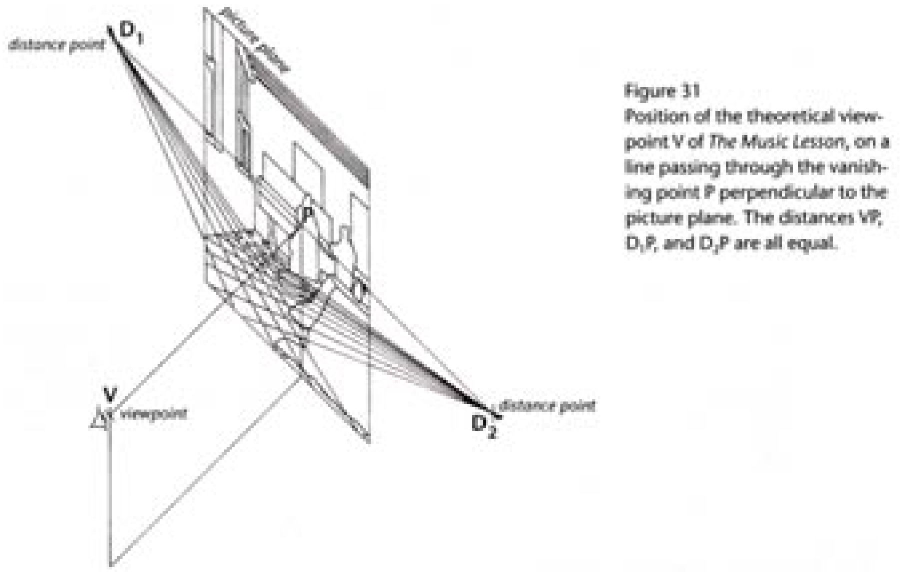

Figure 31
Position of the theoretical viewpoint V of *The Music Lesson*, on a line passing through the vanishing point P perpendicular to the picture plane. The distances VP, D_1P, and D_2P are all equal.

Figure 5a: Vermeer's Perspective – Steadman's reconstruction of the perspective of Vermeer's The music lesson.

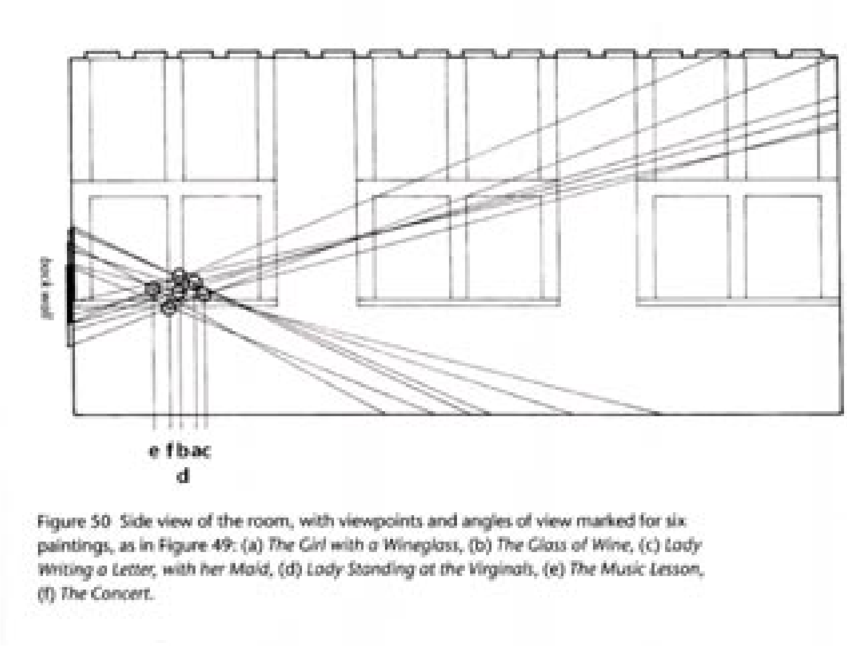

Figure 50 Side view of the room, with viewpoints and angles of view marked for six paintings, as in Figure 49: (a) *The Girl with a Wineglass*, (b) *The Glass of Wine*, (c) *Lady Writing a Letter, with her Maid*, (d) *Lady Standing at the Virginals*, (e) *The Music Lesson*, (f) *The Concert*.

Figure 5b: Vermeer's Perspective – Steadman's reconstruction of the perspective of six of Vermeer's paintings apparently painted in the same room. The reconstruction of the image size argues for the use of a projection on the back wall.

5. Reconstructing the perspective

In the following, I rely heavily on Philip Steadman's work, who reconstructed perspectives of Vermeer's paintings resulting in some remarkable findings. Among these the certainly most astonishing one is the verification of a common projection plane of several of Vermeer's domestic interiors which was very likely situated at the rear wall of the room (figure 5b).

For complex spatial depictions, Vermeer apparently reconstructed the perspective, as evinced by the markings of the vanishing points on his canvases. Since the linear perspective serves as orientation for later movements with the camera-lens, the most important positions of the perspective, like the vanishing point, the horizon and distance points are reproduced on the reference projection: The vanishing point is determined by following the course of the orthogonal lines (orthogonal to the image plane) to their point of intersection (the vanishing point). Thus the height of the horizon is also determined.

6. Determining the distance points

Even in the pertinent tracts on perspective of the age (Vredemann de Vries et al.), the incorrect determination of distance points led to momentous errors in the perspective depiction of space. Vermeer's perspectives, in contrast, are practically faultless. A suitable aid in the geometric determination of the distance points is a real "reference square", for example a square made of wood, the side of which is positioned parallel to the horizon (and thus to the image plane) on the floor of the motif. Because it is easily visible in the image-projection, it is simple to determine the distance points by drawing its extended diagonals on the projection plane to the line of the horizon. In Vermeer's interiors these points are usually located outside the expanse of the projection or of the selected image format. Taking a look at Steadman's model of Vermeer's space (figure 5a, we see that the large surface of the back wall, on which the reference projection is located, offers enough room to determine the distance points, which lie outside of the projection and far apart from each other, using nails or similar implements to mark them. Threads can then be attached to these (for producing chalk lines by snapping the powdered strings onto the surface of the painting) or rulers laid along them to draw additional orthogonal lines. The large surface of a real free standing wall is particularly suitable for this operation. Using the positions elicited on the reference projection, the vanishing point and the distance points, it is easy now to draw a layout of the most important lines of perspective on the reference projection. However, these points are imperative in the following, both for the orientation of the canvas and also because of the focusing movements to be carried out using the canvas.

7. Mounting the canvas

Once the reference projection has been "charted" as described above, then the canvas can be mounted. First of all it is important to establish a controllable relationship between the reference projection and the canvas projection. For this the canvas must be mounted exactly the same distance away from the lens as is the back wall, the projection surface of the reference projection. When both projection surfaces are thus located in the same position relative to the lens, i.e., given the corresponding setting of mirror 1 (see figure1a), both show a projection of exactly the same size, so that the points just established in the reference projection can be transferred to the canvas.

8. Transferring the reference projection to the canvas projection

Methods of transferring drawings made after the projection to the canvas as proposed in many reconstruction attempts, by means of punctured stencils, tracing paper, reticules or similar instruments,[44] are so imprecise and laborious that I chose to avoid them. In W3 the elements of the picture are transferred to the canvas through optic projection: The graphically reconstructed vanishing point on the reference projection is transferred to the real space first, and from there, via deflection by mirror 1, projected back to the canvas. To do this, the position of the point in the real space of the motif that corresponds the vanishing point on the RP must be located and can best be marked on the real wall in the background, using paint, for instance. Once the vanishing point in the motif has been marked in this manner, mirror 1 of camera W3 is shifted from the reference projection setting to the canvas projection setting. Now the motif with the marked vanishing point is displayed on the canvas projection. Such markings guarantee a precise match on both projection surfaces. For practical application it is a great advantage that these markings cannot be shifted through movements of the lens or other parts of the camera; they are fixed measuring points in the real motif and thus visible in every projection.

In contrast to the generic character of a classically structured perspective construction, this approach corresponds more closely to a manipulation of real space. The perspective reconstructed in the projection is thrown back onto the real space. This “retrotransfer” of virtual data of the image, which were determined using the two-dimensional projection, to the real, three-dimensional space of the motif, indicates a change in the way the motif itself is dealt with by the artist.

9. Fixing the canvas projection

Once the canvas is positioned with reference to the selected “frame,” the vanishing point is punctured. With this punctured hole the position of the canvas is determined unequivocally and can be located again at any time.[45] A thread is pulled through this hole in the canvas, by means of which orthogonal lines are drawn. We also use this thread to determine the distance points.[46] So the same basic structure of perspective is marked on the canvas as on the RP, but this time way-

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[44] An example for one such a complicated method of indirect transfer is given in a reconstruction of C. Lüthy, “Hockneys Secret Knowledge, Vanvitelli’s Camera Obscura”, *Early Science and Medicine*, Vol. X, No.2 (2005). Seymour and Fink, [note 39], also suggest the transferring of drawings made with the camera obscura to the canvas for Vermeer’s application of the instrument.

[45] The punctured vanishing point can even be localized when it is painted over (see scratched grooves by Caravaggio, geometric drawings, perspective constructions of the age in general).

[46] In order to transfer the spaces between the distance points, a fine thread is laid along the back wall to record the space between the vanishing point and the distance point on the perspective drawing. Then the position of the distance points marked on the thread is transferred to a strip of wood fixed behind the stretcher. For this the thread is stretched in both directions of the distance points in order to mark their position. In contrast to transferring methods using templates or tracing paper outside of the camera obscura, this method has the advantage that the thread leaves both the painting on the canvas and the projection visible while the artist draws the markings.

up and laterally correct. Now the reference projection and the canvas projection have the same picture distance and "frame" and a perspective drawing has been established. The precise match in location, especially of the vanishing point marked on the central optical axis, is important to monitor the position of the canvas during the subsequent focusing movements. The perspective drawing can be reconstructed so unambiguously only in the examples consciously selected here.

10. The first layout on the canvas

For application of the first layer of paint on the canvas, the camera is set in the following way: M1 to CP, lens: null position, diaphragm: half open. By this, a projection is obtained that is brighter than the reference projection, but still shows all of the objects of the motif relatively sharply. The purpose of painting this base layer is to establish a uniform, monochrome structure for the distribution of light and shadow over the entire motif. This is achieved by modulating a dark mixture of paints over a light ground.[47] The gradations of the modulation are defined not by mixing, but by merely applying different thicknesses of one mixture of paint, or by using a more or less diluted consistency of the same paint. Working with the paints this way allows tactile sensitivity to come into play, that allows a controlled handling of paint even in the darkness of the camera. The technique of painting a base layer with dark oils for the shadows and applying white tempera for highlights (in this order) corresponds to historical techniques as related by contemporary instructions.[48]

Working with the camera requires a fundamentally different approach to the motif. In contrast to an image formation that starts from a linear construction or preliminary drawing (*a la disegno*), in this method it is not desirable to determine sharp contours of lines on the canvas at such an early stage; these are found only in the projection of the RF. The modulation of the colored base leaves the precise definition of details open for successive working steps. Its task is to establish an overall context of the light/dark distribution, a kind of undertone.

After the entire canvas has been covered in this manner with a thin, monochrome underpainting, the lights can be heightened by adding white tempera paint wet on wet.[49] This texture should be quite muted in the first layer of paint (without setting points of light yet); the shadows remain transparent, the lights are opaque (through the white). A balanced modulation of the areas and volumes is more important than the formulation of details. The entire layout should be kept as light as possible so that a good (relatively light) projection surface is always available for any further projections.[50] Once this first layout has dried, the next step of work can begin.

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[47] For examinations of Vermeer's canvases see the contributions of Karin Groen and Claudia Laurenze-Landsberg to this volume, also K.Groen, Inez D. van der Werf, Klaas Jan van den Berg,Jaap Boon, "Scientific Examination of Vermeer's Girl with a Pearl Earring", in I. Gaskell and M. Jonker (eds.): *Vermeer Studies*, New Haven 1998; E. Melanie Gifford: "Painting light: Recent Observations on Vermeer's Technique", ibid., 1998. – For both Vermeer and Velazquez, this is not true for the early works. In these the base of red ochre typical for Carravaggesque tenebrism is used. For examinations of Velazquez canvases see Carmen Garrido Pérez, *Velázquez: Técnica Y Evolución,* Madrid 1992.

[48] For a contemporary source on a technique that combines tempera and oil paint see for example, Horst Vey: "Anton van Dyck über Maltechnik", *Bulletin Musees Royaux des Beaux-Arts*, IX(1960), pp. 193-201.

[49] For a finding of (white) egg tempera in Vermeer see Koller, Fiedler, Baumer: "Vermeers Maltechnik – eine Mischtechnik", in *Johannes Vermeer: Bei der Kupplerin*, Ed. Neidhardt and Giebe, Staatliche Kunstsammlungen Dresden, Gemäldegalerie Alter Meister 2004.

11. Color: glazes and dead colors (Dotwerve)

When and how color is applied in this process is a purely artistic decision. There may have been applications in which the painting in the camera remained restricted to the monochrome modulation of form described above (Grisaille), while the use of color for the production of the picture was reserved for outside the camera. A partial introduction of what were known as the *Dotwerve* (dead colors) – opaque color areas laid under a local hue – can be smoothly interposed with the procedure of painting with the camera. Yet thorough investigations of Vermeer's pictures have shown that the extremely subtle modulation of color was achieved through the repeated overlaying of colored glazes and opaque textures (or likewise transparent, dark modulation).[51] For a reconstruction of a corresponding painting process with the camera obscura, this means that between the individual settings, in which light or dark color (in the glaze) are modulated in the dark, the shades are opened to let light into the camera so that the painter can work with color. Since the painter and the canvas are already positioned at their optimum positions relative to the motif – a great advantage of the W3 over other camera models – the given settings of the camera modules need not be changed for this working step. The camera can then be darkened again, so that modulation in the wet glaze can continue. Thus an *integrated* use of color becomes possible.

This effortless shifting between painting with and without the camera projection is the prerequisite for modulation and coloring flowing into each other. A separation between shape and color, as is prescribed in the classical tracts, is dissolved in the continuing process of painting. So, for instance, the contour of a shape can be determined merely by a gradual transition, which was structured through modulation and colored glaze without ever a line being drawn. Even lines are defined rather indirectly in Vermeer's work, as interstices or through the juxtaposition of two values – directly drawn contours rarely occur.[52]

12. Opening the aperture

For the next projection, the same camera setting (lens still at the null position) is selected, but now with the aperture opened all the way. Opening the diaphragm to its maximum yields an image with low depth of field, but the greatest possible brightness. Now sharp contours are shown only for a smaller area of the picture in the center of the projection, but this area issignificantly brighter than in the previous projection. Only those objects that lie on this level of focus are worked on in the manner described. Corresponding to the brighter projection, more detail and contrast can now be defined in this "focus spot." The canvas projection with an open aperture is thus supposed to show us a single focus area at maximum brightness and sharpness, so that this area can be worked on in the painting.

By tilting the lens horizontally or vertically while maintaining its central position, it is also possible to bring into focus a narrow band of the motif without distorting, an optical effect that is based on the *Scheimpflug* rule. Through this effect, even areas at the margins of the focus level can

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[50] An impression of the appearance of such a monochrome layout is imparted by the autoradiographs taken of several paintings of Vermeer. See figures 6 in the article of Laurenze-Landsberg in this volume.

[51] See the contributions of Claudia Laurenze-Landsberg and Karin Groen to this volume. See also the article of Koller et al., note [49].

[52] Gowing describes this circumstance in detail, categorizing it as a consequence of the use of the camera.

be focused to some degree without changing the position of the lens. Thus, spherical abberation is reduced.

13. Refocusing

If this "focus spot" of this lens setting with an aperture opened to the maximum has been worked on, the image must be refocused in order to bring other objects of the motif into the picture. Yet by moving accordingly the optic (lens or mirror, respectively), the proportional scale of the image changes as well: the objects visible in the projection change not only in terms of their sharpness, but their depiction size also changes, thus destroying the coherent proportional context.[53] For refocusing means not merely "sharpening" the image of an object with the lens by selecting a new focus level; moving the lens actually entails a shift in the observer's vantage point and thus a change in the entire perspective. Refocusing and maintaining one central perspective are thus mutually exclusive. If only the lens is moved, not only the distance between the lens and the object changes, i.e. the "object distance," but also the "image distance," the distance from the lens to the fixed projection surface.[54]

Thus in order to approximately maintain the proportional context of one perspective when the focus is changed, not only the lens must be moved, but also the projection surface, which is not possible for a camera obscura with a fixed projection surface such as the box camera. Yet it is not possible to refocus on the fixed back wall in a "boot-type" camera like the W3, either – the image is therefore refocused on the movable canvas instead. This is achieved in W3 by moving the dolly, so that initially only the object distance in the canvas projection changes, but not the image distance (see figure1a and 1b). After leaving the lens's null position (using the dolly), we thus maintain the same focus (of the canvas projection) in terms of image distance while moving along the optical X-axis through the space to a new layer of focus in the motif. The newly focused object is thus depicted in the same image size as the previously focused object. Thus, to adjust the image size of the newly focused object to the perspective of the reference projection (null position), the as yet unchanged image distance of the canvas projection (distance between lens and canvas) must be adjusted accordingly.

Here is where the reference projection of the marked null position on the fixed back wall comes into play. It serves as a reference for the proportionate scale of the image of the newly focused objects. The scale of the objects to be focused is obtained by closing the aperture in the reference projection for sharp definition and measuring the proportion using a simple compass. By tilting M1, the projection can then be switched from RP and to CP. The object portrayed in the CP can now be adjusted to the reference scale through single or combined movements of the canvas, the mirror unit M2/M3 or the lens. To compare the correct image size, we lay the compass setting with the dimensions of the desired image size from the reference projection against the canvas projection. Ideally, only the mirror unit M2/M3 need be shifted to the point where the image size corresponds to the dimension, so that the canvas does not have to be moved. Should

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[53] See Allan A. Mills [note 39], p. 215, 216..

[54] This is not the case for the uniform movement of a compact apparatus, e.g., of a box camera without a changed distance between the lens and the projection surface. Here only the object distance changes. The context of perspective is lost; here the process is not actually refocusing.

the distance by which the mirror unit can be shifted not be enough to achieve a sharp focus, the canvas can be moved as well – both movements modify the image distance of the canvas projection. (See the figures 1a and b)[55]

14. Processing the new setting pictorially

The newly focused projection now hits a canvas on which the structures of the previous projection, which had a different focus, were recorded as a monochrome modulation. Only in the area that is now in sharp focus are the shapes of the new projection congruent with the previously completed underpainting. This projection of the newly focused area of the motif is now worked into the picture, with the aperture open. The aperture must be opened so that the image of the focused objects is projected with the optimal definition and brightness. This image quality is needed to work with more sophistication than in the first layout with the dimmed projection. This diaphragm setting would also explain the pictorial depiction of optical imaging errors in a number of details of Vermeer's paintings, errors that can only be observed when the aperture is open. The perspective upon which the picture is based could never have been mapped correctly by an objective with an opened aperture, however. This fact suggests a painting technique that combined various projections. After working in one setting, the focus is shifted to the next focus layer.

15. Step-by-step refocusing through the entire image space

With the projection of the newly focused layers we thus move like a spotlight across the structures of the underpainting. The exact measurements of the reference projection prescribe the image size of the new focus settings of the canvas projections. Since the non-focused areas in this projection blur into a mush of light, the situation resembles movement through a dark space with a spotlight. The image projections appearing in the area of the given focus are very different in form from those of the dimmed reference projection. With the diaphragm wide open, the imaging errors known as Seidel aberrations occur here: spherical aberrations, coma, astigmatism, etc.

16. Playful manipulation

Without having to maintain fixed positions, by moving the optic gently we can swirl the sharpness of the focus around through the objects portrayed in the projection to feel out successive forms. During this process it can be observed that not only the image sharpness changes, but also the position of the contour. Manipulating the ray of light using different apertures even shows (through the selection of various beams) an apparent shift in the position of the object portrayed. Since the design in the picture builds on the skeleton of the underpainting, we now have the

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[55] What is special about W3 is that this adjustment of the image distance requires no movement of the lens or the canvas. Thus it is possible, even when mechanically more imprecise devices are used, to realize relatively reproducible settings, as it is easier to find previous positions with only one movable module. For a coordinated sequence of focusing movements it is not only more "elegant" if these can remain restricted to the mirror, i.e. lens and canvas are not moved, but it allows also for more precision practically. (In W3, by shifting the unit M2/M3 by 1 cm, the image distance is enlarged by 2 cm.)

freedom to investigate individual light phenomena, each of which appear only for the detail in focus at the given time. These phenomena do not occur in a "generally sharp" image (RP with small aperture opening).

Like an object one picks up and moves around in order to regard it from all sides, the image of the projection can be manipulated and investigated in every conceivable way. Every change through the manipulation of the camera supplies new information. Within a calculated methodology, suddenly a playful free space opens up. Here there are no prescribed limits or previously declined rules that differentiate between optical errors and correct optics and censor them. After all, in 1650 there was no such thing as an optical imaging error. Especially in this stage of the painting process, the painter in the camera becomes a researcher, who, like Van Leeuwenhoek with his microscope, discovers new phenomena in the structures of the familiar environment. The camera obscura opens up a new view of things for the painter; like the microscope and telescope it is an instrument of enquiring sight.

17. Vermeer's "globules of light"

The points of light that are so often described in Vermeer's paintings (*Milkmaid, View of Delft*) are discussed to illustrate the translation of optical phenomena into painting. Gowing compares the "*globules of light*" with the astigmatic points of light he observes on the translucent ground glass screen of a box camera obscura. This assumption that light has literally been converted into paint is a more apt description for a process of photographic exposure than for the painter's process of testing out the interplay between painting and projection.

