Projecting and painting: codifications of the camera obscura, 1568–1711

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Abstract
The camera obscura is best known to historians of science and historians of philosophy for its role in early theories of human vision and cognition. Art historians have discussed the instrument mostly as a predecessor to the photographic camera. Building on recent literature that combines these strands of scholarship, I argue that the codification and circulation of the main philosophical and artistic problems of the camera were more closely intertwined than previously believed. I show that, throughout the sixteenth and seventeenth centuries, discussions of the setup of the camera obscura as a painting tool and of the conceptualization of its optical projection often coincided. For both, finding the distances between the lens, object, and image was a persistent problem until mathematicians provided explicit solutions, around 1700. Therefore, I argue, the conceptualization of these distances in projection and the codification of the camera obscura's material use for painting were inextricably linked.

Keywords
camera obscura, practical mathematics, geometrical optics, circulation of knowledge, codification of practices

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1. Introduction

> Everyone knows with what ease one can, by means of a single convex lens, represent naturally, in a dark place, the objects outside of it […] it is moreover so easy to render this invention useful for painting that the care of treating the matter at such a length as we do here will appear, without a doubt, unnecessary.[1]

The camera obscura had been around for a long time when Willem Jacob 's Gravesande (1688–1742) published his short treatise, the "Usage de la chambre obscure pour le dessein," in 1711. The instrument was widely regarded as analogous to the human eye in early modern natural philosophy. It had been used in astronomy to study the sun without having to look at it directly since the early sixteenth century. And from the second half of the sixteenth century onwards, various authors suggested using the instrument to produce stable images on a sheet of paper, so that these images could be studied or directly copied.[2]

The aim of this article is to cast light on the circulation of this last use of the camera obscura: its use as a technical innovation in painting, as a copying machine *avant la lettre*. Evidence on such circulation directly from practitioners is sparse. There are few sources on the working methods of painters, and the use of the camera obscura in painting generally does not leave unequivocal traces. Because of that, existing studies have relied on anecdotal textual sources and reconstructions of painting techniques to establish that specific individuals, including prominent figures in art history, used the camera obscura. Hence, it is clear there was some circulation. Yet the available evidence indicates that, before the eighteenth century, those using the instrument were part of a small minority.[3] In other words, and in contrast to what 's Gravesande's claims suggest, the use of the camera ob-

1 's Gravesande, "Usage," [i]. "Tout le monde sçait avec quelle facilité on peut, par le moyen d'un seul verre convexe, représenter au naturel dans un lieu obscur, les objets qui sont au dehors […] Il est d'ailleurs si aisé de rendre cette invention utile pour le dessein, que le soin de traiter cette matiére aussi au long qu'on le fait ici, paroîtra sans doute peu nécessaire." Throughout, translations are mine unless indicated otherwise, and attempt to maintain the conceptual terminology in the originals.

2 For chronologies of the camera obscura, see Waterhouse, "Notes," Hammond, *Camera Obscura*, Kemp, *Science of art*, 188–199, Steadman, *Vermeer's Camera*, 4–24, and Lefèvre, "Camera Obscura."

3 Scholarship on the camera obscura and painting has centered on the question of when painters started to use the camera, and particularly on its possible use by Johannes Vermeer (1632–1675). Steadman, *Vermeer's Camera*, offers compelling arguments for Vermeer's use of a camera. Other painters associated with the camera obscura in the literature include Caravaggio, Van Wittel, and Canaletto. For discussion, see, e.g., Gorman, "Art," Dupré, "Introduction"; Lüthy, "Hockney's Secret Knowledge," and Steadman, "*Canaletto's Camera*."

scura as a painting instrument seems to have been slow to take off. Why was that the case?

To answer this question, I draw on a body of early modern texts recommending the camera obscura as a tool for artists. Such texts appeared first in mid-sixteenth-century Italy and spread over Latinate Europe during the seventeenth. They were mostly written by mathematicians as part of treatises on the geometry of perspective painting. Many of their authors reveal substantial knowledge of the techniques used by "practitioners."[4] Such texts are well known to the historical scholarship on the camera obscura and art. Yet they have been cited predominantly as illustrations of the fact *that* camera obscuras were in use for painting.[5] On the other hand, philosophically oriented scholarship on the camera obscura has mainly been concerned with how such texts used the camera obscura to explain the functioning of the human eye.[6] Instead, I look more specifically at *how* these texts described the functioning of the camera obscura, and if those descriptions might have aided its use in painting. I document both historical developments in the conceptualization of projecting images with the camera obscura, and concrete advice on the material setup needed for its potential innovative use in painting.[7]

My evidence reveals a remarkable overlap between a persistent problem in geometrical optics, on the one hand, and continued lack of precision in descriptions of the camera obscura as a copying machine, on the other hand. For both, the lack of precision is directly connected to the absence of an explicit technique for finding the distances between image, lens, and object. I build on earlier studies on similar problems for mirrors and the telescope to explain these conceptual difficulties. For telescopes, the more central instrument to seventeenth-century optics, questions of image location were solved early in the second half of the seventeenth century.[8] But, as I explain below, the camera obscura posed an even

4 For my purpose, little is at stake in how "practitioners" is defined here. What matters is that the authors of treatises on geometrical perspective techniques tended to have knowledge of painters' techniques. On perspective techniques and painting techniques, see e.g. Dupré, "Historiography."

5 See the literature cited in notes 2 and 3.

6 On early modern optical theories, see Smith, *From Sight to Light*, 333–349. On the challenges that optical theorists faced, see e.g. Pantin, "Simulachrum," Chen-Morris, *Measuring shadows*.

7 Camera obscuras had still other uses. For example, various metaphysical and religious connotations were ascribed to such instruments, especially in works of seventeenth-century Jesuit authors such as Athanasius Kircher, and Caspar Schott, as well as in that of their student Johannes Zahn. On these dimensions, see e.g., Vermeir, "Kircher." For a helpful collection of printed images of their camera obscuras, including Zahn's, Schott's and Kircher's, see Warwick, "The 'Sky Optick.'" A discussion of this variety of writings on the camera obscura is outside the scope of this article. I here concentrate on works that attempted to describe either the projection of images or the use of the camera obscura for painting.

8 For the problem of image location in geometrical optics, see Shapiro, "*Optical Lectures*," Dupré, "Ausonio's