On the canvas in the camera, projections of highlights build on already painted highlights and thus exaggerate the distribution of contrast. Not only the painting on the canvas changes during the painting process, but also the image of the projection in the camera: While the projected image initially was cast on a neutral priming, an empty canvas, now it is projected on the painting in progress and "blends" with it. The optical image is cast upon a topography of painted shapes. Projected shadow is cast on painted shadow, projected light on painted light. Dark and light amplify each other. The light becomes lighter. If we proceeded at the outset from a balanced, soft structure, now we set excessive accents in a mediating glaze. According to this interpretation, "pointillistic" pixels like those in the *Milkmaid* or the *Girl Reading a Letter* in Dresden are not a true depiction of existing optical imaging errors, but rather an interpretation and exaggeration of these phenomena that originated in the process of painting. Such an painterly interpretation is linked with the phenomenon, but does not (literally) represent it.

18. Concluding painting in the camera

When the painter works intensively in the dark on the shapes of light in the projections, he reaches the point where painting and projection begin to compete with each other. After repeated refocusing, multiple layers of glaze and overlaying modulation, the paint on the projection surface grows toward the projected light. Painting and projection gradually begin to cancel each other out. This neutralization makes further work impossible. The camera obscura is "switched off," light is admitted into the camera; the sight axis is cleared by removing the lens, and the process of painting can be continued and concluded in the same position relative to the motif.

19. The meta-image and image-space

The direct view of the motif obviously differs from the images of the projections. The glance now directed toward the motif is no longer impartial. It investigates the motif for information to use in formulating a meta-image, which emerged from a synthesis of the various views of the motif in the camera. This synthetic and fictive image is the actual motif. Successively adding images and blending the individual camera settings and direct views of the motif into each other results in a hybrid image, for which there is no corresponding, individual optical image. Thus the described painting process generates a meta-image.

Through the systematic movements of the focus along the central optical axis, the view has "wandered through" the depicted space optically. Here the concept of a central perspective in the image space, with a *fixed* observation point (Alberti) is nullified by the movements of the lens. The perspective of space is distorted. These movements describe a "time space" (temporal space), which is different from the simultaneity of the central perspective. They document the course of a process of perception. Such a topography of sight charts not only a complex process of sight,[56] but also its chronology. I interpret this concept of time to be a significant aspect of Vermeer's concept of mimesis. The timeframe of the observer is contrasted with the timeframe of the picture(which creates a awareness for a passage of time).

IV. PAINTING WITH THE CAMERA OBSCURA – VELÀZQUEZ

In counterpoint to Vermeer, Velazquez is interesting in this context because those features that serve so exemplarily to suggest the use of the camera obscura by Vermeer are initially difficult to identify clearly in Velázquez oeuvre. The majority of his work, his portrait painting, offers hardly any indications of perspective analyses in the style of Swillens or Steadman.[57] The most striking and most famous feature of Velázquez's painting is the brush flow of his pictorial gesture, especially in his later work. The individual brush stroke, clearly readable from up close, became important in contemporary Spanish literature as the *borron* or *mancha*, embodying an aesthetic concept that was influenced both theoretically and pictorially by the Venetian *colore.*[58] The praised ability to use the interplay of these non-descriptive brushstrokes set with *sprezzatura* to evoke a picture that is accessible to the user only through association and from a certain distance, "from afar," elicits astonished comprehension among even today's viewers standing before Velázquez's late work. The act of beholding the picture becomes a visual experience in itself.

As regards the camera obscura, these qualities of Velázquez's painting lead to the fundamental question as to the connection between a pictorial language and the optical projection. The demonstrative nature of the *borrón* as a personal signature stands in striking contrast to the image produced by optical projection: the *borrón* therefore does not imitate the form of the projection.

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[56] Svetlana Alpers defines the "cartographic view," in S. Alpers, *The Art of Describing*, London 1989, chap. 4, "Cartography and Painting in Holland".

[57] The method of reconstructing the perspectivist space of a picture was introduced first in Wittkower and B. A. R. Carter, "The Perspective of Piero della Francesca's Flagellation", *Journal of Warburg and Courtauld Institutes* XVI, 1953, pp. 292-302; Swillens was the first to apply that method for Vermeer; Moffit reconstructed the room of Velazquez' *Las Meninas.*

[58] For a thorough discussion of the meaning of the *boron* in 17th century Spain , see: Gridley McKim-Smith, Greta Anderson-Bergdoll and Richard Newman: *Examining Velazquez*, New Haven 1988, pp.15 ff.

Velázquez does not render the projection. To what extent can a correlation nevertheless be drawn between what is painted and what may have been projected?

I would like to advance the thesis that for Velázquez the *borrón* is directly linked with the camera obscura. I interpret it as a pictorial gesture, which relates to the optical projection of the camera obscura. Through its mode of action the *borrón* emphasizes the dualism between the signature nature of painting and the "naturally" projected optical image. Every brushstroke seems to investigate the form of abstraction in which the *mode of action* of applying color can correspond to the *mode of action* of optical projection, not to imitate it, but rather to evoke a similar, direct – that is, in this context, true - effect (*aemulatio* instead of *imitatio*). The *borrón* transforms light into form, so to speak – its materiality is the means by which light, understood to be "immaterial," is portrayed. As such the pictorial forms of translation produced are analogous to optical phenomena.[59] The effect of the means can be controlled using the instrument of the camera obscura, which simulates the apparatus of visual perception. The camera can be used to develop an artistic language, which is adopted to the very process of perception and thus can be particularly effective in its formulations. Since *"nature"* performs the projection of light, it offers an objectivated view. The criteria of depiction thus shift from an emblematic iconicity attributed to the object to its optically investigated, spontaneously changeable external manifestation.

In the following I would like to discuss Velázquez's use of the camera obscura, which is clearly different from Vermeer's and, of course, hypothetical (as far as the historical Velázquez is concerned).[60] In this I will concentrate on the only picture by Velázquez that allows such manner of investigation with reference to a real space, as was shown for Vermeer. The picture in question is *Las Meninas.*[61]

In contrast to Vermeer's interiors, in this case it is possible to identify the *historical* space shown in the picture and where it also originated,[62] on the basis of documents and plans.[63] The space in question is the hall called the *Pieza Príncipal* in the *Cuarto Bajo del Principe* on the *Planta Baja* (ground floor) of the Alcázar.[64] This royal palace was destroyed completely by a devastating

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[59] The means of painting emphasizes autonomy – it does not pretend to be an object, it is paint. It is not hidden under the gloss of a closed layer of varnish like some expelled flow of color, but lies openly on the rough canvas. In contrast to the traditionally smooth surfaces of pictures by the "Nordic School," in the Venetian School the materiality of the object picture (paint, canvas) is fully employed to generate visual signals. The contradiction this brings about between what is depicted and its depiction generates an intentional ambiguity, which was celebrated playfully in various ways during the Baroque era. The dissimilarity of the two-dimensional image in comparison to the three-dimensional space does not present a deficit in terms of the truth content of what is depicted , but rather emphasizes the particular charm of the consciousness of perceptual processes and their manipulation.

[60] In the posthumous inventory of his studio though, under no.174, there is mention of a thick, round glass placed within a box: „174.-Vn vidrio grueso redondo, metido en vna caja" (A. Gallego y Burín: *Varia Velázquena* vol.2, Madrid 1960, p.393

[61] It is impossible to say anything about Las Meninas without referring to the impressive body of literature on this work, probably one of the most extensive scientific apparatus on a single painting. However, here I will only go into those few works which have to do directly with the question complex studied here.

[62] Palomino's extensive description of the painting and its history is generally accepted. Antonio Acisclo Palomino y Velasco, *El museo pictórico y escala óptica*, Madrid 1724; 2nd ed., vol 3, 306-7. For a recent English translation see N. Mallory: *Lives of the Eminent Spanish Painters and Sculpters*, Cambridge 1987.

[63] Brown, Jonathan, *Images and Ideas in Seventeenth-Century Spanish Painting*, Princeton 1978, pp. 87 ff. Moffit, John F., "Velázquez in the Alcázar Palace in 1656: The Meaning of the Mis-en-Scene of Las Meninas", *Art History*, Vol. VI/ 3(1983).

[64] Moffit, ibid. p. 289

Painting Technique in the Seventeenth Century in Holland and the Possible Use of the Camera Obscura by Vermeer

Karin Groen

INTRODUCTION

Constantijn Huygens (1596-1687), in the Autobiography of his youth (1629), writes that the Dutch painter Torrentius' rendering of lifeless objects resembles a miracle. These objects of glass, tin, earthenware and iron, with their particular type of gloss, would be really too difficult to paint with the brush.[1] Torrentius, whose real name was Jan Simonsz van der Beek (Amsterdam 1589-1644 Amsterdam), in all discussions about his use of a deviating sort of pigment, oil and, incredibly even brushes, left everybody in uncertainty about how he did it.

Huygens was suspicious of Torrentius. On one occasion Torrentius's behaviour had struck Huygens as strange. That was when the painter had come to see him. Huygens had brought back from London an instrument of – in Huygens' words 'simple construction, which allows objects to be projected in a closed room, when one holds them in front of the instrument, on the outside, in bright sun light.' The Dutch inventor Cornelis Drebbel, who lived in London between 1630 and 1641 (or 1642) had given it to him. The painter, on seeing the projections, pretended not to know how the apparatus worked. He had asked innocently if the dancing figures on the screen were life figures outdoors. This question surprised Huygens, the instrument had, after all, been shown to many painters and everybody knew about it. Huygens suspected 'this cunning fox', when painting, of using such an instrument to achieve his special effects. This effect was such that 'the simple, uncritical public in their way would have liked to ascribe it to bursts of *Divine inspiration*'. The 'holy quack', Huygens' concluded, must have made his paintings with the aid of a camera obscura.

Figure drawing was not Torrentius' *metier*. Another surprise for Huygens: were not people the main subject in the mysteries? The rendering of Torrentius' figures was shamelessly primitive and for connoisseurs not worth a glance. He was sure, for Torrentius it was just impossible to make his paintings without mechanical aids. In the lifeless objects '... the similarity between Torrentius' work and the (projected) silhouettes is so striking and, also, compared to the real object, his work has *elusiveness* and *perfection*'. Unfortunately the enigmatic painting *Still-Life, Allegory on temperance* of 1614 in the Rijksmuseum is the only painting by the notorious Torrentius that has come to us to judge for ourselves his remarkable way of painting (Fig. 1).

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[1] Huygens [1629, 1994] 91.

Figure 1: Torrentius, Emblematic Still life with flagon, glass jug and bridle, round panel approx. 51 cm, signed and dated: T.1614. Rijksmuseum Amsterdam.

Reading Huygens' diary it appears that the camera obscura was very popular in Huygens' time. Many painters knew about it and were delighted by it. Huygens does express his surprise that not more painters showed an interest in using 'this pleasant and useful instrument' for making their paintings.

The possible use of the camera obscura by artists has been a subject of debate up to our time. As in Torrentius' time, the argument sprouts from the style used in the paintings. The painter mentioned most often in connection with the camera obscura nowadays is Johannes Vermeer. In the case of Vermeer, everything from spatial organisation to the rendering of objects and the use of pigments – in short much of what we think of as his distinctive style – has been at some time attributed to the camera obscura.[2] The camera is thus regarded as a source of style and the artist copied the quirks of the device.

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[2] Alpers [1983] 31.

Arthur Wheelock, curator of Northern Baroque Painting at the National Gallery of Art, Washington and a major writer on the relation of Vermeer and the camera obscura, understandably states that it is difficult to perceive the extent of the role the camera played in Vermeer's particular style.[3] In spite of this, he lists items that could possibly indicate the use of a camera. Vermeer would be attracted to a number of optical effects the camera produces, for instance the accentuated perspective seen in his pictures,[4] the heightened colours, the heightened contrasts of light and dark and, especially the halation of highlights. The heightened sense of light and colour, Wheelock states, could be due to the use of lenses or mirrors. The effect would be caused by the reduction of scale in the image, without a reduction of intensity of the colours. The colours would be concentrated by the lens. The item that convinces Wheelock most is the haloing, the diffused highlights seen in Vermeer's paintings after the late 1650's. These small globules of paint would be equivalents of the circles of confusion, diffused circles of light that form around unfocused specular highlights in the camera obscura image. Diffused highlights can be found in several works, for instance in the side of the boat in *View of Delft*. Arthur Wheelock states that *The girl in a red hat*, in his collection, comes closest to all of Vermeer's paintings for being painted with the aid of a camera obscura, just because of these globules of light. In an experimental set-up such light effects were shown by Charles Seymour to be produced in the image cast by a camera obscura; the diffused highlights trapped onto photographic paper closely resembled those in the painting of the girl. Especially the rendering of the lion heads on the chair showed a striking resemblance to the *soft focus* image of the same object seen through a camera obscura.[5] Vermeer would have exploited the impression of the blurred spots of light seen with the camera in the service of realism, so important in Dutch seventeenth century painting.

LINEAR PERSPECTIVE

Jorgen Wadum argued against the use of the camera obscura by Vermeer because of the vanishing point he found in many, (thirteen) of Vermeer's paintings. Vermeer would have used a chalk line attached to a pin at the vanishing point in the painting to create the central perspective in his pictures.[6] Vermeer's special compositions would be based solely on his exercising the laws of linear perspective and not on the use of the camera obscura. The vanishing points were discovered as actual holes where pins had been stuck into the paint. This find, plus the fact that Vermeer plays with perspective and changes the position of vanishing points, would contradict the belief of some that Vermeer's interiors were faithful portraits of actual rooms and that this realism could only be explained by the use of the camera obscura.

In my paper the reader will not find the definite answer to the question of the use of the camera obscura by Johannes Vermeer. What I will do, is look under the surface of a few of Vermeer's paintings, searching for certain phenomena and following an approach suggested by Svetlana Alpers.[7] Alpers suggested that trying to solve the problem of the artistic use of the camera obscura had to proceed by establishing specific phenomena present in paintings that are not seen by

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[3] Wheelock [1988] 36.

[4] A striking example is *Soldier and laughing girl* in the Frick Collection, New York.

[5] Wheelock [1988] 100. Wheelock [1996] 162, Seymour [1964].

[6] Wadum [1995] 67-78.

[7] Alpers [1983] 30.

unaided vision. I will explore material aspects of the paintings – coming from analytical research and readings – in connection with painting techniques and artistic use of the camera obscura in seventeenth century Holland .

Needless to say that any results obtained will provide only circumstantial evidence of the use of either camera obscura.

PAINTINGS INVESTIGATED AND METHODS OF EXAMINATION

The survey in this article is necessarily limited to paintings that have been investigated earlier, with other objectives in mind than the elucidation of the possibility of the use of the camera obscura by artists. In my investigation I will present again results obtained by technical examination of paintings, chemical analyses of samples and technical photographs of the paintings and scrutinise these results anew. With the camera obscura in mind, the author's results of the technical examination of *Girl with a pearl earring* of c. 1665-66 at the Mauritshuis in The Hague will be discussed (Fig. 2).

Figure 2: Johannes Vermeer, Girl with a pearl earring, c. 1665, canvas, 44.5 x 39 cm, Royal Cabinet of Paintings Mauritshuis, The Hague.

Results of the technical examination of *View of Delft* of c. 1660-61, also at the Mauritshuis, (Fig. 3), *A lady at the virginals with a gentleman*, sometimes called *The music lesson*, of c. 1662-65 in the Royal Collection in London and other paintings by Vermeer will be taken into account as well. Recently, Torrentius's *Emblematic still life with flagon, glass jug and bridle* has undergone restoration and investigation, providing some interesting information in connection with the camera obscura.[8]

Figure 3: Johannes Vermeer, View of Delft, c. 1660–1661, canvas, 96.5 x 115.7 cm, Royal Cabinet of Paintings Mauritshuis, The Hague.

Photographic techniques used include X-radiography, infrared photography and infrared reflectography. X-radiographs permit an image to be seen of passages and layers that contain heavy chemical elements, especially lead white. Lead white absorbs X-rays and therefore does not blacken the X-ray film. Since lead white was used extensively in painting through the centuries, X-radiography provides a useful tool for looking at underlying paint layers containing lead and other heavy elements such as mercury, depending on the thickness of the layers. Infrared reflectography provides an extension to infrared photography. It was developed in the 1960s as a method for seeing underlying shapes and drawing not visible to the naked eye. It is used to reveal drawing and paint below the surface paint, which are reached by the longer wavelengths in the infrared range

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[8] Wallert [2007].

of the electromagnetic spectrum. Infrared reflectography shows contrasts in light-and-dark. A black, carbon containing underdrawing on a white preparation of the support can, for instance, be made clearly visible. A drawing in white chalk can not. Several methods of infrared reflectography are now used to 'capture' individual details of an underdrawing in paintings. These are taken in a sequence and assembled in a composite called an infrared reflectogram.

For studying painting techniques the surface of the painting is examined with the naked eye, with the help of magnifiers and stereomicroscopes. Minute paint samples are removed and made into paint cross-sections enabling the study of the build-up of the layering using a research microscope with magnification up to 1000x. The layers are further examined and the pigments analysed with an electron microscope with energy dispersive X-ray analysis (SEM-EDX).

SUBJECTS FOR INVESTIGATION AND DISCUSSION

The painting support

In the Northern Netherlands in the first quarter of the seventeenth century panels were mainly used as a painting support. Canvas came into use slightly later. Apart from two – *The girl with a red hat* and *Young girl with a flute* both of 1666-67 and in the National Gallery of Art in Washington – all 36 of Vermeer's still existing paintings are on canvas. Wheelock suggests that for *The girl with a red hat* and *Young girl with a flute* Vermeer would have deliberately chosen for the rigid, smooth support of a panel, to match as closely as possible the sharp image cast by the camera obscura onto the projection screen.[9] If Wheelock's argument about the need of a rigid support is valid, then the priming of Vermeer's late paintings, -supposedly they were made with the use of the camera – must have been adjusted to make them smooth. They are namely on canvas.

In this respect, it is interesting to note that the wooden panel used by Torrentius is circular, just like the lenses in the camera.

The preparatory layer

The preparatory layer or ground differed depending on the type of support.

In contrast to the early Italian panels covered with various layers of gesso, investigation has shown that seventeenth century Dutch panels were prepared with a mixture of chalk and glue, thinly laid on. Treating the panel with chalk was primarily intended to seal the openings in the wood grain in order to obtain a smooth surface. When it had dried it was scraped with a knife and then a thin layer of lead white and umber was applied. The oil-containing top layer isolated the strongly absorbent chalk-glue ground from the (oil) paint layers to be applied during painting and provided a yellowish ochre-coloured surface to work on. As a result, it could function as an intermediary tint among the dark and light areas of the composition and the colour of the ground often remained partially exposed. The white ground in *Young girl with a flute* was covered with a second grey ground. *The girl in a red hat* is painted on top of an earlier painting.[10]

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[9] Wheelock [1996] 162-163.

[10] Wheelock [1996] 204, 160.

There were various ways to prepare canvases. The *Mayerne Manuscript* is the most important contemporary source regarding the preparation of canvas. De Mayerne gives numerous – almost identical – recipes for this treatment.[11] First the protruding threads and other irregularities were removed after which the canvas was brushed with glue. Then one or two coats of paint were applied to fill any irregularities in the canvas and provide a smooth surface of a particular colour. The one most often mentioned is that of a reddish-brown earth with a grey or 'flesh coloured' one on top. The top layer contains mainly lead white. Examination of paintings has shown that this type of ground was used most often for the preparation of canvasses in the seventeenth century in Holland. In Vermeer's paintings this type of ground was found only once, namely in *The love letter* of c. 1669-70 in the Rijksmuseum.

Much less frequently one finds in Mayerne's papers the recipe for another type of ground:

> 'After [applying the glue] prime with lead white and a little umber. One priming is enough; if you apply two, then the cloth will be more even.'[12]

A mixture of lead white and a little umber would give a light buff or greyish colour. A buff coloured ground is easy to work on: the division of light and dark areas can quickly be made in the early stages of painting. Mixtures of lead white, chalk[13] with more or less umber, ochre and sometimes a small amount of black were found in the grounds of the Vermeer's canvases. As far as could be judged, – from examination with the naked eye or from paint samples – the colour of the ground ranged from white to grey. *View of Delft* was painted on a light buff coloured ground (Fig. 4).

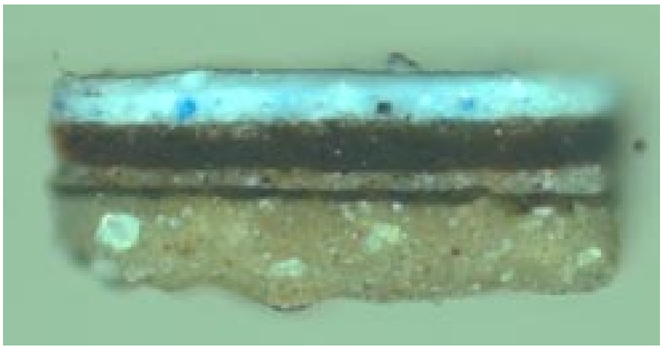

Figure 4: Paint cross-section of View of Delft. The lower layer is the light buff coloured ground, containing lead white, chalk and a little umber.

Within our context of the possible use of a camera obscura a white ground could be significant: the image cast by a camera obscura would be strongest on a white ground, if painters would have used this instrument as a mechanical aid. The ground in *Girl with a pearl earring* turned out to be relatively light in colour, indeed almost white.[14] Only a tiny amount of ochre and a little carbon

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[11] Berger [1901], Van de Graaf [1958].

[12] Berger [1901] 116: 'Apres imprimés auec blanc de plomb, & vn peu d'ombre. Vne imprimeure suffit; si on y en met deux la toile sera plus vnie.'

[13] The Dutch *lootwit* is the cheaper mixture of lead white extended with chalk. Goedings [1994] 85-87.

[14] Groen [1998] 170.

black had been added to the white mixture of lead white and chalk. A few more of Vermeer's paintings seem to have been started off on a white ground, namely *The girl with a wineglass* of c. 1659-60 and *Woman with a pearl necklace* of c. 1664 in Berlin. In both paintings, dark paint layers, – locally applied – were detected directly on the ground, underneath the final paint, as is the case in *Girl with a pearl earring*, as we shall see below.

In paintings by Rembrandt the light coloured ground is often visible at the surface of the painting, between adjacent areas of paint, where different areas do not meet. Obviously, the ground had just the right colour and could be left uncovered. This way of working is spontaneous. Vermeer clearly had a different attitude towards the painting process, the phenomenon of 'open spaces' is lacking in his paintings, or is at least, not so obvious. Vermeer covered what would have been open spaces by blending the paint of adjacent areas. Such blending provided Vermeer's typical smooth contours.

The X-ray of *Girl with a pearl earring* shows that a knife was used for the application of its ground (Fig. 5). Priming a canvas using a knife would not only fill the pores in the canvas, but also provide a smooth, – white – surface to work on, ideally suited for matching the sharp image cast by a camera obscura.

Figure 5: X-radiograph of Girl with a pearl earring.

Preparatory drawing and painted sketch

Many sixteenth and seventeenth century treatises discuss the artistic use of the camera obscura recommending tracing its image.[15] Were outlines indeed drawn directly on the prepared support, tracing the projected image? Huygens states that his optical instrument enabled projections onto a *white* surface of the contours of things outside.

The recent examination of Torrentius' *Emblematic still life with flagon, glass jug and bridle* has shown that he used a white ground on a panel, with black lines for drawing his composition. The examination of this painting with infrared reflectography revealed the presence under the paint layers of lines drawn along a straightedge or ruler. Straight lines projected through seventeenth century lenses would become slightly curved at the edge of the image.[16] Torrentius' adjustments to his drawing with lines along a ruler makes a compelling case that indeed he has used the camera obscura.

Contours of things or lines drawn directly on the ground preparation were hardly found in Vermeer's paintings. Only one paint cross-section of a sample from the *Girl with a pearl earring* showed a few particles of charcoal under a black paint layer, which could possibly indicate the presence of a linear, carbon black underdrawing. This evidence is too scant for drawing a definite conclusion. The reason for the absence of underdrawing in the paintings could be that a material was used that evades detection by the available examination techniques. Such is the case when the material used for underdrawing does not contain carbon black. A few lines, apparently in black chalk, have been noted in the *Allegory of faith*, of 1671-74 in The Metropolitan Museum in New York, notably along a line dividing the wall from the ceiling.[17] Instead of an underdrawing in black, the unfinished painting on the easel in Vermeer's *Allegory of painting* (c. 1666-67) in Vienna shows a white chalk underdrawing. A drawing in chalk defies detection in infrared photography or reflectography, X-radiography and other (analytical) techniques, so even if Vermeer had used white chalk this could not be detected. If the material for the white drawing would be lead white paint, applied with a brush, then the white sketch would be detected in X-radiographs. Lead white sketches were absent in the X-radiographs of the actual paintings by Vermeer.

Also, a white drawing on a white preparation, – the most likely candidate for the colour of the preparation in connection with the camera obscura – does not make sense. The ground of the canvas on the easel in the *Allegory of painting* is grey.

Although Torrentius seems to have drawn the projected image directly onto the prepared wooden support, other artists could have made a drawing after the projected image on paper and transferred this drawing to the prepared canvas or panel. As Martin Kemp has shown, Antonio Canaletto, in the eighteenth century, traced the image obtained by the camera obscura by drawing on paper. Sketchbooks with such drawings have survived.[18] Pin holes are found in Canaletto's papers, obviously for transferring the composition to another support, such as canvas or panel. Kemp showed that Canaletto adjusted the drawings made with the use of the camera with additional correction lines, as did Torrentius as stated above. Canaletto added buildings without the use of the camera but by drawing them freely into the rest of the drawing.

As far as we know no drawings on paper by Vermeer exist and it is not clear whether they ever existed. No punch marks or black dots, evidence of transfer of a drawing from paper to canvas, were detected in his paintings.

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[15] For an account of the development of the camera obscura and the type possibly used by artists in the seventeenth century in Holland, see Steadman [2001] 4-24. Also: Delsaute [1998].

[16] Wallert [2007] 60.

[17] Costaras [1998] 153.

[18] Kemp {1990].

Vermeer would not be an exception as far as the absence of black underdrawing is concerned. There is no carbon black underdrawing in paintings by Rembrandt either. Rembrandt made monochrome wash drawings executed with the brush in oil paint. Such a monochrome painted sketch underlies paintings by Vermeer as well.[19] Technical examination using the microscope has shown that also *Girl with a pearl earring* was first designed in dark paint. This dark paint underlies the right shadow part of the girl's face, the shadows of the blue turban, the yellow drapery and the (now dark, originally greenish) paint of the background. No dark paint was found where the light falls on her face. The underpaint varies in colour from mid-ochre to dark brown, almost black.[20] Sometimes there is more than one layer, as is the case at the transition of the turban and the background and of her neck and the background. The cross-section from a sample from this area shows an extra application of black on top of a slightly different mixture of black paint. Although it is dangerous to base a hypothesis on a less than 0.3 square millimetre area in the painting, this find suggests that first the background was laid-in with paint, almost black, and then the shadows in the face were modelled.

The monochrome painted sketch in the *Girl with a pearl earring* and in other Vermeer paintings must have had two functions: painted lines would define the composition, while broader areas of brown paint represented the areas of shadow, while the light colour of the ground served as the lights. The lights were strengthened in this early stage of the painting process, as can be seen for example in the cross-section of sample from *View of Delft* (Fig. 4 mentioned above) and, with the naked eye, in for instance *The milkmaid* of c. 1658-60 in the Rijksmuseum in Amsterdam. For the rendering of the bread rolls first a thick layer of coarse, granular lead white was applied, followed by a translucent reddish paint. Some of the coarse grains of lead white stick through the red from underneath, while larger areas of the white parts of the bread have been left exposed at the surface of the painting. (In the final stage of painting the bread was completed with small yellowish white highlights). The can and the breadbasket were treated in the same way.

Not only the light underpaint, but also the monochrome sketch was sometimes further used in the final painting. The shadows at the back of the girl's yellow drapery, for instance, were modelled by letting the dark underpaint shine through the final layer of ultramarine blue. (Fig. 6).

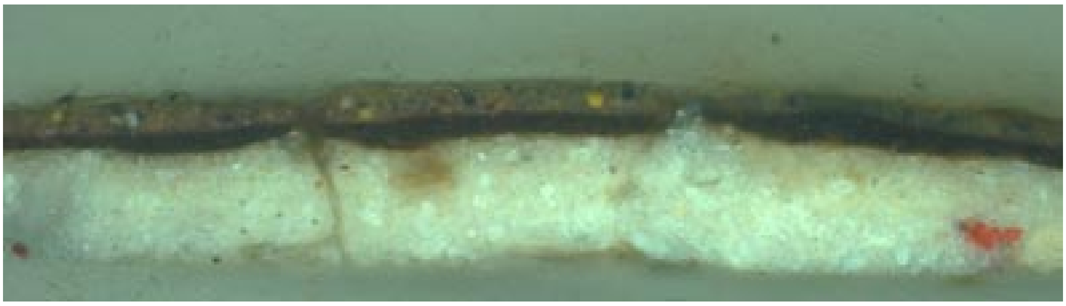

Figure 6: Paint cross-section of Girl with a pearl earring, showing the layer of dark underpaint between the light coloured lower layer of the ground and the paint of the shadow in the drapery.

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[19] Nicola Costaras observed brushed dark brown lines in *Diana and her companions* (1655-56). Costaras [1998] 153. Melanie Gifford found a brown sketch in *Woman holding a balance* (c. 1664) and in *The girl with a red hat* (c. 1665).

[20] Groen, *Vermeer Studies* [1998], 171-173.

For making such a painterly sketch, artists would not particularly need a mechanical aid such as the camera obscura. Rembrandt certainly did not use one. Now the question is: to what extend does Vermeer's underpainting differ from Rembrandt's and other seventeenth century painters? With the techniques available for examination it is not very plausible to say to what extend the monochrome undermodeling, – and the distribution of light and dark – in Vermeer's paintings was applied sketchy, or 'painterly'. Is there something *extra* in Vermeer's underpainting that would make the use of the camera obscura feasible?

Undermodelling in different colours

What seems special in Vermeer's paintings is that, besides the monochrome undermodelling, Vermeer applied flat forms, in different colours. In *The glass of wine*, for instance, the whole of the foreground of the black-and-white tiled floor was first blocked-in with a layer of red earth paint.[21] In *The music lesson* different coloured paints can be seen clearly through little damages in the top paint. There is a reddish paint underneath the paint of the black-and-white tiled floor and black underneath the girl's dress and the jug on the table and brown under the shadow of the tablecloth (Figs. 7, 8).[22] Also, the dark underpaint of the background in *The girl with a pearl earring* (the underpaint mentioned above) would not need much modelling, it is probably a rather evenly applied dark paint.

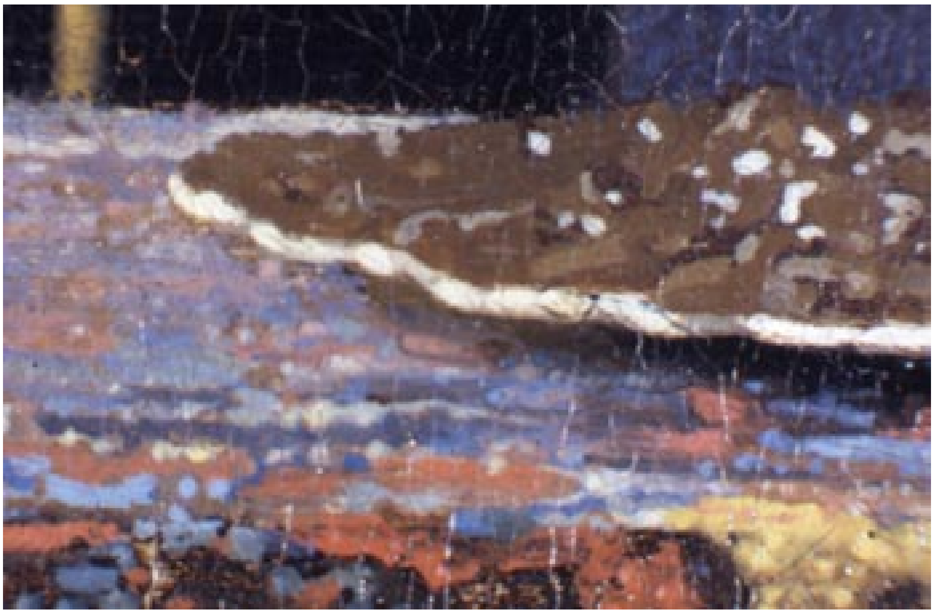

Figure 7: Detail of the tablecloth in Johannes Vermeer, A lady at the virginals with a gentleman (The Music Lesson), c. 1662–1665, canvas, 73.3 x 64.5 cm. Her Majesty Queen Elisabeth II.

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[21] Costaras [1998] 154.

[22] Technical information and documents kindly provided by Rupert Featherstone, conservator at the painting conservation studio of the Royal Collection at Windsor Castle.

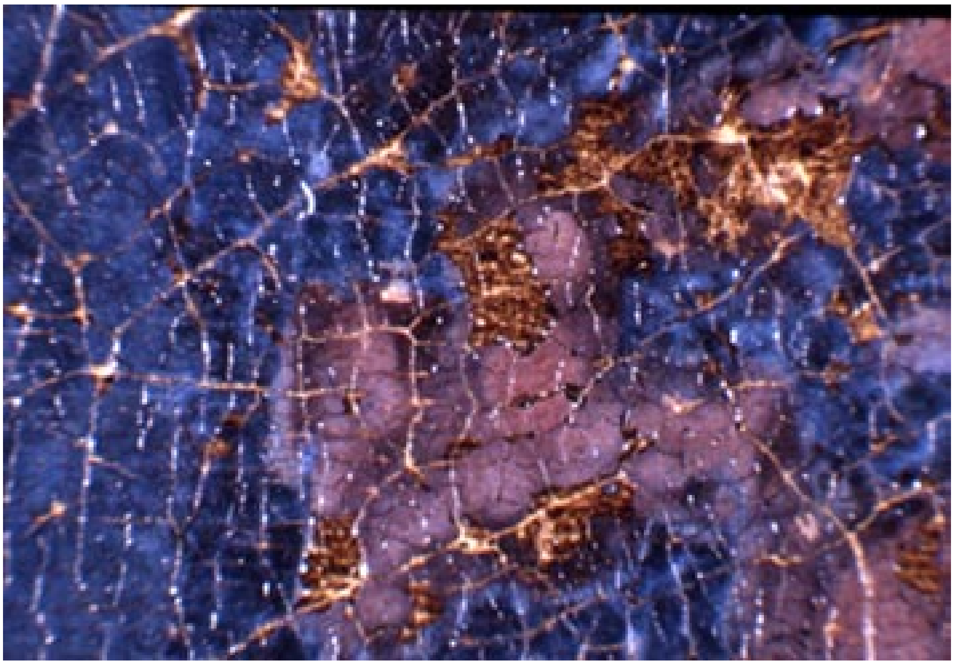

Figure 8: Microphotograph of a detail in the tablecloth in Johannes Vermeer, A lady at the virginals with a gentleman (The Music Lesson), showing the brown underpaint.

It may have been possible for an artist like Vermeer, when working in relative darkness in his cubicle-type camera, to directly paint the bright colours of the image cast by the camera in coloured paint onto a flat surface[23]

In a reconstruction of Torrentius' *Still life* set-up in front of a seventeenth century camera obscura, the image of the projected still life, with the flagon, wine glass and stone water jar neatly in a row, – as Torrentius would have done to facilitate the right focus – appears in its natural colours against a dark background (figs 9, 10). Highlights and colours stand out strongly. It must have been not too difficult for Torrentius to cover these forms with paint. The distribution of lights and dark as well as of the main colours would be established straight away. Vermeer could have done the same, applying black for the dark parts, white at places where highlights should come and other colours, grey, brown, red and yellow as appropriate.

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[23] Images projected by a camera obscura built at the Max Planck Institute in Berlin in 2006 did show bright colours.

Figure 9: Reconstruction of Torrentius' still life, set-up in front of an old camera obscura.

Philip Steadman, citing Gowing in his book *Vermeer's Camera, Uncovering the truth behind the masterpieces*, speaks of Vermeer's canvases as 'mosaics of shapes'.[24] The effect of 'embedded flatness of inlay, or tarsia' would be the logical consequence of forcing three-dimensional space into two dimensions. (Tarsia or *intarsia* is the decorative or pictorial mosaic of inlaid wood or

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[24] Steadman [2001] 158.

sometimes ivory of a style developed in the Italian Renaissance and used especially on wooden wall panels). A process that takes place automatically during the casting of the image by a camera obscura onto a flat object. Vermeer would have first carefully controlled and adjusted his composition, following the camera image and simultaneously abstracting from this image. This implies that the painting may have been, after a more-or-less detailed monochrome sketch, laid-out in even areas of local colour.

Figure 10: The image of the still life reconstruction as projected by the camera obscura.

However, one has to be careful here, as the effect of *intarsia* could be caused by something different than the use of a camera. There may have been a technical reason related to the materials available to painters at the time. Tube paint, with a consistency equal for whatever colour the artist wanted to use, did not exist as yet. Each colour had to be prepared separately and shortly before use. The resulting way of working had direct influence on the style, the way we see the picture.

Ernst van de Wetering, in 'The palette; on the relationship between style and painting technique' comes to the conclusion that painters used small size palettes, since small size palette sufficed, as artists in the seventeenth century executed the different areas in their paintings one by one.[25] In this respect, painting practice, and as a consequence style, in the seventeenth century differed from practice in, for instance, the nineteenth century. While in the seventeenth century the rendering of specific coloured areas was done one after the other (the technique of *giornata* in Italian mural painting springs to mind), in the nineteenth century the artist could work on the whole of the canvas at once, mixing whatever colour he wanted on his large palette.

Figure 11: Detail of the lit part of the nose and the cheek behind it in Girl with a pearl earring.

With Vermeer, the restriction posed by the materials on painting techniques does not seem sufficient to explain the *intarsia* look of his finished paintings. One of the things that make Vermeer's paintings look different from other paintings is the frequent lack of clear contours in his finished work. (In the work of other seventeenth century artists one can see all sorts of *sfumato*). Gowing already noticed this phenomenon.[26] There are no sharp lines, contours are soft or altogether missing, even within one area. For instance in the face of the *Girl with a pearl earring*, the lit part of the nose extends into the lit part of her right cheek without any change in tone or hue of the flesh paint between the nose and the cheek behind it (Fig. 11). Also, open spaces in which two adjacent areas meet, a consequence of the working in patches and so typical for seventeenth century painting, do not appear so frequently in Vermeer's paintings. Notwithstanding the restriction posed by the available materials, artists could have had a spontaneous way of working. However, for Vermeer the word 'spontaneous' does not seem to be appropriate. There is no emphasis on form, there only seem to be blocks of lit and shaded areas. Steadman illustrates this phenomenon with Vermeer's treatment of hands, which he attributes to the use of lenses.[27] With a single uncorrected lens it is impossible to achieve perfect focus throughout all parts of a large image. Such a lens introduces effects of softening and simplification.

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[25] Van de Wetering [1997] 132-152.
[26] Steadman {2001] 42.
[27] Steadman [2001] 160.

The areas of coloured underpaint suggest that the absence of lines extends to Vermeer's preparatory work on the canvas. The tonal and chromatic values in the underlying image could be due to the incorrect focussing of the lens and perhaps to the darkness of the room. This tentative conclusion is underscored by the impression of some features in the X-radiographs, that appear as 'blocks of light and dark', as happened with the girl's face of *Girl with a pearl earring*.

CONCLUSION

Experimental set-ups of a camera obscura have shown that the camera can produce clear images which painters could have used in the creation of their paintings. It could have been possible to draw outlines or roughly block-in different areas of white and coloured highlights and dark. The device would have been a help in designing the composition. The examination of paintings by Vermeer does not contradict the use of the camera obscura. Furthermore, the results of the examination provide, – only circumstantial – evidence of how he may have used the camera obscura for the undermodeling of his paintings.

What would working from the image projected by the camera have meant for the practising artist? Recently David Hockney has demonstrated that he could trace the projected image, using a pencil.[28] Perhaps he could also have used a brush with paint.

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[28] Hockney [2001].

Neutron-Autoradiography of two Paintings by Jan Vermeer in the Gemäldegalerie Berlin

Claudia Laurenze-Landsberg

In collaboration with the research reactor in Berlin, the Hahn Meitner-Institute, the Gemäldegalerie Berlin is the only institute world wide, which systematically employs the non-destructive method of Neutron-Activation-Autoradiography to analyse paintings. Today we have investigated about 60 paintings. The main advantage of this investigation compared with other analytical methods is that the distribution of different pigments both over the entire picture plane and in the various paint layers is recorded on film and that readings can lead to pigment identification.

First a brief description of the method: The Painting is placed in front of a neutron guide where it is scanned with neutrons for several hours. This activation produces isotopes of different half-life values in several pigment types. They emit beta and gamma rays. For a period of up to six weeks following the activation a series of today four, formerly 5 or 6, x-ray films are placed on the surface of the painting and exposed to the beta rays. The beta rays emitted from all layers in the painting from the ground, under painting, up to recent retouching, cause a blackening of the film. By exploiting the different half-life values, paint layers which vary in colour can be shown separately on film. Invisible under painting and changes in the composition, as well as the technique of paint application, and the condition of the painting are made visible. In addition the pigment composition employed by the artist can be identified by measuring the gamma rays. Neutron-autoradiography does not replace other analytical methods which record the distribution of pigments on film. As lead is hardly activated by neutrons, x-radiography completes the range of colours visible on film. With both, x-radiography and autoradiography, paint layers in nearly all colours, which are invisible to the naked eye, are detected and tell us the story of a painting.

Such a story is described in the book by Tracy Chevalier “Girl with a Pearl Earring”, which was adapted for the screen in 2003. The maid who helps in Vermeer’s house and who is shown into the painter’s atelier dusting the room sees for the first time a painting by her master. It is the painting “Girl with a Pearl Necklace”, dated about 1664, which today is in the possession of the Gemäldegalerie Berlin. She admires and remembers every detail also that a map was hanging on the white wall behind the woman. Several days later she sees the painting again. Now the wall is bare, without leaving any trace the map has disappeared. The maid is confused by the change of the composition.

The normal reader of the book is not aware of the thorough research the author undertook while writing the book. Actually only a small group of people know that there is in fact a map hidden beneath the surface of the painting. The existence of the map was revealed by the investigation of this painting with neutron-autoradiography. Here only the last autoradiography, which shows the distribution of bone black within this painting, reveals the map.

Figure 1: Jan Vermeer van Delft, Girl with a Pearl Necklace, Gemäldegalerie, Staatliche Museen zu Berlin.

On this film we also discover the pentimenti of a lute lying on the chair in front of the composition and of the dark blue cloth on the table that originally opened the view on to a larger part of the black and white tiled floor. The author of the book gives no explanation for Vermeer's reason for first planning to paint a map and a lute only to reject both elements. Even the question of why he did so is the first and obvious people would ask. What we see today is a young woman caught in a pose that betrays no movement, gazing into a mirror and holding the ribbons of a pearl necklace. Her horizontal gaze is emphasized by the horizontal line of the chair and, though not visible, that of the table. The white wall behind the woman gives no interruption to the "room crossing gaze" which in its intensity is the centre of the composition.

Figure 2: The 5th or last autoradiography, exposure time 8 to 52 days after activation, shows mainly the distribution of phosphorous in boneblack.

The interpretation of the content of this painting is dependant on the meaning which is assigned to the attributes. As Vermeer's work is understood to provide moral guidance for human endeavours, the mirror and the pearl necklace were attributes of vanity. The last autoradiography reveals that Vermeer originally supplied even more allegorical hints in the scene which impart a moralizing didactic content. The map on the wall which frames the female figure identifies her as "vrouw wereld", the personification of worldliness, the most condemnable form of vanity. On the chair a musical instrument lies. This lute, symbolising, that, just as the sound of music fades away, worldly pleasures are only for the moment. In fact, with all these attributes, the context of the originally planned painting is a most urgent admonition with regard that life is short and that virtues should not be abandoned. No other interpretation is possible. But by the elimination of the map and the lute other associations for the meaning of the mirror and the necklace could be possible. Arthur Wheelock now interpretates the mirror as a sign for truthfulness and sees in the white shiny pearls a symbol of purity and faith. Thus for him the implication of the composition turns from negative to positive. But still a woman is shown, embellishing herself with pearls and facepowder. For Jan Kelch mirror and pearl necklace cannot be but attributes of vanity in the iconography tradition. In his opinion Vermeer reduced the overabundant references in order to encourage the spectator to receive the message without being discouraged and in favour of a well balanced composition. Vermeer also eliminates the view of the tiled floor which would have disturbed the plainness and sidetracked from the woman's gaze.

Figure 3: This detail from the 3rd autoradiography, exposure time 28 to 48 hours after activation, shows the pentiment of a piece of cloth. The paint layer contains a copper-pigment and boneblack, which blackens the last autoradiography.

Another pentiment on the table is of significance for the content of the painting but is also an improvement for the composition. The space where the powder brush points in the direction of the woman was before filled with another piece of cloth. A fold of this cloth behind the large blue cloth in front of the chair was over painted, too. The remaining folds of the blue cloth now are in form of a curve that leads the spectator's view from the mirror back to the necklace and the girl's eyes. A small correction in the position of her right arm served to bring both arms in alignment. Vermeer took care to create parallel lines which we can also observe in the folds of the curtain and which are parallel to the position of the arms, as well. These correspondences in the composition create the atmosphere of a frozen moment in which all movement has stopped. These smaller modifications show us how carefully Vermeer revised the painting to achieve a well balanced composition. Nothing in this painting is left to chance. The viewer is manipulated to sense and realise exactly what Vermeer wants him to.

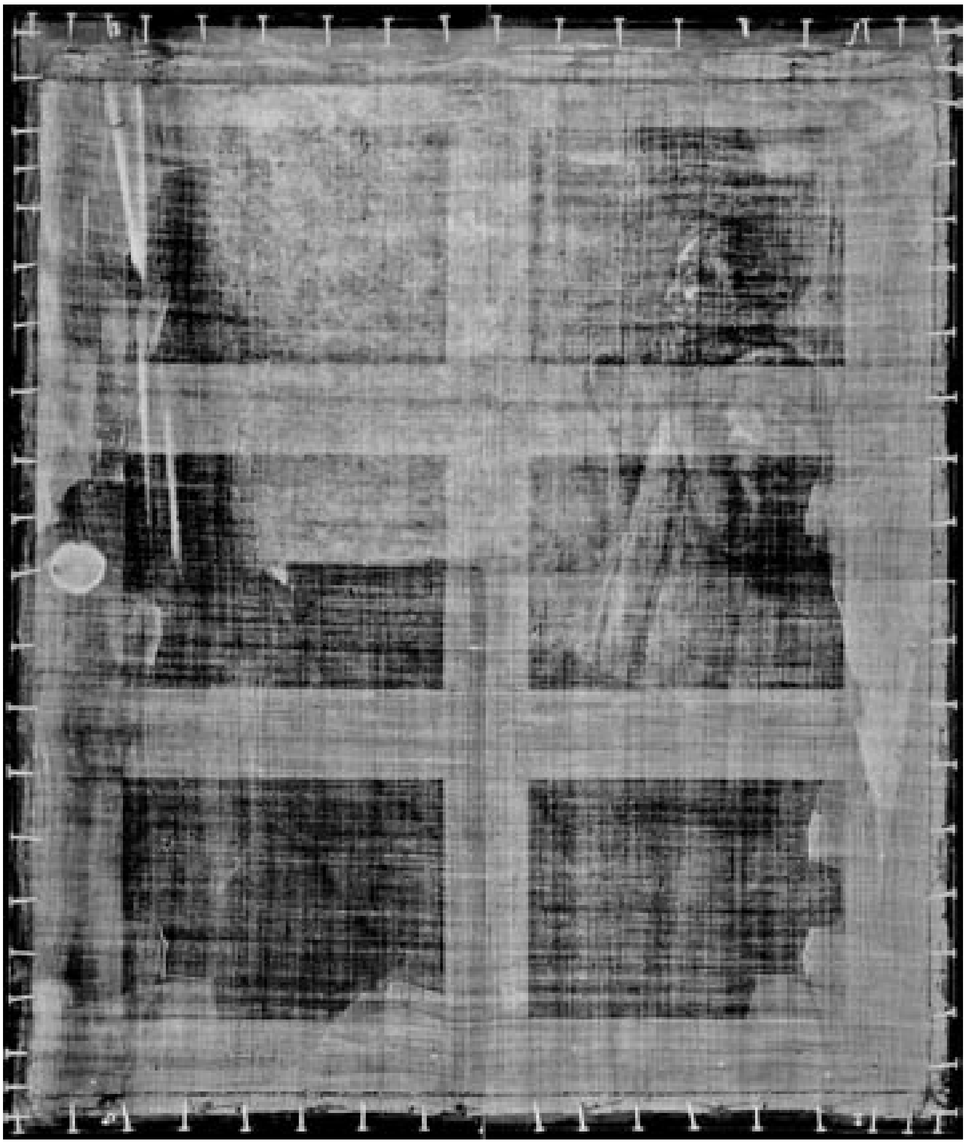

Figure 4: X-ray radiograph, showing the distribution of lead white.

We now have a look at the x-ray film. The wall behind the mirror was in the initial design lighter and in stronger contrast to the dark frame of the mirror. Vermeer had given the mirror more prominence which is in correspondence with his original concept with the emphasize on moralizing attributes.

The x-ray film shows that Vermeer's version of the composition was smaller than today. Marks from the old strainer bars indicate the original size. Autoradiography reveals that the pigment composition of the addition differs totally from the pigments used by Vermeer. The yellow curtain is extended with Naples Yellow, a pigment never analysed in a painting by Vermeer.

Neutron-Autoradiograph also tells us about Vermeer's painting technique.

We can see the map and the lute on the last film, because the paint layer contains boneblack. Though we cannot say for certain, most probably the bone black was used as an under paint and the painting process had not advanced further. During the restoration of the painting only black under paint was observed underneath the white wall. Under the microscope a black layer underneath the dark blue cloth on the table was also found. This was a surprise for that area is without any blackening on the last autoradiography. The explanation for this must be that this under paint is done in carbon black. Carbon is not activated by neutrons and thus causes no blackening of the film. Most painters used a monochrome preliminary sketch with only one kind of colour for the definition of the composition. It astonishes that here not only different colours, as were found in other works by Vermeer, but even different blacks were used. Bone black has a shade of brown and is a warm black whereas carbon black like charcoal and lamp-black rather tends to be a bluish cold black. We become aware of Vermeer's understanding of the optical effect of the under painting and of how carefully he built up paint layers to obtain the extraordinary effects of colour we so admire.

When considering how carefully Vermeer planned the composition of this painting one would also expect that he handled his brush the same way. It astonishes to find in the under painting a quick sketchy stroke done with a rather broad brush. These brush strokes can best be observed in the under painting for the map. With a broad brush and rather long strokes he sketched the map, already defining the fields for scenic views of towns, similar to the map of the united Netherlands in "The Art of Painting" (1666/67), Kunsthistorisches Institut, Vienna.

By comparing the different autoradiographs taken from this painting and by analysing the gamma-rays, which are specific for every created radioactive isotope, quite a number of pigments used can be identified.

The first film tells us that there is an admixture of manganese containing brown earth in the ground, because the canvas weave is visble. In the x-ray-film an addition of lead white to the ground is also evident. The pigments employed to paint the cloth are most probably azurite and smalt, as the isotopes identified by gamma-spectroscopy are from copper and arsenic. They cause a blackening from the first up to the fourth autoradiography. When the last film was exposed on the painting the copper and arsenic isotopes had already decayed. In addition to the phosphorous in boneblack also a blackening by mercury in vermillion can be seen on this film. This was the pigment used for the ribbon in her hair.

Neutron-autoradiography and x-radiography enables us to become witness to Vermeer's change of mind. At first he intended the painting to be a severe moralizing lecture. His first version of the composition is filled with attributes, such as the map, the lute, the set off mirror, the pearl necklace. By reducing the attributes the moral message now only forms the background to a composition perfect in colour and mood.

Figure 5: Jan Vermeer van Delft, The Art of Painting, Kunsthistorisches Institut, Vienna.

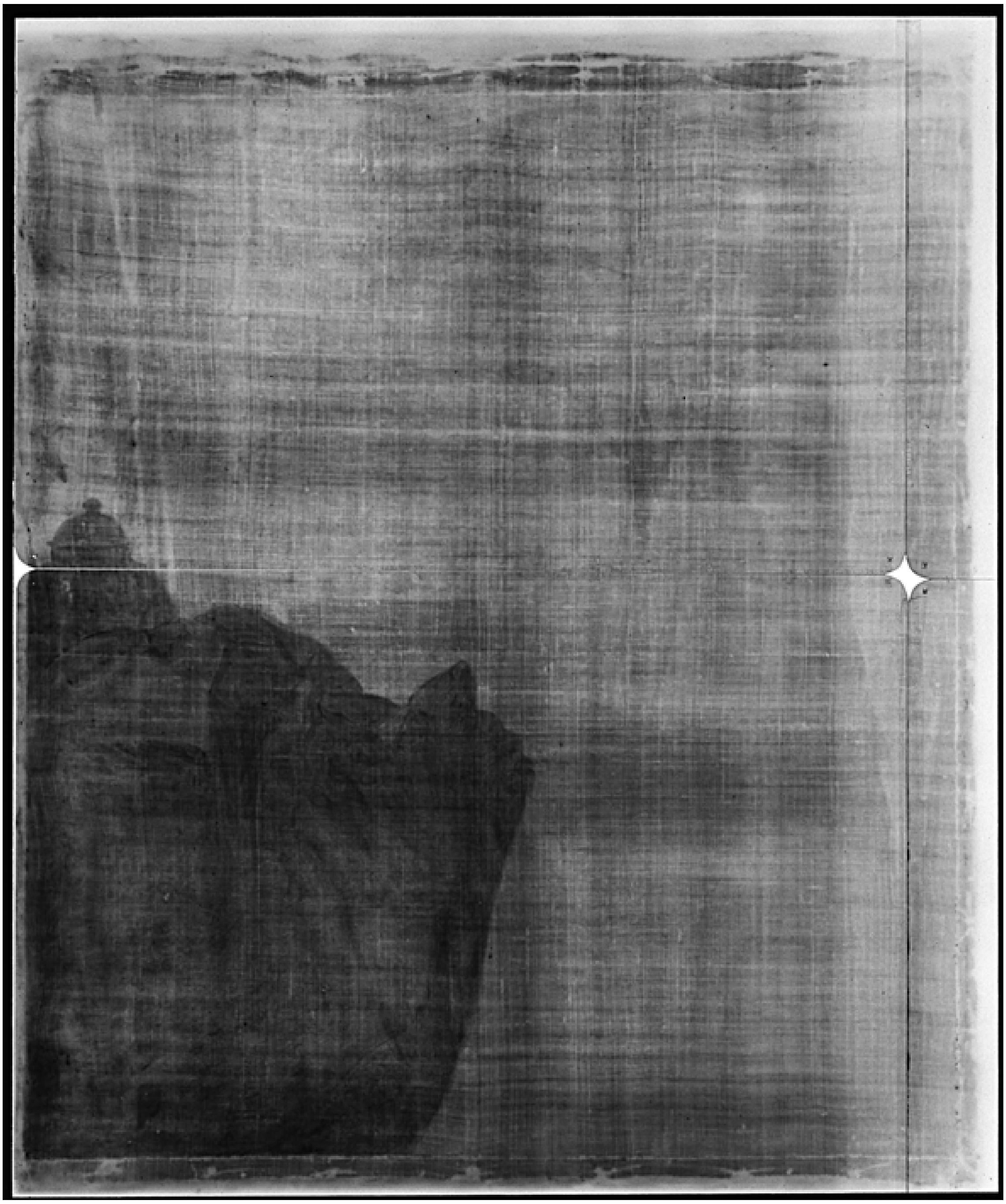

Figure 6 a:The 1st autoradiography, exposure time 0,5 to 2 hours after activation, shows manganese in brown earth pigments in the ground and a copper pigment in the cloth.

Figure 6 b: In the 5th autoradiography the activity of manganese and copper isotopes have decayed. Because of the long exposure time of seven weeks isotopes with long half-lives like phosphorous in boneblack or mercury in vermillion can be seen.

Every detail within the painting was well calculated, even the direction of her little finger. The viewers look is guided from powder brush over the little finger to her eyes. Her gaze crosses the room; the bare white wall gives no interruption. From the mirror the view is guided by the folds in the cloth on the table again to her eyes. The viewer is forced to accept this room crossing gaze as the centre of the composition. The extraordinary calmness of the painting in which all movement has stopped is well planned by parallel lines and the balance between the dark lower half of the painting and the white wall. Also the choice of subdued colours of which the tonality is influenced by the colour of the under painting contribute to the calmness imparted. The only bright colour, yellow, distributed evenly and again in parallel lines, does not disturb the viewer.

Figure 7: Jan Vermeer van Delft, The Glass of Vine, Gemäldegalerie, Staatliche Museen zu Berlin.

The other painting by Vermeer in the possession of the Gemäldegalerie is called "The Glass of Vine" dated around 1658-60, four or six years earlier than "Woman with a Pearl Necklace". A woman, dressed in a precious red satin dress, empties a glass of wine while a gentleman, wearing hat and a large scarf, watches her. Holding his hand on a pitcher, he is ready to fill her glass once more. In the open window a family coat-of-arms can be seen, a figure holds a set of reins, indicating that the represented scene shows the lack of restraint, reminding the viewer of the virtues of moderateness and temperance.

The result of the investigation with neutron-autoradiography seems to be at first sight not as exciting as the one of "Woman with a Pearl Necklace". Only the pentiment of the man's hat catches our eye. But a closer look reveals interesting details. In the third film we see that Vermeer probably originally intended to refer to the moral message of the composition with the painting at the wall. The outline of a hat can be seen on the left hand side of the painting. A male figure standing there must have had a corresponding figure on the right hand side of the small composition. As in "Woman with a Pearl Necklace" Vermeer reduced the moral message by replacing the planned genre scene with a landscape.

Figure 8: 5th or last autoradiography, exposure time 9 to 51 days after the end of activation.

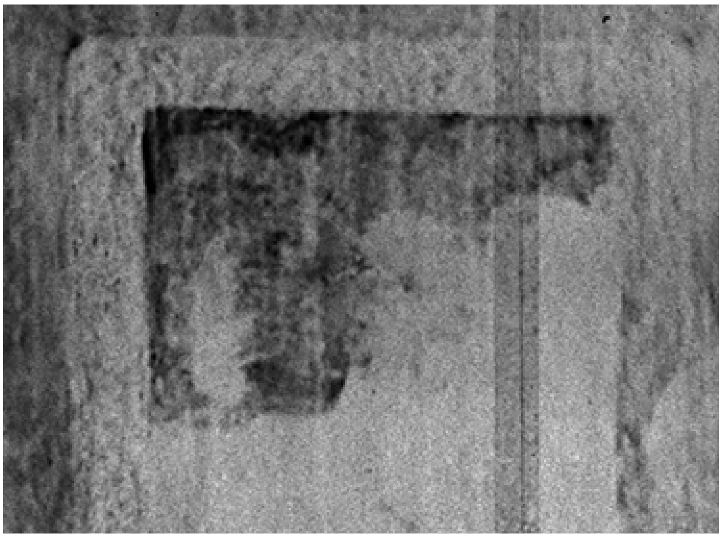

Figure 9: Detail from the 3rd autoradiography, exposure time 1 to 3 days after the end of activation, showing the painting on the wall.

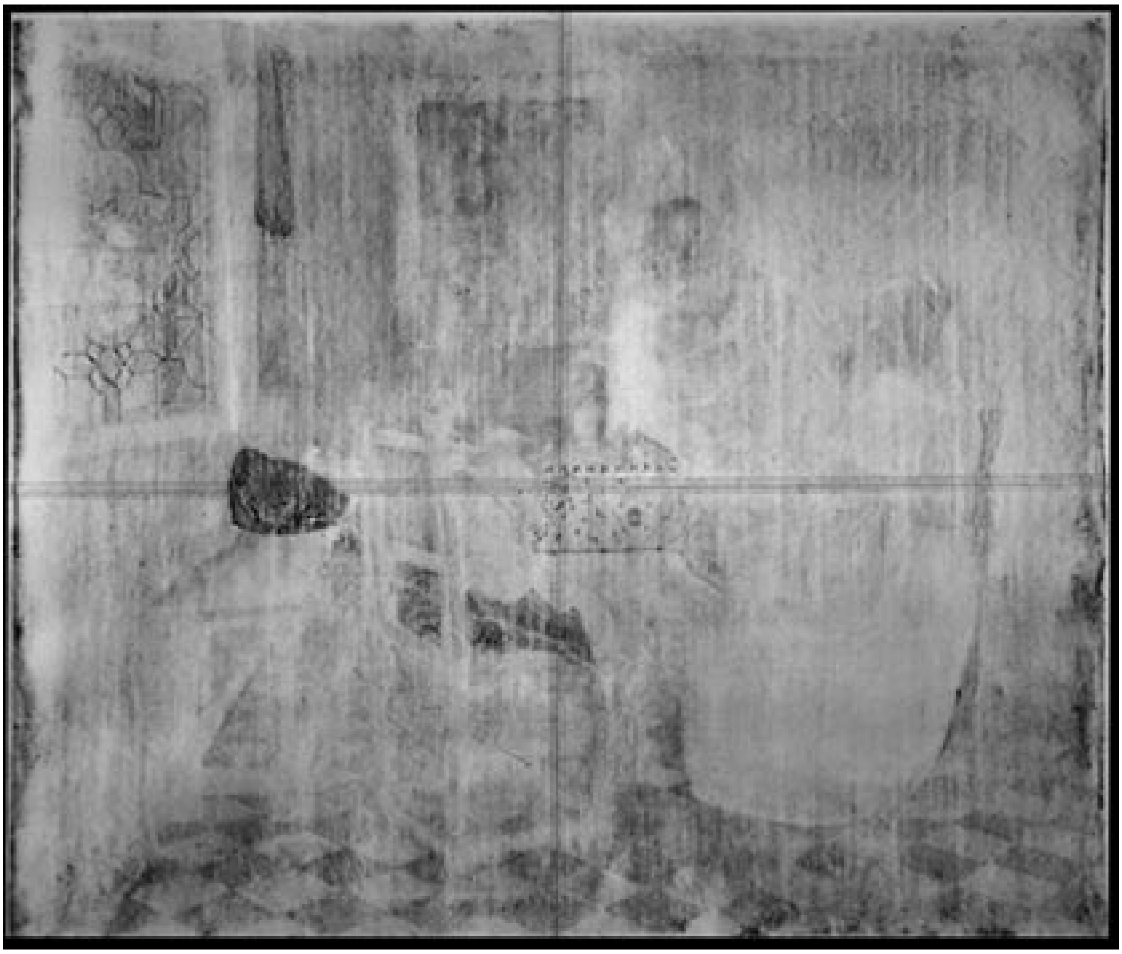

Figure 10 a

Figures 10 a & 10 b: The 1st autoradiography, exposure time 0,5 to 2 hours after the end of activation, and 5th autoradiography.

Interesting lines can be observed in the first and the last autoradiography. These lines become visible because there is no blackening at all. They can only be caused by an underdrawing up to which Vermeer applied paint and left the lines in reserve. In the first film the outline of the chair can be seen because the adjoining colour is manganese containing brown earth. In the last film lines for the pattern of the tiles can be seen. The boneblack added to the paint layer of the dark tiles does not cover the lines. The lines themselves cause no blackening at all because the pigment of the underdrawing could not be activated with neutrons. Pigments which create no radioactive isotopes are carbon black, chalk or earth colours. The lines cannot be seen under the mikroskop because Vermeer covered the lines with a paint layer containing earth pigments during the painting process. Vermeer may have used white chalk, as with the outline drawing seen in the unfinished painting on the artist's easel in the "Art of Painting". (Figure 11)

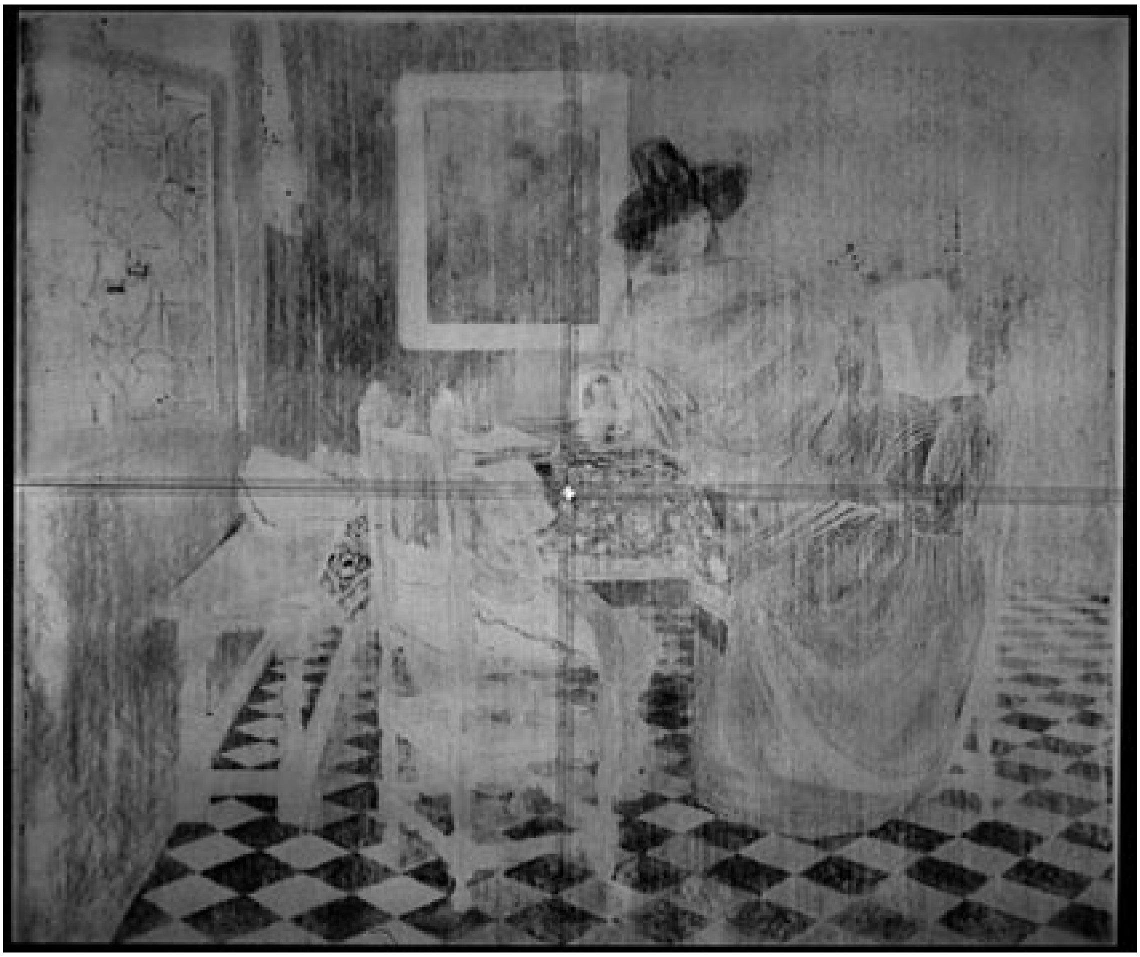

Figure 10 b

Obvious lines were found of two perspective diagrams. The extended vanishing lines of the tiles meet at two distance points outside of the composition. They are at the same height as the central vanishing point. This central vanishing point is in the lower left of the painting on the wall where the diagonal lines of the tiles meet. The hole caused by the pin to which the string was attached to determine the position of the diagonals can be seen in the x-radiograph.

The extended perspective lines for the construction of the chair meet in a seperate vanishing point which is on the left hand side of the painting on the horizontal line. We notice a distortion of the tiles in the upper corner. Here Vermeer did not stick to the correct lines. As Jorgen Vadum observed in an article “Vermeer in Perspective” (Johannes Vermeer, National Gallery of Art, Washington, 1995) Vermeer apparently was vexed by the distortion of the tiles which is caused by the high horizon and that the horizon in Vermeer’s earlier works is higher than in the later ones.

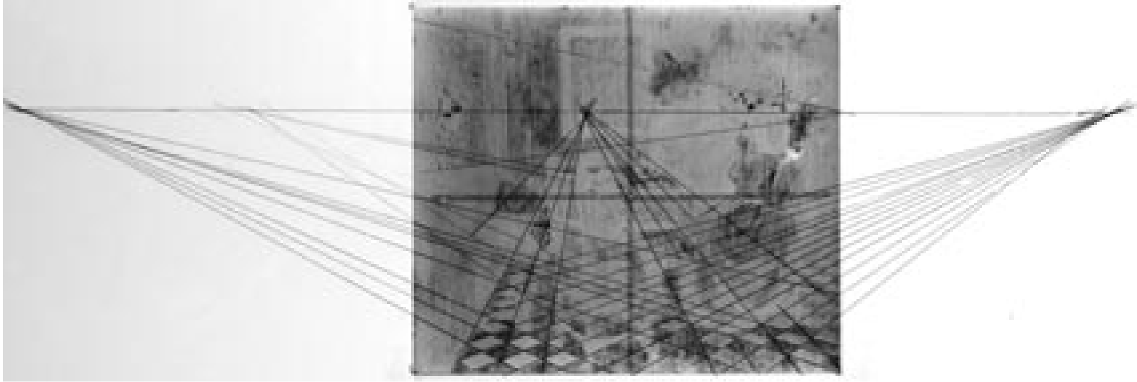

Figure 11 a

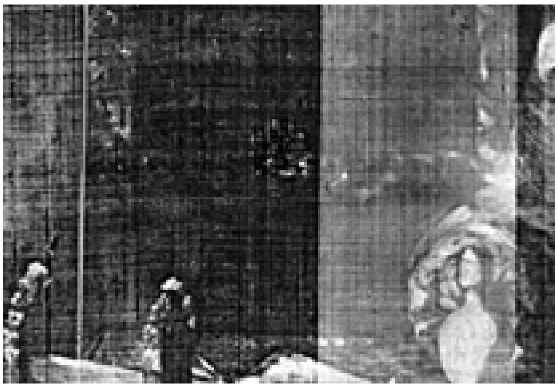

Figure 11 b

Figures 11a & 11 b: Lines within the painting are extended until they meet at distance points outside the composition. The central vanishing point is in the lower left of the painting on the wall.

He argues that this is not caused by the use of a Camera Obscura but that he deliberately used the high horizon in order to keep the spectator at a distance. As in other works by Vermeer the central vanishing point leads the eye of the spectator into the composition and the meaning of the content. Thus the content of the painting on the wall must have contained a specific hint in Vermeer's initial intention.

As we have seen by the investigation with neutron-autoradiography of both paintings in the possession of the Gemäldegalerie, Berlin, Vermeer had a very clear concept of emotions he intended to provoke wthin the spectator. This aim in mind every detail in his compositions was planned carefully as to create the desired effect. But the way this effect is achieved is different in both paintings. In the earlier painting "Glass of Wine" we find a perspective constructed with a pin and a string. This method is difficult to combine with the use of a Camera Obscura.[1] In the painting "Girl with a Pearl Necklace", which is dated 4 to 6 years later, Vermeer used dark colours for the under painting of his composition. Here it could be possible that the sketch was done in a dark room while the image of a Camera Obscura was projected onto the canvas.

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[1] For a possible combination of both methods, see Carten Wirth in this volume:

References:

Kühn, Hermann, "A Study of the Pigments and the Grounds Used by Vermeer", Reports and Studies in the History of Art 1968, National Gallery of Art, Washington

Kelch, Jan, "Ein Blick über die Schultern des Malers", Museumsjournal, 5. Folge, Nr. 1, 3. Jahrgang, Jahrgang 1989, S. 52 ff.

Arthur K. Weelock, jr. and Ben Bross, "Woman with a Pearl Necklace", Catalogue for the Exhibition Johannes Vermeer, National Gallery of Art, Washington and Royal Cabinet of Paintings Mauritshuis, The Hague, 1995, p. 152.

Vadum, Jorgen, "Vermeer in Perspective", Catalogue for the Exhibition Johannes Vermeer, National Gallery of Art, Washington and Royal Cabinet of Paintings Mauritshuis, The Hague, 1995, p. 67.

Gerrit Dou and the Concave Mirror

Philip Steadman

The Dutch painter Gerrit Dou (1613-1675) is known for his tiny genre scenes and his obsessively meticulous technique. Dou's reputation in the 17th century was on a par with that of his teacher Rembrandt. He was admired above all for his untiring patience in depicting the detail of faces and still life objects. In the later 19th century his star began to fade, and what had previously been admired as miraculous technical skill came to be viewed, in Arthur Wheelock's words, as 'pedantic and dry'.[1] Recent years however have seen a reassessment. The very first international exhibition of Dou's work was held in 2000/2001 and travelled to Washington, London and The Hague.[2]

Figure 1 shows one of Dou's many self-portraits.[3] The panel is just 43 centimetres (17 inches) across. Other paintings measure 20 centimetres or less. Many of Dou's portraits are almost miniatures. Dou went to enormous pains to render this level of detail on such a tiny scale. The German artist and writer Joachim von Sandrart visited Dou around 1640.[4] In a famous anecdote, he describes how Dou kept all his paints and brushes in a closed chest to keep them scrupulously clean. On entering his studio in the morning, Dou would sit motionless in his chair for a while until the dust settled and he could then open the chest and begin work. The French writer Roger de Piles describes Dou working on a portrait and taking five days just to paint one of the sitter's hands.[5] Another visitor to Dou's studio in the 1660s was the Danish savant Ole Borch. By that time in his life, according to Borch, Dou "[...] had the habit of putting on three pairs of spectacles to see more clearly."[6]

Several writers mention that Dou made use of different kinds of optical apparatus, and not just eyeglasses. The most detailed account is by the French art historian Jean Baptiste Descamps, in his *Lives of Flemish, German and Dutch Painters* published between 1753 and 1765.[7] Here is my translation:

> I do not know whether it is to him that we owe a rather ingenious invention – although one with various drawbacks – for reducing large objects into a small space. He made use of a type of screen on a stand, in which he had fashioned and framed a concave mirror [*miroir concave*], on the level of his eye when he was seated. This screen was a sort of enclosure [*cloison*] between

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[1] Arthur K. Wheelock jr., 'Dou's Reputation' in *Gerrit Dou 1613-1675, Master Painter in the Age of Rembrandt*, Yale University Press, New Haven and London 2000, pp. 12-24. See p. 14.

[2] *Gerrit Dou 1613-1675, Master Painter in the Age of Rembrandt*, exhibition held at the National Gallery of Art, Washington 2000; Dulwich Picture Gallery, London 2000; Royal Cabinet of Paintings Mauritshuis, The Hague 2000/2001. Note 1 references the catalogue.

[3] Gerrit Dou, 'Self-Portrait' c. 1665, oil on panel, 59 x 43.5, private collection, Boston.

[4] Joachim von Sandrart, *Teutsche Academie der edlen, Bau-, Bild-, und Mahlerey-Künste*, 2 vols., Nuremberg, 1675-79. See vol. 1 p. 321. Also ed. A. R. Peltzer, 4 vols., Munich 1925.

[5] Roger de Piles, *Abregé de la Vie des Peintres. Avec des reflexions sur leurs Ouvrages*, Jacques Estienne, Paris, 2nd edn 1715, p. 428.

[6] Described by Karl Madsen, 'Une visite chez Dou et une note sur Rembrandt', *Bulletin uitgegeven door den Nederlandschen Oudheidkundingen* Bond 8, No 6, December 1907, pp. 228-230. See p. 230.

[7] Jean Baptiste Descamps, *La Vie des Peintres Flamands, Allemands et Hollandois*, C.-A. Jombert, Paris 1753-64, vol. 2 1754, pp. 220-221.

> him and the object to be represented. The object formed a reduced image of itself [*se traçoit en petit*] in the concave mirror, and the painter needed to do no more than imitate the outline [*trait*] and the colour.
>
> Once his composition was laid out, he brought to his canvas – divided into an equally spaced square grid – the objects that he needed. This division was repeated with threads on a little framework whose size was that of the circumference of the concave mirror, in such a way that when he fixed the framework on the mirror, it represented a square inscribed in a circle. This method, which had its advantages, led to great faults; it made unnecessary that judgement of the eye essential for drawing, and which one does not acquire other than through the habit of drawing direct from the subject and without these other aids. Also, in bringing the detailed objects from which it was made up into the painting one after the other, this method of placing them gave an impression of invention contrary to harmony and elegance – and it is this for which Gerard Douw was often criticised.

Figure 1: Gerrit Dou, 'Self-Portrait', c.1665, oil on panel, 59 x 43.5, private collection, Boston.

This is possibly the first and only explicit mention in print of a painter using a concave mirror, up until David Hockney's *Secret Knowledge* of 2001.[8] There is indeed a brief allusion to this passage

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[8] David Hockney, *Secret Knowledge. Rediscovering the lost techniques of the Old Masters*, Thames and Hudson, London and New York 2001, *passim.*

by Descamps in a letter to Hockney from Peter Sutton, reproduced in the correspondence collected at the back of *Secret Knowledge*.[9] Notice in this context the very interesting criticism of the consequences of Dou's method: that by "[...] bringing the detailed objects [...] into the painting one after the other, this method of placing them gave an impression of invention contrary to harmony and elegance." This surely echoes the characteristic 'collage-like' quality that Hockney diagnoses in pictures that, as he argues, were produced with the help of concave mirrors. The various component items are drawn or painted separately, resulting in a certain incompatibility in their lighting, shadows and perspective, and a failure to integrate these various elements into a harmonious whole.

Figure 2: Gerrit Dou, 'Old Man Lighting a Pipe', c. 1635, oil on panel, 49 x 61.5, private collection, England.

Figure 2 gives an example of this compositional incoherence in 'Old Man Lighting a Pipe'.[10] There is one freestanding still life composition on the table and another on the floor, neither of them having much to do with the old man and his smoking ritual. Dou frames many of his other compositions with arched window openings, and sets out an odd assortment of objects along the sill. Figure 3 shows 'Kitchenmaid in a Window with a Chicken'.[11] We know the fate of the chicken,

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[9] *Ibid* p. 241.

[10] Gerrit Dou, 'Old Man Lighting a Pipe', c. 1635, oil on panel, 49 x 61.5, private collection, England.

[11] Gerrit Dou, 'Kitchenmaid in a Window with a Chicken', 1650, oil on panel, 26.5 x 20.5, Musée du Louvre, Paris.

but what are the bucket, the jug and the candlestick doing here? It is not so easy to detect perspective inconsistencies in Dou, since the architecture of his interiors, unlike the figures and objects, is painted quite schematically, often in heavy shadow, and without tiled floors or other prominent recession of orthogonal lines. One obvious discrepancy can be seen however in 'Artist in his Studio' from the early 1630s (Figure 4).[12] The images of the parallels in the easel must converge to a much lower vanishing point than that of the table. We see the table from a high vantage point, but the easel from a low one.

Figure 3: Gerrit Dou, 'Kitchenmaid in a Window with a Chicken', 1650, oil on panel, 26.5 x 20.5, Musée du Louvre, Paris.

Let us go back to Descamps's account of Dou's optical apparatus. What precisely is the nature of the device that he is describing, and how much confidence can we place in what he says? There is an obvious problem in the fact that Descamps is writing in the 1750s, nearly a century after Dou's death. He *must* be relying not on direct knowledge but on secondary sources of some kind. But is he depending on such sources as are still known today?

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[12] Gerrit Dou, 'Artist in his Studio', c. 1630-1632, oil on panel, 59 x 43.5, Colnaghi, London.

In the catalogue to the recent exhibition, the curator Ronni Baer refers very briefly but a little dismissively in a footnote to Descamps's text, suggesting that it is some kind of combination or garbling of mentions of Dou's use of optics by several previous writers.[13]

Figure 4: Gerrit Dou, 'Artist in his Studio', c. 1630-1632, oil on panel, 59 x 43.5, Colnaghi, London.

Ole Borch was the earliest of these. As already mentioned, Borch actually visited Dou in his studio in Leiden.[14] Borch talks about seeing a couple of paintings that are today in Copenhagen. He goes on to write about Rembrandt; and then as an afterthought comes back to Dou with the single sentence about him wearing three pairs of glasses. These certainly could be described as optical apparatus; but their purpose is to help Dou to see minute detail in his painting – nothing more

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[13] Ronni Baer, 'The Life and Art of Gerrit Dou', in *Gerrit Dou 1613-1675* pp. 26-52, note 137 p. 51.

[14] Madsen, 'Une visite chez Dou'.

than that. One of the pictures mentioned by Borch is a self-portrait, in the painting of which he says Dou made use of a mirror [“*qu’il a fini* [...] *en se servant d’un miroir*”]. The obvious inference here is that Dou had studied his own reflection in a *plane* mirror, in the way that artists have worked on self-portraits since Dürer. There is however another type of mirror that he might conceivably have used, as we shall see.

Parmigianino, *Self-Portrait in a Convex Mirror* (1524). Kunsthistoriches Museum, Vienna, Austria.

Figure 5: Parmigianino, ‘Self-Portrait in a Convex Mirror’, 1524, Kunsthistorisches Museum, Vienna.

Next in time to mention optics in connection with Dou was Roger de Piles, in his biographical dictionary of European painters, published in Paris in the early 18th century.[15] Here is the totality of what de Piles has to say on the topic. “He represented nothing which he had not studied from life in a convex mirror.” [“*Il ne saisit rien que d’aprés le vray qu’il régardoit dans un miroir convexe.*”] The difficulty in this case is the word ‘convexe’. What use could a *convex* mirror have had for Dou? With the mirror at close range, he would have seen in it what anyone sees in such a mirror: a strangely distorted image of his own head and body. Parmigianino painted a famous self-portrait in a convex mirror (Figure 5).[16] But none of Dou’s self-portraits betrays any distortion of this nature. It would not have been easy for him to study any other kind of object in close-up. He might have studied the image of the room behind him, but then the architectural features –

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[15] De Piles, *Abregé de la Vie des Peintres,* p. 428.

[16] Parmigianino, ‘Self-Portrait in a Convex Mirror’, 1524, Kunsthistorisches Museum, Vienna.

windows, beams, floorboards – would again have been curved. The famous reflection in van Eyck's 'Arnolfini Wedding' shows this curvature of architectural features introduced by the mirror's convexity.[17] The reflection in the mirrored ball hanging from the ceiling in Vermeer's 'Allegory of Faith' provides another case.[18] I suggest we might conclude that de Piles has made an understandable slip here. Maybe he intended to say 'concave mirror'. Perhaps as a historian he did not really appreciate the difference, or the implications.

Finally, Arnold Houbraken wrote about Dou in his multi-volume study of Dutch painting published in Amsterdam between 1718 and 1721.[19] The detail in Dou's paintings was so fine, Houbraken says, that "[...] one could hardly discern some things with the naked eye. (For this reason Dou, from his thirties, actually used a magnifying glass [*vergrootglas*].)" Clearly this glass had the same purpose as – and was presumably much more convenient than – the three pairs of spectacles mentioned by Borch.

"In addition" says Houbraken, "regarding our Gerrit Dou, it was in all peace and with the greatest possible patience that he painted from life. He used for this a framework in which strings were stretched crosswise. [*Hij gebruikte daarbij een raamwerk waarin draden kruiselings gespannen waren.*] This is a good aid for artists who do not dare to work freehand. In our time, the instrument is no longer used by anyone because people grow all too accustomed to drawing slowly. For the same reason my master Samuel van Hoogstraeten rejected even the compass."[20]

What might Descamps have taken, then, from these previous sources? There is no mention in any of them of a *concave* mirror. The spectacles and magnifying glass are for studying and guiding brushwork on the canvas, not for obtaining images in the first place. The one point in common with Descamps is Houbraken's grid of threads. It certainly begins to look as though much of Descamps's description comes from somewhere else. He is very specific and circumstantial about the screen, the 'enclosure', the fixing of the grid of threads to the mirror. Maybe he relied on some other source that has since been lost. Maybe he even saw Dou's actual apparatus. Despite all the problems, I suggest we take him seriously, at least in the first place.

Meanwhile what evidence can we glean from the paintings themselves? There are many recognisable studio props, recurring in more than one picture. They include a sculpted portrait head (see Figures 1 and 4), a rectangular wicker basket with a lid (see Figure 2), a birdcage (see Figure 3), two designs of lantern, a globe (Figure 2 again), and several distinctive items of crockery and metalware. Some other objects, as for example artists' palettes, or human skulls, are of

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[17] Jan van Eyck, 'Arnolfini Wedding', 1434, National Gallery, London. Criminisi, Kemp and Kang have shown, interestingly, that if the image in the 'Arnolfini Wedding' is transformed using image-processing software into the form that it would have taken had the mirror been flat, then the architecture is represented in correct and consistent perspective. (See A. Criminisi, M. Kemp, S. B. Kang, 'Reflections of Reality in Jan van Eyck and Robert Campin', antcrim@microsoft.com, consulted June 2006.) This is very strong evidence that Van Eyck transcribed the image – using whatever technique – by observing an actual room reflected in an actual convex mirror.

[18] Johannes Vermeer, 'Allegory of the Faith', c. 1671-1674, oil on canvas, 114.3 x 88.9, The Metropolitan Museum of Art, New York. For an analysis of the reflection in this sphere, see Philip Steadman, *Vermeer's Camera*, Oxford University Press 2001, pp. 107-109.

[19] Arnold Houbraken, *De groote schouburgh der nederlantsche konstschilders en schilderessen*, 3 vols., Amsterdam 1718-1721. Selections reprinted in Jan Konst and Manfred Sellink eds., *De Grote Schouwburg. Schildersbiografieën van Arnold Houbraken*, Em. Querido's, Amsterdam, 1995, pp. 49-57. See pp. 52-53.

[20] *Ibid* p. 52.

standard design, so one cannot say whether it is the very same object in different pictures. But in the spirit of Dou's saintly patience I have counted the number of bars in the various images of the birdcage, and the number of wicker strands in the images of the basket, and they are the same in every case. I have compared some of these images at their actual painted sizes. Figure 6 shows tracings to a common scale from reproductions of the respective paintings. It becomes clear that the precise same view is *not* in general repeated; nor, in the cases I have studied, is the same image used at larger or smaller sizes. Dou is *not* it seems using standard drawings again and again and copying them into different compositions. It is possible of course that he made a separate paper drawing for every distinct image. But it is equally possible that he had no paper drawings at all, and drew directly onto the canvas in the way that Descamps describes.

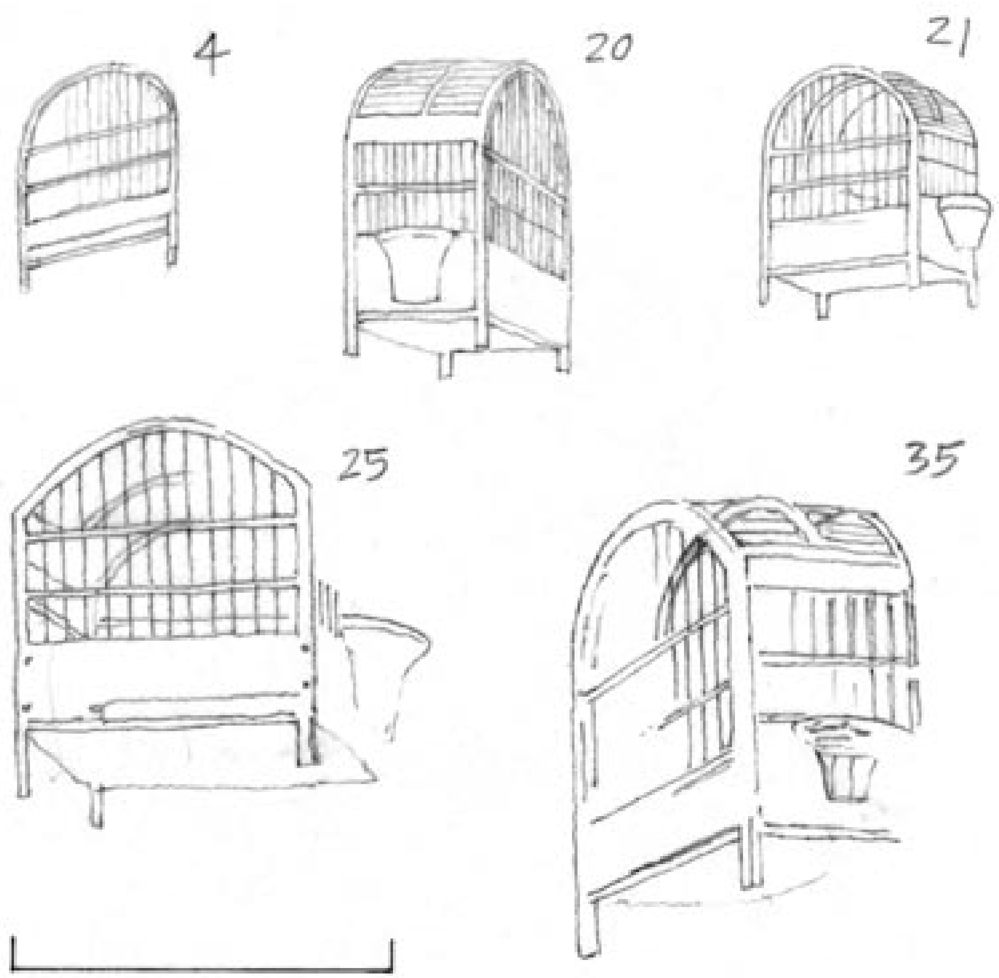

Figure 6 A

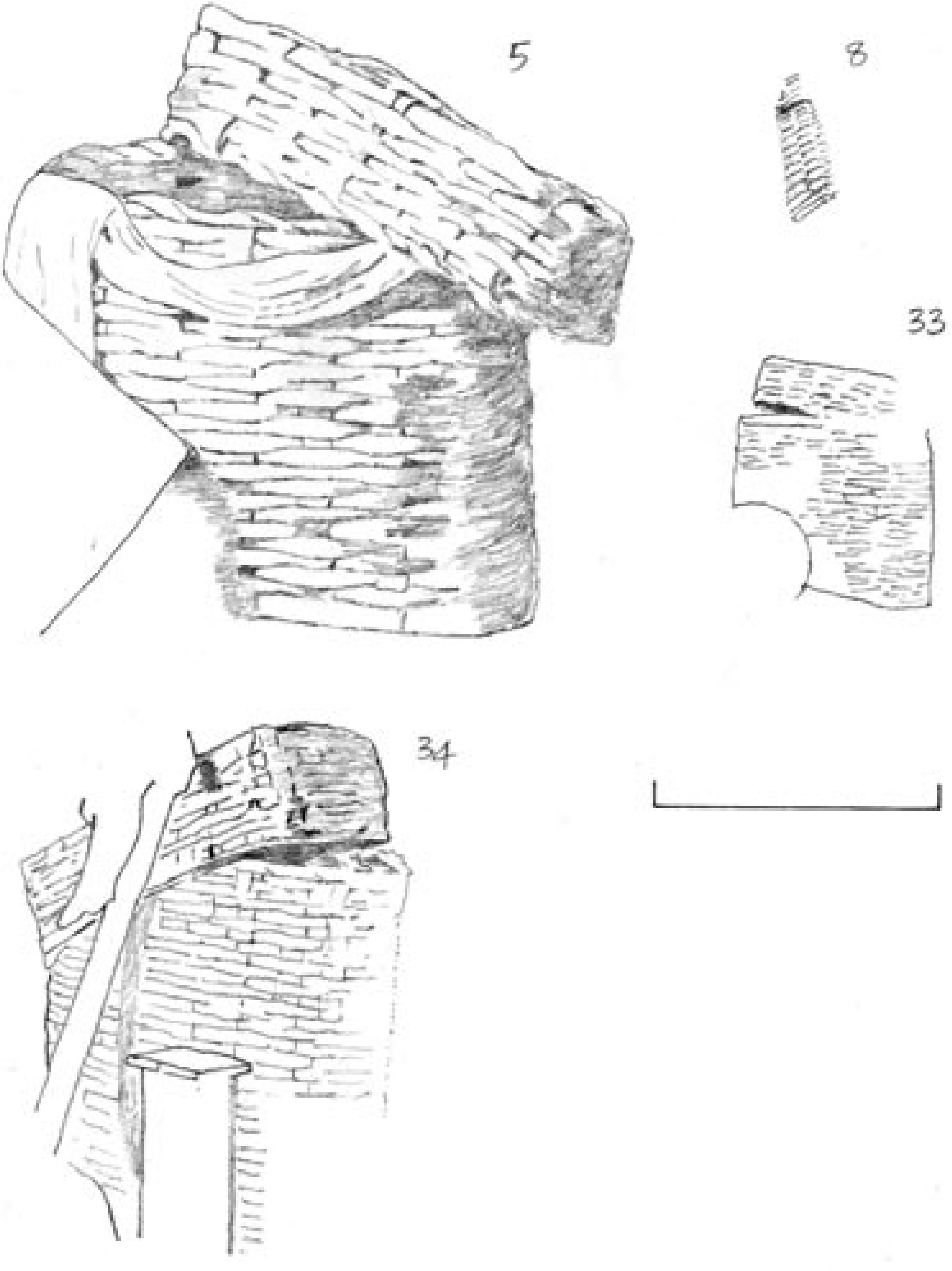

Figure 6 B

Figure 6: Tracings to a common scale from Dou's paintings of images of a birdcage, and of a wicker basket.

One of the most remarkable cases, to my mind, of a repetition of what is very nearly but not quite the same image is in two renderings of what is clearly the exact same tapestry in 'The Doctor' (Figure 7)[21] and 'Woman at the Clavichord' (Figure 8).[22] The folds in the cloth are in the same places and the light falls at the same angle. But we see the tapestry from two marginally differing viewpoints. The two views must have been painted from life at around the same time – before the hang of the tapestry was disturbed. Here Dou's obsessiveness is surely bordering on the pathological.

Figure 7: Detail of tapestry from Gerrit Dou, 'The Doctor', c. 1660-1665, oil on panel, 38 x 30, Statens Museum for Kunst, Copenhagen.

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[21] Gerrit Dou, 'The Doctor', c.1660-1665, oil on panel, 38 x 30, Statens Museum for Kunst, Copenhagen.

[22] Gerrit Dou, 'Woman at the Clavichord', c. 1665, oil on panel, 37.7 x 29.8, Dulwich Picture Gallery, London.

Let us return once again to Dou's 'ingenious invention'. What sense can we make of Descamps's description? Arthur Wheelock in his doctoral thesis on *Perspective, Optics and Delft Artists Around 1650* dismisses the device as 'totally unworkable'.[23] But Wheelock was disposed not to take Descamps seriously, and did not actually try to build a version, as I have.

Figure 8: Detail of tapestry from Gerrit Dou, 'Woman at the Clavichord', c.1665, oil on panel, 37.7 x 29.8, Dulwich Picture Gallery, London.

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[23] Arthur K. Wheelock jr., *Perspective, Optics and Delft Artists Around 1650* (reprint of dissertation submitted to Harvard University 1973), Garland, New York 1977, pp. 165-166.

My first thought, inspired by Hockney's example, was that the concave mirror served Dou as a means for *projecting* an image onto a screen: that is to say, the mirror played the same role as a convex lens in a conventional camera obscura. The general method is perfectly practical, as Hockney has demonstrated on many occasions.[24] The mention by Descamps of the *cloison*, the screen between the artist and the object to be represented, is suggestive in this connection. To cast a useable projected image with a concave mirror, it is necessary to have the subject in bright light, and the image in semi-darkness. The *cloison* could have served to shield the optical image from the light.

Figure 9: Concave mirror with square grid of threads attached.

Other features of Descamps's text are less easy to reconcile however with a projected image. Descamps is quite definite that the framework of threads is fixed onto the surface of the mirror itself. This has no purpose that I can determine, if the image is to be projected. No image of the threads is projected onto the screen. (I have tried this.) What *does* work is if the *screen* onto which the image is projected has a grid drawn on it. The screen might be either opaque, or translucent and viewed from the opposite side. But this is not what Descamps describes. He says very plainly that Dou 'fixed the framework on the mirror'.

My (rather infrequent) experience of following recipes in cookery books is that one should always do exactly what the author says, however improbable it might seem on the face of it. In this spirit, I made a square framework with a grid of threads, mounted it at the centre of a convex

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[24] As for example in the BBC *Omnibus* television film 'David Hockney's Secret Knowledge', 2001, directed by Randall Wright.

mirror, and studied the reflection (Figure 9). Mine is a shaving mirror with a relatively short focal length. At close range one sees of course one's own face, right way up and somewhat enlarged. In the terminology of physical optics, this is a *virtual* image, whose location is beyond the mirror. Moving back from the mirror, there comes a point at which the image of one's head turns upside-down; and a second, further point beyond which the inverted head becomes progressively smaller. It is necessary to keep one eye closed while observing these effects.[25] With the grid attached to the mirror, the threads can be seen at the same time as the head, and seem to pass through or over one's inverted face. *One's head becomes gridded up.* The image, if it could be turned the right way up, would be mirrored left to right. But it is not otherwise distorted.

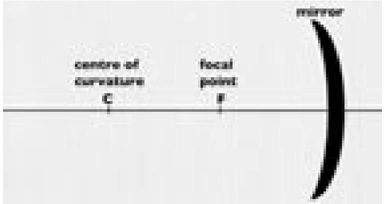

Figure 10: Diagram to show the formation of images of different types in a concave mirror, depending on the object's position. The horizontal line is the central axis of the mirror. F is the focal point. C is the centre of curvature. (See text.)

To be slightly more technical about all this: the two critical points in front of the mirror are the point of focus (F) and the mirror's centre of curvature (C). Figure 10 shows the situation diagrammatically. An object positioned between F and the mirror has a magnified, upright, virtual image. Moving the object away from the mirror: beyond F its image becomes inverted, and beyond C the image is still upside down and gradually decreases in size relative to the object. All these inverted images are in technical terms *real* images, and could in principle be projected onto a screen – although we are not envisaging that option here.

To see a similarly gridded image of some other object than one's head, one must move slightly aside, and position the object beside or behind one's shoulder (or hang it above one's head). I have found it necessary to set objects against a neutral background, such as a black or white cloth, to obtain an uncluttered image (Figure 11). Strong lighting helps. Dou's studio was tall and faced north onto a canal, so it presumably had good natural light.[26] The colour of the thread is also important, a black thread reading clearly against a white background, or a grey thread against a black background. (White is too bright). I have made a number of still-life drawings by this method. Figure 12 gives an example. I would not want to compare my skill or eyesight, let alone patience, with Dou's. But at least these experiments prove that the technique is workable.

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[25] If one looks at this distance with both eyes open, one sees initially two images. Relaxing one's focus, and allowing these images to drift towards each other, they suddenly fuse into a single solid-seeming image that appears to float in space, some way in front of the mirror. The image is now stereoscopic (and is still gridded). It is not however possible to trace such an image.

[26] Von Sandrart, ed. Peltzer 1925, p. 196.

Figure 11: A draughtsman studying a still life in a concave mirror. The photograph is taken from the location of the mirror. The draughtsman fixes the position of his head and eye with the vertical wooden rod.

It is not easy, all the same. One difficulty is that one must fix one's head and eye securely in position, otherwise the image moves relative to the threads. I have done this by resting my nose on a vertical rod. A further problem is that the threads themselves are a few millimetres in front of the mirror's surface. The result is that, looking at the mirror from some position off its central axis, as one must do to view objects other than one's head, one sees both the threads and their reflections, and the lines become doubled. This difficulty would be solved if it were possible to engrave or otherwise mark the lines directly onto the glass. Dou's father was a glassmaker, and Dou himself was apprenticed to one Pieter Couwenhoorn, a glass painter and engraver.[27] So this would not perhaps have been beyond the combined skills of the Dou family. But Descamps talks about stretched threads.

There are other difficulties in refocusing one's eye to look now at the reflected image, now at the paper. The grid of threads tends to interfere with the image of an object that is itself gridded or striped, as for example the bars of a birdcage. One way of working is to use the grid just to obtain a basic outline and the positions of the principal features. One can then remove the grid, taking care not to disturb the position of the mirror, and add more detail by reference to the lines already drawn. One might even then paint, using the mirror image to judge hues and tones and to position highlights. (Alternatively of course one could paint direct from the subject.) Dou made some very small still-life pictures that are just 15 or 20 cm across. These could have been painted from single mirror reflections.

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[27] Houbraken, *De Grote Schouwberg,* p. 50.

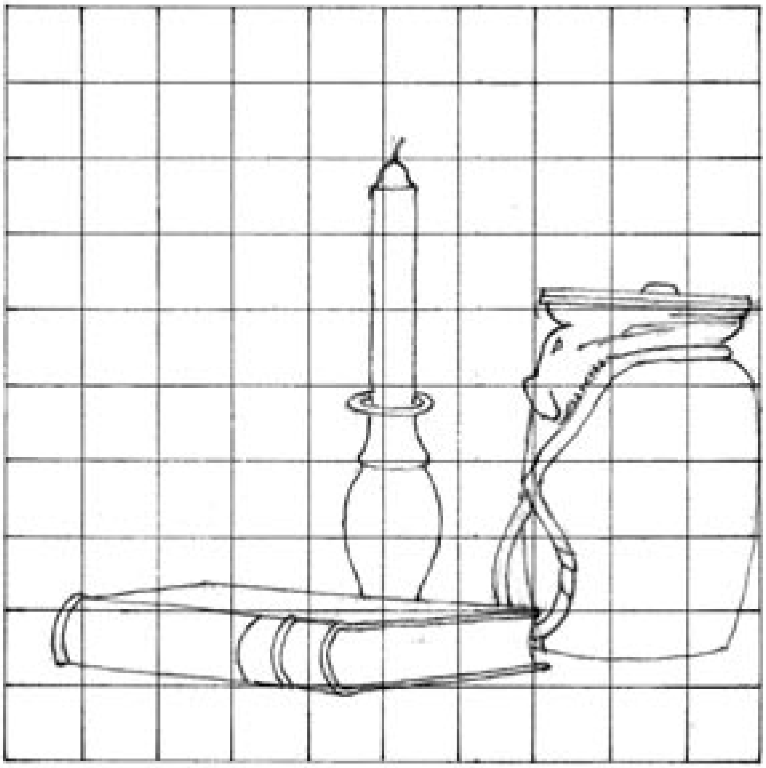

Figure 12: Drawing of a still life composition made using a concave mirror, following Descamps's method as described.

There remains one inconsistency with Descamps's text. He says that the mirror was fixed in a screen, and that this screen was a sort of enclosure *between* him and the object to be represented. In my arrangement the object is – necessarily – on the *same* side of the mirror as the artist. How else could he see a reflected image of the object? Descamps would appear to contradict himself on this point.

What conclusions can we draw? We have considered two different interpretations of the passage from Descamps. 1) An image might have been projected onto a gridded screen with a concave mirror. In this context the *cloison* makes sense. This arguably would have been the more useful and convenient of the two methods for the artist, giving a real image that would have been easier to study and trace. On the other hand this first interpretation cannot be reconciled with Descamps's very clear statement that the grid of threads was fixed on the mirror. 2) A virtual image might have been observed directly in the mirror. This second method is feasible, as I have demonstrated, if rather cumbersome compared with other alternatives – as for example viewing the subject directly through a grid of threads, in the manner of Alberti's 'veil' or some of Dürer's perspective machines.[28] The interpretation, it has to be admitted, is incompatible with what Descamps says about the relative positions of *cloison*, object and mirror. My own feeling is still that

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[28] Although the use of the concave mirror does mean that the grid appears to be directly superimposed onto the objects or scene, and one has no problem in focusing simultaneously on the grid and the subject, as one does with a 'veil'.

this second reading does less violence to the text than the first. *Both* suggested methods are consistent with a 'collage' technique of making separate drawings and paintings of smaller elements within some larger composition. I leave these questions open.

I would not want to make exaggerated claims. The fact is that Descamps's description remains considerably removed from Dou in space and time. At the very least what we have here is either a very early and rare reference to a projection technique using the concave mirror; or else a different way of using the concave mirror as an aid to painting – and what is more, a documented method and one not previously discussed in the recent literature of art and optics. And if we cannot be confident that Dou himself used the very device, we can still say that here is another possible optical tool at the disposal of painters in the 17th century.

ACKNOWLEDGEMENTS

I am grateful to Christina Malathouni and Willem de Bruijn for translations from the Dutch, and to Joe Lynes and David Graves for their enthusiastic practical help in trying to understand Descamps.

Imitation, Optics and Photography
Some Gross Hypotheses

Martin Kemp

What follows is not a measured scholarly discourse. It retails some personal thoughts about some of the overarching issues in the history of western art, above all its course towards increasingly perfected imitation of nature (essentially the story told by Gombrich in *Art and Illusion*) and the ruptures that occurred in the age of photography and modernism. These thoughts are framed in relation to my direct engagement with David Hockney as he forged his ideas on the centrality of optical devices to the naturalistic ambition of painters from the Renaissance to the 19th century. My treatment of the general issues are followed by two case studies that look at the internal evidence within pictures to determine what kind of staging or "tableau vivante" was involved before the act of imitation was accomplished. The first looks at the earliest of the possibilities explored by Hockney, namely the remarkably naturalistic effects achieve by Netherlandish painters in the 15th century. The second examines effects of Caravaggio's "camera obscura" – using "camera obscura" in its literal sense of a "dark room" rather than specifically to denote the optical device that has assumed this name.

Hockney's ideas, as expounded in his book *Secret Knowledge*, in the media and in various forums, have been subject to widespread excitement and criticism in the world of art history and beyond.[1] The scholarly response has been almost predominantly directed towards the destruction of his arguments about individual cases, often in the most blinkered manner. This has occurred even where, as in the case of Vermeer, the evidence about the use of optical devices is as about as secure as it could be.[2] The reactions seemed to have been conditioned by a series of factors. One is a sense of professional *amour propre*. What right – the unstated objection seems to run – has a "mere" artist, not a proper historian, to tell us the truth about histories that we have spent years researching? It seems to me that an artist who has spent his career grappling with various modes of representation might well have looked at historical works at least as perceptively as "mere" historians. Another objection is the old conviction that "great artists don't cheat". This argument should not be sustainable in the face of the creative use of photographic images by many contemporary artists. It is certainly not sustainable historically, since the devices never transformed a bad artist into a good one, and the adapting of optical technologies to artists' needs demanded skill and high creativity. The professional reaction has, in short, been disappointing in its overall tone. The wider claims he has been making have become lost in petty vitriol about details.

I am not going to claim that Hockney is "right" in all the cases he adduces. I have been sceptical from the first about the 15th-century examples, and I still believe that Italian artists before Caravaggio worked in a framework that excluded such raw imitation in their finished works. The

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[1] Hockney [2001]. The story of the refinements that his theories and arguments have undergone since the publication of the book, not least to strengthen his case against various criticisms, needs fully telling elsewhere.

[2] Steadman [2002].

possible use of optical devices by Netherlandish artists in the 15th century is more complex and will be discussed below. Caravaggio himself will be also subject to a case study towards the end of this paper.

What I am claiming is that Hockney's greater vision of the course of western art, represented not least by the astonishing walls of images he pasted up in his studios, can act as a creative force in re-thinking the history of imitation. Stimulated by his example, I will be formulating and exploring two gross hypotheses, both of which seem so obvious that it might seem absurd to state them. However, as historians we spend so much time differentiating one thing from another – one period from another, one region from another, one artist from another, an early work from a later work and so on – that we not only loose sight of the wood for the trees but we even fail to notice when we have emerged from the wood into a different landscape.

The first gross hypothesis is:

The dominant goal of progressive western art from 1300 to ca. 1880 was the imitation of nature. This hypothesis is coupled with the ancillary hypothesis that such a goal is very odd in world visual cultures across the ages, though it has now ubiquitously invaded image propagation throughout the world.

The term "progressive" is framed in relation to the idea that imitation is progressively perfectible. It does imply any progress towards art that is better than what went before. "Imitation" relates to something that claims to create a close match to our visual experience under certain constraining circumstances. "The imitation of nature" embraces everything from the most raw form of naturalism to the most idealising representation of beauty or underlying order. In other words, I am rolling into a single ball a series of modes of imitation that are normally corralled into separate categories. I require, in a way that may be regarded cavalier, that Masaccio and Monet (at least earlier Monet) are doing essentially, the same thing. This is to say that Masaccio's *Tribute Money* in 1427 (S. Maria del Carmine, Florence) and Monet's *Dejeuner sur l'hebre* in 1865 (Pushkin Museum, Moscow) share far more in common with each other than either share with an African mask.

The second gross hypothesis is:

From 1839 onwards the dominant goal of western art was increasingly and successively assumed by photography, film, television, computer graphics and certain kinds of popular, public art. The ancillary hypothesis is that "Fine Art" – defined as an aesthetic pursuit within social structures and institutions devoted to its means and ends – became a specialist activity differentiated by knowledge, techniques and goals in the manner of a laboratory subject.

This second hypothesis is based on Hockney's contention that photography and film are the logical heirs of optical imitation in western art. It is here developed in relation to the progressive differentiation between professional activities and disciplines during the 19th century. It carries with it his little-noticed claim that those who command the naturalistic image have a tool of immense power in their possession.

Let me first give an outline of Hockney's ideas, roughly in the order that they developed.

Optics and "Eyeballing"

The trigger for his thinking about optical imitation was the Ingres show in New York in 1999. He was stuck by certain consistent oddnesses in the pencil portraits that provided Ingres with a steady source of income, particularly during his youthful years in Rome. The formats were remarkably uniform, and the heads were almost identical in size. Compared to the finish in the heads, the draperies and other ancillary details were characterised in a schematic way that seemed to "trace" the contours that defined their shape rather than drawing them in the normal sketchy manner. The nature of the line in these subsidiary areas reminded him of the drawings that Warhol traced from projected slides. The lines in such drawings track the contours of the object as projected on to the flat plane rather than presenting a natural graphic response to the three-dimensional object as it appears before the eye. It was a characteristic I had observed in drawings made with optical devices in the 18th and 19th centuries. Once seen, it is not easily mistaken.

Figure 1: David Hockney using the camera obscura (Photo by Phil Sayer).

Hockney determined – assisted by my book *The Science of Art* amongst other publications – that the optical device most appropriate to Ingres's task was the camera lucida, (fig. 1), the prism-based instrument that had been patented by William Hyde Wollaston in 1807.[3] The advantages of the camera lucida over the more traditional camera obscura are that it can be used in any lighting conditions, that is portable and that it is relatively unobtrusvive. Hockney was stimulated to undertake a series of drawn portraits using the device. He found that it was best used for the rapid mapping of the main facial features, particularly if a relatively transitory expression was to be captured. The features were subsequently drawn by eye over a longer period, with no use of the camera. It was thus used, relatively briefly, as a tool to achieve a specific end. It was certainly not used in a sustained way in a process of copying or tracing. I was entirely persuaded, as were others, that Ingres had utilised a camera lucida, as a tool in an essential similar way. This did not means that Ingres was "cheating". He was skilfully using the latest technology to help achieve his ends – ends that no-one else achieved even with the same technology.

This insight encouraged Hockney to look for other evidence of the use of optical devices. He cast his net far and wide, supported by historical research undertaken for him by David Graves. There were the obvious cases, like Vermeer, about whom Philip Steadman was increasingly developing a water-tight argument – even though some of the specialists continued to writhe in discomfort and denial. Holbein's drawn portraits were also a natural subject for attention. I had long thought that they were produced with an optical device, perhaps the drawing frame illustrated by Albrecht Dürer.[4] Looking at Dürer's Netherlandish predecessors, Hockney detected what he called a "many windows" technique; that is to say an image formed from discrete zones of astonishing naturalism that were not subordinated to a overall optical system. He claimed that the "many windows" resulted from the collaging of portions of the picture studied separately with an optical device. It was a technique that he recognised through his own photographic "joiners" – views collaged from series of Polaroid photographs. There were also some very surprising candidates, Frans Hals for instance. Hals's *alla prima* spontaneity seemed far removed from any conventional idea of optical imitation. However, Hockney argued that an optical device could be hugely useful in rapidly capturing the lineaments of a spontaneous expression and in laying in remarkable foreshortenings without any apparent drawing. A comparable argument was used for Van Dyck. The overall point was that a creative artist could use optical devices for very different ends from those assumed to be standard.

The detailed observations about particular artists were themselves collaged into remarkable historical 'joiners". Sets of images were arranged on long walls in a great chronological parade that revealed the changing "shape" of imitative modes over the centuries (fig. 2). Some of the images were clearly "eyeballed" – his term for drawing or painting directly by eye – while other seemed to be "photographic". The "eyeballed" images tended to reveal "awkwardness" in how the parts relate to the whole and how the foreshortenings are accomplished. The optically formed images perform the foreshortening of patterns and other naturalists tricks with apparent ease and total visual conviction. This division is not a judgement of quality but of artistic means and ends. He became fascinated with the re-introduction of "awkwardness" in the later 19th century, above all

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[3] Kemp [2001], 200-1.

[4] Ibid. 172.

with Cezanne. By this time, he observed, the mainstream of naturalism had been diverted into photography.

Figure 2: The late Mediaeval to Renaissance section of Hockney's wall of western paintings. (By courtesy of The David Hockney No. 1 U.S. Trust)

Mainstreams and Diversions

Actually, "diverted"(my word not his) is the wrong term. Photography only seems to be a diversion if we tell the story of "Art" from the standpoint of art as an aesthetic product. This was a story that itself became "tellable" in modern terms only when the notion of the "aesthetic" was formulated in the late 18th century. It was a story that was increasingly retailed from the mid 19th century onwards, with the rise of a sense of "art for arts sake". If we dispense with this retrospective definition of the pre-19th century mainstream, we are free to see the predominant course of image-making in western culture as flowing uninterruptedly into the ever deeper and broader channel of photographic imitation that used still and moving cameras. In fact this is more or less how Hockney illustrates it in a diagram immersed deep in the book (fig. 3). His diagram and the accompanying commentary have passed without much comment.

The straight red line tracks "the lens-based image", while the green line denotes the tradition of "eyeballing". It is the green line that diverges from the main track, most notably from Manet and Cezanne onwards as painting loosens its base in optical imitation. The fat red line 1930-60 marks the heyday of movies. The post-1970 scribbles indicate the chaos precipitated by computer manipulation and, presumably, the multiple practices of Postmodernism. The jumble of lines also indicate an element of uncertainty. "Where are we now?" he asks.[5] I would hesitate to see any continuous line in lens-based or even device-based imitation before the 17th century but the

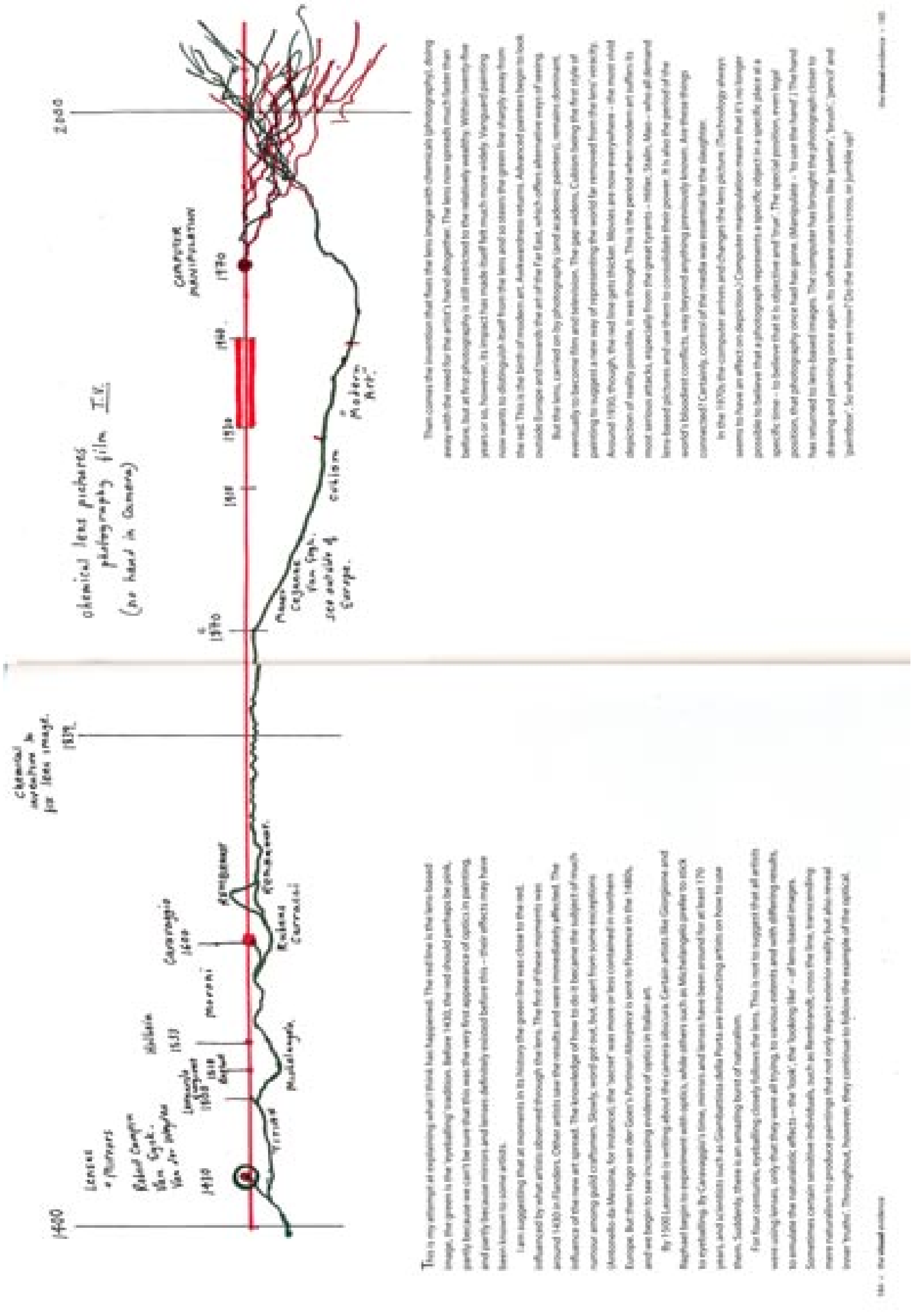

Figure 3: Hockney's diagram of "photographic" and "eyeballed" traditions in Western art. (By courtesy of The David Hockney No. 1 U.S. Trust)

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[5] Hockney [2001], 184-5.

diagram does have the overriding virtue that the modern photographic media are characterised as standing in a straight line of succession from naturalistic western art, while it is the "Fine Arts" that diverge from the mainstream.

Where my "gross hypotheses" depart from Hockney's diagram is that I am characterising the mainstream more broadly in terms of naturalism (or modes of veridical imitation) whatever the means used. Titian, Michelangelo and Rembrandt are in this view as integral to the mainstream as Holbein, Caravaggio and Vermeer. This is not to say that his main varieties of naturalism do not serve as productive categories in their own right. Rather, I prefer to see the photographic media as continuing the whole of the naturalistic tradition rather than only those aspects of it that may have used optical devices.

Both the pioneers of photography illustrate this point in different ways. William Henry Fox Talbot came to his invention via wide-ranging accomplishments in the sciences and humanities, though conspicuously not as an able draftsman.[6] His confidant and fellow pioneer, William Herschel, who coined the name "photography", was one of the leading scientists of his age and a master of landscape drawing with a camera lucida, the instrument that Talbot notably failed to use with acceptable results. The story of Talbot's shame on his honeymoon in the face of the accomplished camera lucida drawings by his wife and half-sister, and his resulting determination to fix the image in a camera obscura using the "Pencil of Nature" alone, is well-known.[7] In these respects Talbot's invention belongs to the technological history of optical devices in art. However, his efforts in both drawing – "melancholy to behold"- and photography are immersed in the tradition of picturesque landscape painting, particularly in its amateur guise, and deeply imbued with the aesthetics of English taste. And the nature of his "callotypes", Rembrandtesque in their soft chiaroscuro as commentators recognised, lent them "artistic" qualities far removed from mere mechanical recording.

Louis Jacques Mandé Daguerre converged on the invention from an almost diametrically opposed direction. An able landscape painter and leading entrepreneur of the diorama, he was drawn into the scientific technology of imitation by Joseph Nicephore Niépce, inventor and amateur scientist.[8] The diorama, with its variety of scenic and lighting effects was the natural heir of the kind of "theatrical" landscape painting practised by Joseph Vernet in 18th-century France. Sociologically, alongside the panorama, it signals the move of imitation into the larger arena of the public spectacle, exploiting the growing resources and demands of the rising middle class. Lauded by the French Academy of Science, Daguerre's invention subsequently moved into the popular arena that he understood so well. The Daguerreotype portrait brought the aristocratic genre of the portrait to a broader public – a move prefigured by the cheaper silhouette portraits, particularly those made using the physionotrace.[9]

Talbot's and Daguerre's backgrounds, inventions and subsequent practice both simultaneously stand in the succession of device-based imitation and represent the broad stream of naturalistic art that I am embracing. Neither man's visual achievements can be wholly restricted to the track of lens-based imitation. I believe that this is also true of the main subsequent

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[6] Schaaf [2000].

[7] Kemp. [1997].

[8] Barger and White [2000].

[9] Kemp [1990], 186-7.

extensions to the photographic medium, namely stereoscopic and moving pictures. Film, with its mixture of "high" and "low" genres, and its "arthouse" and "popular" polarities, mirrors precisely the range of the visual arts and their consumption in their 18th- and 19th-century guises.

I am sure that Hockney is right when he emphasises that those who command the naturalistic image have a tool of great power in their hands. He points to the way that

> The great tyrants – Hitler, Stalin and Mao – …all demand lens-based pictures and use them to consolidate their power. It is also the period of the world's bloodiest conflicts, way beyond anything previously known. Are these things connected? Certainly, control of the media was essential for the slaughter.[10]

Again, I would extend this prescription to the naturalistic image more generally rather than limiting to those using lenses. One of the points of skill in naturalistic representation is that its virtuosi can portray the false as convincingly as the real. Leonardo could draw a dragon as convincingly as he drew a cat.

Figure 4: Signed poster of Felix de Weldon's *Iwo Jima Memorial* as advertised on the Internet.

The Church well understood this power, although from diametrically opposed points of view in its Catholic and Reformed versions. Rulers and national institutions used the naturalistic image to broadcast the "reality" – factual or fictional – of their glories and accomplishments. Raphael's *Battle of Constantine*, Baron Gros's *Napoleon at Eylau*, Eisenstein's *Battleship Potemkin*, photographs of Churchill in battledress and Felix de Weldon's huge bronze group of the heroes of

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[10] Hockney [2001], 185.

Iwo Jima raising the American flag belong to the same tradition. De Weldon's sculpture (fig. 4) perfectly serves my argument and Hockney's view of the mainstream.

The Iwo Jima Memorial (dedicated in 1954) was based very directly on a news photograph by Joe Rosenthal. The photograph represented a reprise of an earlier, more modest flag-raising ceremony that had not been captured for posterity.[11] The survivors were modelled from life, and as much physical data as was available was obtained for those who had not survived the campaign. The sculpture serves as a kind of 3-D photograph, set up in such a way as to convince the viewer of its gritty veracity. It speaks the "rhetoric of reality". The flag-raising had already been re-enacted on the basis of Rosenthal's photograph for the 1949 John Wayne film, *Sands of Iwo Jima*. It was now featured centrally in Clint Eastwood's new film of the bloody battle and its aftermath, *Flags of our Fathers*. The memorial and its photographic source have subsequently served inseparably as the basis for multiple re-stagings, including a real-life tableau enacted by the Marines, which was in its turn photographed and displayed in the newsletter of their Heritage Centre.[12] Signed posters were produced and are still being marketed. The original photograph, which won a Pulitzer Prize, has become an iconic image in its own right. It has featured on a postage stamp and been widely exploited by the military in publicity images and recruiting posters. Then, following the destruction of the World Trade Centre in 2001, fire fighters were photographed by Thomas Franklin raising an American Flag in conscious emulation of the Iwo Jima image. A certain kind of art is here shaping both actual behaviour and its public recording.

I think there is a real case for aligning De Weldon's representation with the "realistic" public media – most specifically with a Hollywood war film – rather than "Fine Art". It is difficult to see how it comfortably belongs in the same category as a severely abstract metal construction by David Smith, a contemporary of De Weldon. This proposed reclassification is not necessarily linked to "value", since the Iwo Jima Memorial clearly does its job supremely well, and has become something of an icon. It has a brief that is quite different from that of the kind of gallery sculpture produced by Smith, which is to be appreciated by viewers attuned to the specialist criteria of abstract art. I happen to think that Smith's work is of a higher order than that of De Weldon, but this is not the issue here.

Avant-garde "Fine Art", in terms of self-proclaimed aesthetic excellence and historical progress, went in a quite different direction from the public media that rely upon naturalistic modes of represnentation. Vital for this was the definition of the "aesthetic" as an essential expression of something distinct in the human mind, autonomous and special, as a kind of sixth sense. What this gave to art, artists and the developing institutions of art education was the essential separateness that is necessary for any discipline that is to build up its own internal standards, definitions of excellence, specialist criteria and vocabulary. Not least it facilitates ways of defining those who are "outside" the circle of initiates. To be sure there were elements of this exclusivity from Alberti onwards, but the definition of the aesthetic as an autonomous goal in itself moved the nature of "Fine Art" on to a different and more consciously exclusive plane.

This happened within the context of multiple re-definitions of professional practices in the 19th century, each of which competitively established its own membership organisations – the "Royal College…" of this or that, "Institute…" of that or this- with actual or implicit licenses to

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[11] Gentile [1997].

[12] *Legacy* V/1.

practice, to control education and to define the rules that governed "quality". The professions, such as medicine and engineering, defined themselves at least as much in relation to what they were not and what made them distinct as with respect to what they actually were. "Fine Art" defined itself is different from the vulgar spectacle, the popular media and the applied arts. It educated its student elite wilfully to demonstrate aesthetic excellence and originality. Even when "Fine Art" later exploited the popular arts and design its identity with the popular was tinged with aesthetic knowingness and irony.

This, I believe, is the context in which Hockney's divergent track of "awkwardness" – or, as I would say, non-naturalism – comes to diverge from the mainstream of image-making and consumption. It is inevitable that the western academies would be left behind in this, since their values were tied indissolubly into the naturalistic image as a source of central power. This explains the huge grip retained by the traditional academies in the Soviet Union. Though the western academies were crucibles of aesthetic value they were unable to cope with consequences of its eventual autonomy. The baby they nurtured grew so large that it kicked out the bathwater. In the USA the reverse happened, paradoxically alongside the state exploitation of academic naturalism. The value of "artistic freedom" as presented by Pollock & co became identified with the declared values of the state – even if the actual art was little understood in ruling circles – so that the avant-garde effectively took over as the new academy. In Britain it became enshrined through state funding of the Arts Council, using the "arm's length" principle.

The setting of professional specialisation was that within which "Fine Art" became a laboratory subject, with an increasing emphasis upon discovery, experiment and originality. It aspired not only to the kind of technical excellence that characterised the technological disciplines but also the higher qualities of brilliance that were the attributes of scientists, musicians and authors. Cezanne, rightly accorded a key place in Hockney's diversion, embodied all the new attitudes perfectly. He consciously set himself up as the divergent revolutionary, both in his person and in his experimental art, at the same time as extracting (or rather abstracting) the aesthetic "essence" from classic art of the past. He looked to specialist commentators, above all Zola, who could understand the experiments, to broadcast their merits. Shorn of its naturalistic base, art came to depend on a specialised public. Those who knew how, why, where and what *should* be liked took pains to differentiate themselves from those who merely knew what they liked. By the time of Cubism, avant-garde "Fine Art" was about as immediately accessible as theoretical physics. Whether or not Cubism was some kind of expression of the new Physics, the trajectories of the public careers of Einstein and Picasso follow notably similar general paths from limited appeal to specialist audiences to wider recognition – a recognition that was somehow insulated from wider public comprehension of what they were actually doing.[13] That this specialist audience has now expanded hugely does not affect that basic premises of the argument.

Collapse into Complexity, and the Reassertion of "Eyeballing"

I am sure that Hockney is also write to characterise the period from 1970 onwards as one of bewildering diversity – and I do not think this is simply a matter of our being to close to see the larger picture. I do not think there is a coherent larger picture or even a single phenomenon we

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[13] Miller [2001].

can still call “art”, any more than there is any substantial defining feature that unites all the many branches and sub-branches of what we still call “science”. Whether 1970 is the right date is another matter. I would signal the dissolution of the modernist mainstream – characterised by an avoidance of naturalism – at least to the origins of Pop Art in the 1960s, a development in which Hockney himself played a seminal role. And the lens-based media had long since seen various strands of non-naturalism and abstraction – to say nothing of “fake” photographs, like the famous “Cottingley Faries”. However, the most sustained interpenetrations of the two streams did occur in the second quarter of the century. I am not intending to enumerate the many complex cross-overs here. I will limit myself to mentioning the photorealism of painters like Malcolm Morley on one side, and the video works of Bill Viola on the other. Viola’s slow motion homages to classic works of art are a perfect example of the eclecticism that complicates the issue of imitation to a degree where the standard sense of mimesis becomes inoperable. Layers of types of imitation merge in the context of a deeply serious irony.

Figure 5: David Hockney, *Martin Kemp and Marina Wallace*, watercolour on paper, 122 x 91.5 cm, 2003. (By courtesy of The David Hockney No. 1 U.S. Trust)

Where one stream does persist in obstinate defiance of what we know is the photograph as a documentary record. We know how the photographic image can be manipulated – Hockney points to the root of the word manipulation in *manus*, hand – and that such manipulation in the age of digital photography is no longer the province of those familiar with Photoshop. However, we still instinctively trust an image that is the product of a photographic process. I believe that such trust is so deeply instinctual in perceptual terms that we can do little about it, whatever our conscious awareness. This persistent trust in photography corresponds to Hockney's ever persistent red line perusing its remorselessly straight course.

Hockney's own delight in the film *Who framed Roger Rabbit*, in which Bob Hoskins and other human actors filmed in the normal manner share the frame with the animated rabbit, reminiscent of "Bugs Bunny", is consistent with his enduring fascination with modes of rendering. In the film, lens-based imitation and schematic "eyeballing" entertainingly come together in a single visual space.

Figure 6: David Hockney, *A Closer Winter Tunnel*, 2006. (By courtesy of The David Hockney No. 1 U.S. Trust)

Following his experimentation with the camera lucida and the tests he undertook with various room-sized camera obscuras (equipped with lenses and concave mirrors), Hockney has undertaken a series of very large watercolours in which the unmediated business of "eyeballing" is given absolute priority. The first was a set of large watercolours of sitters and pairs of sitters produced from spring 2002 onwards. The double portraits, on four sheets of paper, measure 122 x 91.5 cm (4 x 3 feet) and involve no standard drawing (fig. 5). Every stroke of his brush, as his hand responded to what he saw, had to tell absolutely. The effects are direct, sometimes uncomfortably so. The simple, translucent medium somehow persuades us that it describes far more than it actually does. Like all great artists, Hockney understands precisely when to stop in order to get the spectator to do the rest. More recently, landscapes in his native Yorkshire have been subjected to a comparable *alla prima* portrayal (fig. 6). He desribes effectively the process as "feeling the space with big brushes".[14] The results look simple, almost naïve in their directness. However, the transformation of watercolour into illusion – as much an illusion of the nature of the place than an illusion of "reality" as such – is the result of great pictorial sophistication in knowing what one simple coloured mark can do to all the abutting and neighbouring marks, in a warp and woof of considerable intricacy.

For Hockney, the "eyeballed" watercolours reassert painting in the face of the mechanical media of imitation:

> I'm quite convinced that painting can't disappear because there's nothing to replace it [...] The photograph isn't good enough. It's not *real* enough.[15]

The large Hockney watercolours are an integral part of the story of the reception of modern media of imitation.

Figure 7: Robert Campin, *St. John the Baptist and Heinrich von Werl*, Madrid, Prado.

The Naturalistic Stream – how Early?

A crucial element in Hockney's arguments and in my gross hypotheses is that there is an essential continuity between the kind of naturalism that arose in European art after 1400 and the photographic media post 1839. Art history has traditionally and almost exclusively focused on the

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[14] Fax to the author, 26 July 2006.
[15] Livingstone and Heymer [2003], 214.

diverse things that artists have done *to* nature to change it rather than imitation as such. It is seen as uneducated to say "how real" when confronted by a Dutch interior by Pieter de Hooch or a Venetian *veduta* by Canaletto. Yet this reaction is absolutely at the core of what the artists were striving to achieve. It is not *all* they were trying to achieve, but it was the bedrock for everything else. Outside old-fashioned "art appreciation" classes, only Gombrich's *Art and Illusion* has fully given imitation its overarching due as a visual and cerebral achievement.

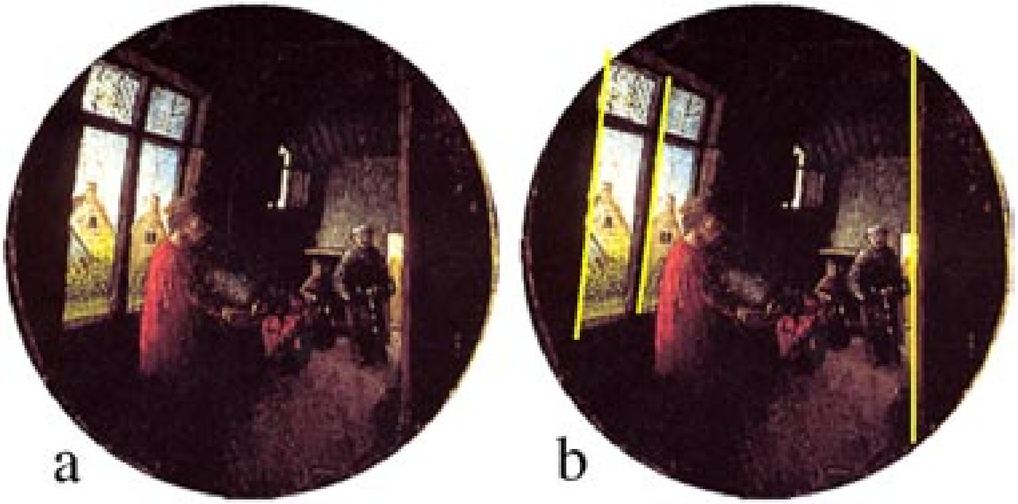

Figure 8: Antonio Criminisi, Recification of the convex mirror in Campin's St. John the Baptist.

The earliest works of art that play unreservedly to the "how real" reaction are the Netherlandish paintings of the early 15th century, above all those by Robert Campin ("The Master of Flemalle") and Jan van Eyck. Recent investigations undertaken by Antonio Criminisi and myself involve startling evidence of how "photographic" their paintings are.[16] Using techniques from computer vision, specifically those dealing with images reflected from curved surfaces, Criminisi has rectified the reflections in the convex mirrors in the left panel of Campin's van der Werl altarpiece (fig. 7) and van Eyck's "*Arnolfini Marriage*". Both mirrors hang on the end wall of the painted rooms and reflect wide-angle images as seen from the opposite end from the spectator's. The results of Criminisi's work, particularly for Campin's painted mirror, are remarkable. The rectified image of the room (fig. 8), using algorithms to rectify the reflections rather than to straighten lines as such, is incredibly consistent. The straight edges of the main features of the room, rendered as heavily curved in the mirror, become almost unerringly straight. The other remarkable feature of the rectified images is that the occlusions of objects by forms nearer the mirror are observed with astonishing accuracy. In the wing of the Campin altarpiece, for example, the rear margin of the donor's drapery, trailing across the floor, protrudes from the edge of the open door to exactly the right amount.

I believe that a major conclusion follows inescapably from these observations. An image of such accuracy in a convex mirror could not be achieved simply by thinking about it, but requires the staging of a *tableau vivante*. The image in the picture must have been stage-managed with

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[16] Criminisi et al. [2004], 109-21, and Kemp and Criminisi [forthcoming].

costumed “actors” arranged in a room according to the desired effects. Whether this level of naturalism was achieved using an optical device or utterly remarkable “eyeballing” does not affect the basic argument here – which is to assert that Netherlandish painters of the period were capable of achieving remarkably “photographic” effects. My own view is that Campin and van Eyck may well have been inspired by optically generated images – the camera obscura was well known to mediaeval natural philosophers – but probably did not actually use them directly at any stage in the making of their pictures. Either way, the visual and functional continuity between the “*Arnolfini Wedding*” and a modern wedding photograph is evident. Just as the Latin inscription in Jan’s picture declares that “Jan van Eyck was here”, so the wedding photograph declares the presence of witnesses to the couple’s matrimonial vows.

Caravaggio’s Carafe and the Issue of Evidence[17]

Caravaggio, as a young Lombard painter recently arrived in Rome, created a sensation in the circle of Cardinal Francesco Maria del Monte, his first major patron. His strikingly vivid naturalism, in which individual forms were modelled, coloured and textured with an altogether new intensity, stood in sharp contrast to the prevailing academic style in Rome around 1600. He suddenly found himself in demand. This naturalism, as Hockney emphasises, is not dependent on drawing, and it seems as if the images of the objects are transferred directly to the canvas without intervening procedures. His explanation is that Caravaggio exploited one or more optical device, perhaps the miraculous camera obscura described by Giuseppe della Porta or a concave mirror, to project his subjects onto the painting surface, where it could be transcribed in its full naturalistic glory.

Figure 9: Caravaggio, *Lute player with carafe of flowers*, Private Collection.

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[17] The research for this section was conducted in conjunction with Clovis Whitfield and Thereza Wells (née Crowe), to whom thanks are warmly offered.

As in so many of the instances adduced by Hockney, historians have asked, "where is the evidence?" "The pictures are the evidence," is his answer. But the historian wants more.

As it happens, complex bodies of interlocking evidence about Caravaggio's practice and the intellectual circles of del Monte are beginning to provide strong signs that he did indeed use optical devices.[18] My strategy here is not review this evidence, but to undertake the kind of step we have taken with van Eyck and Campin, namely to look at the internal evidence within the paintings to see what we can deduce about the setting-up of the subject in front of the painters' eyes. Again I have chosen a specific motif – in this instance a glass carafe that appears virtually identically in three of Caravaggio's paintings, two versions of the *Boy Bitten by a Lizard* and one of the variants of a youthful *Lute Player* formerly at Badminton and now in a private collection.[19] The prototype for the carafe in Caravaggio's *oeuvre* appears to be a lost painting of the motif on its own, described in the del Monte inventory of 1628, where it is estimated as about 2 *palmi* in height (in the range of 42-48 cm.).[20] Bellori describes the lost work as one of Caravaggio's "pictures of imitation" (i.e. direct naturalism):

> He painted a carafe of flowers with the transparencies of the water and with reflections of the window of a room, rendering the flowers with the freshest dewdrops.[21]

I think it is fairly clear that such was the surge in demand for such eye-catching illusions that he collaged signature motifs like the carafe from one composition to another. But how did he achieve such naturalism in the first place?

The following account of the carafe and reconstruction of its optical creation is based on close analysis of that in the Badminton *Lute Player,* but it applies equally to those in the two pictures of the bitten boy. In all three pictures, the round body of the very fine glass vessel serves as the field for a radiant exposition of light effects.

A vertical light source of some size is signalled in the foreshortened image on the left, reflected from the convex outside of the glass wall. It is accompanied by a thin sliver of light towards just below the level of the water. On the inside of the right wall, the same motif is reflected upside down as if in a concave mirror, albeit at a lower level of brilliance. Cutting across this reflection is a horizontal band of glare, accompanied by a smaller rectangle and two thinner vertical smudges of bright light – all apparently existing on the convex outside of the wall As the light passes through the water in the carafe, by refraction and reflection, it creates a luminous glimmer, particularly towards the right. It catches with wonderful subtlety on the shady stems of the plants. Four speckles of water on the outside of the glass perform in miniature optical games that underscore those played within the carafe itself. The foremost flower stem, pressed close to the inner wall of the carafe, drags the surface of the water upwards in a small peak, bearing witness to what we now call surface tension.

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[18] These issues are to be explored in detail in forthcoming papers by Clovis Whitfield and by Martin Kemp

[19] The two versions of the *Boy Bitten by a Lizard* are in the National Gallery, London, and the Longhi Collection. The carafe also features at a lesser level of optical complexity in the *Luteplayer* in the Hermitage. The *Luteplayer* in a private collection in New York has no carafe.

[20] Frommel [1971], 31 (from the inventory of 1627).

[21] Bellori, in Hibbard [1983], 36. Bellori's *Vite* also in Helen Langdon [2005].

Figure 10: Detail of carafe in fig. 9.

It is difficult to think of a more complex rendering of light in a water-filled vessel. Netherlandish painting comes most readily to mind, but even such masterpieces of reflection and refraction as the glass vessels in van Eyck's and Campin's paintings are more straightforward. Like the Netherlandish masters' effects, Caravaggio's optical medley looks as if it has been meticulously observed. But are appearances deceptive? To answer this question, we attempted a physical reconstruction of the kind of circumstances in which such effects could be replicated as closely as possible.[22] It proved to be far from easy.

The first thing to be said is that anything reflected below the horizontal median line on the outside wall of the left of the carafe must be below the corresponding level in the set-up.

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[22] The model was designed and built by Gilbert McKerragher and Glen Thornley of G & G under the supervision of of Thereza Wells; the photographs of the resulting set up were taken by Sarah Weale.

Correspondingly, any feature in the inverted internal reflection on the left wall that is above the median line must be below that level in the setting. This immediately tells us that the carafe must have been placed at a level that was neither wholly above or below the rectangular source of light. That is to say, the angle of light falling on the carafe is not compatible with the high, diagonal source that Caravaggio describes as illuminating the rear wall in the *Lutenist*. It might just be reconcilable with the lower source in the *Boy bitten by a Lizard*, but the position of the figure's shoulder, arm and hand seems to preclude this possibility.

Figure 11: Model of a room with a carafe illuminated from 2 sources, made by Gilbert McKerracher and Glen Thornley with assistance from Thereza Wells.

It proved possible after considerable experimentation to build a scaled model of a room with a rectangular aperture on the left wall such that the external reflection on the left and internal image on the right could be closely replicated. The reflection indicates that the aperture was divided by at least one horizontal and one vertical bar. The relationship between the carafe and the source indicates that the glass vessel must have been placed on some kind of pedestal or elevated surface level with the opening, rather than sitting on a table below a window.

The glare on the lower right proved more problematic and apparently anomalous. Eventually it was best recreated using a flattish, rectangular aperture high to the right in the rear wall. A strong light entering as a diagonal shaft created very much the kind of glare that overlays the softer internal reflection. The ancillary fragments of glare were observed when there was leakage around the slits that had been cut to make the aperture or when the eye level of the observer was raised slightly.

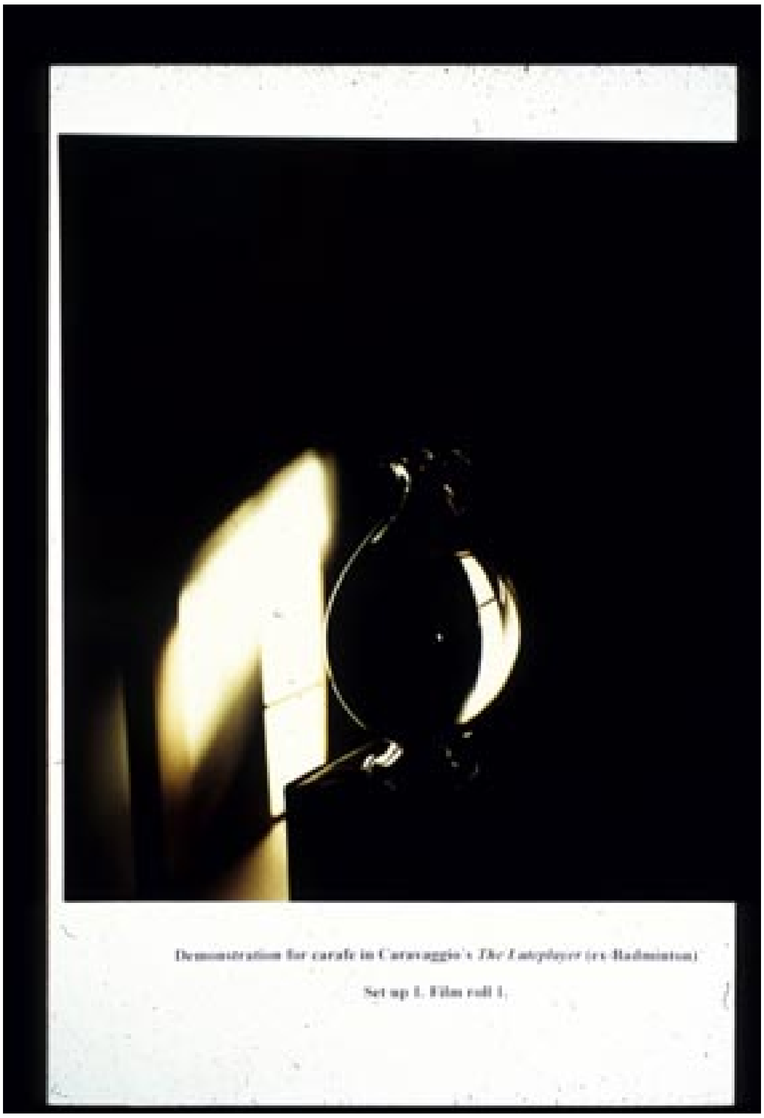

Figure 12: Detail of carafe in fig. 11.

What this suggests about the set-up under which the carafe was studied is that it was deliberately positioned in a darkish room at the level of a lateral window (or just possibly a door), with a second, surprisingly high light source, corresponding to some kind of skylight. Was it this higher aperture to which Caravaggio's incensed landlady referred in 1603, when she accused the painter of having damaged her ceiling?[23] It is likely that some kind of shuttering was employed to create the desired effects, with some leakage of light around the edges and junctions. There is plentiful evidence in his paintings of his innovative orchestration of the height, direction and intensity of the light sources that illuminate figures and objects. His use of a dark room, painted with dark walls as contemporaries attest – literally a *camera obscura* – meant that he minimised generalised and diffused radiance of ambient lighting reflected from light surfaces, above all from the walls. The use of no more than two restricted beams of light results in a series of strong highlights with a series of secondary rebounds within the plastic ensemble of the main subject. It creates extraordinarily striking effects of relief but is highly contrived. As always, the parading of super-real effects is a highly selective business.

To recognise the staging of his lighting is not the same as saying that each picture was set up in his room as an elaborately staged *tableau vivante* (or "*morte*"). As David Hockney has observed, there are numerous signs that Caravaggio's paintings, especially around 1600, were collaged from separate plastic motifs that are not always entirely co-ordinated within the spatial logic of the composition.[24] It was precisely the deficiency in traditional "composition" that resulted from the application of naturalism to each discrete element in the main subject that so upset traditionally-minded observers

This piecemeal assembly of super-real motifs, is consistent with Hockney's claims that each motif is studied with an optical device, most notably what he oddly calls a "mirror lens"; that is to say a concave mirror positioned in a darkened room such that light from a small aperture is reflected from the mirror on to a white surface. Knowledge of the use of a concave mirror to form an image had become widely available in della Porta's compendium, and, most significantly, the Neapolitan showman combined such a mirror with the recently described version of the camera obscura that placed a convex lens in the aperture.[25] He achieved literally spectacular results.

As Hockney has latterly stressed, one of the prime advantages of a projected image is that it is *flat*; that is to say it performs an important part of the painter's perceptual job. Looking at something as complicated as Caravaggio's carafe, the eye continuously scans, altering its centre of attention, focus and accommodation to register each subtle and bright effect. The reflected features are not seen in the same plane as the surfaces on which they are seen. We simply cannot see all the effects at once in such a way that their relative prominence is simultaneously registered and weighted. The projected image accomplishes the simultaneity that they eye cannot. This is not to show definitely that Caravaggio could not have confected his image with incredibly sustained 'eyeballing", but it is to say that the kind of device described by della Porta would have been a godsend (in both the colloquial and literal sense of the term). It may be worth noting that amongst the possessions sequestered by the painter's wronged landlady were two mirrors, one "large" and one shaped "like a shield" (*a scudo*).[26] The shield shape would suggest that it was round and convex, but it is not clear how the maker of the list could have succinctly described an unfamiliar concave one.

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[23] 1605 inventory.

[24] In particular, he stresses the strange plastic, spatial and psychological relationship between the figures in the *Doubting of Thomas* (the prime version is probably that in the Stiftung Schlösser und Gärten, Sanssouci, Potsdam).

[25] Gorman[2003]. The tranlsations that follow are by Gorman, whose advice is gratefully acknowledged.

[26] 1605 inventory.

Equally suggestive is Caravaggio's documented association with someone who was in the mirror business (a *specchiaro*). Cristoforo Orlandi, a Spanish painter, testified that during his third and forth years in Rome (c. 1600-1) he had a room in the premises of a mirror-maker on the Magine de Ponte.[27] The mirror-maker's establishment was, he said, frequented by Caravaggio and many other artists. Orlandi's testimony can be linked to two documents of 1600 involving a picture commissioned by the Sienese, Fabio de Sartis.[28] The transaction of commissioning on 3 April and the making of payments on 20 November were both conducted on the premises of Alessandro Albani in the Ponte quarter of the city "at the sign of the cross". Albani, who was originally from Bergamo, was appointed as one of the two valuers of the painting, acting on Caravaggio's behalf, and he oversaw the final settlement in the absence of the patron. It seems that Albani acted as a trustworthy go-between of some substance for artists and their customers, and may have acted as a dealer in association with marketing his mirrors. If Caravaggio had need of mirrors, he knew where to go.

The fact that we can begin to build up a case for Caravaggio's use of optical devices, compared to the dearth if independent evidence from earlier centuries, is partly a consequence of the increase of surviving documentation for the period in which he worked. However, it does also appear to reflect the widening availability of the new optical technologies and their increasing use to create the very striking kinds of effects that della Porta excitedly describes.

If nothing else, the experimental reconstruction of Caravaggio's set-up for the carafe – like the rectification of the Netherlandish mirrors – allows us to say that the subjects of his pictures were staged with meticulous care and laboriously represented with what we can call, in a generalised way, "photographic naturalism".

Gross but True?

What this essay has aspired to do is to say let us look at the big picture and not be afraid of gross generalisations. They have real power, providing their strengths and weaknesses can be recognised. It is also saying that there is more to be gleaned from Hockney's overview of artistic imitation than the windy disputes about the use or non-use of optical devices in particular cases. This is not to say that individual cases should be neglected – as the two detailed studies here serve to emphasise. The stakes are substantial with respect to our understanding of imitation in western art. They are even bigger if the cultural and political implications are thrown into the pot.

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[27] Bassani and Bellini [1994], 36.

[28] Masetti Zannini [1971].

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List of Contributors

Tiemen Cocquyt, Utrecht University Museum

Fokko Jan Dijksterhuis, University of Twente, Enschede

Sven Dupré, Ghent University

Michael John Gorman, The Science Galery, The University of Dublin

Karin C.M. Groen, Netherlands Institute for Cultural Heritage, Amsterdam

Martin Kemp, University of Oxford

Wolfgang Lefèvre, Max Planck Institute for the History of Science, Berlin

Claudia Laurenze-Landsberg, Gemäldegalerie, Staatliche Museen Berlin

Giuseppe Molesini, Istituto Nazionale di Ottica Applicata, Florence

Isabelle Pantin, Université Paris X and Observatoire de Paris (CNRS-Syrte)

Abdelhamid I. Sabra, Harvard University, Cambridge, M.A.

Alan E. Shapiro, University of Minnesota, Minneapolis

Klaus Staubermann, National Museums Scotland, Edinburgh

J. Philip Steadman, University College, London

Norma Wenczel, Freie Universität, Berlin

Carsten Wirth, Berlin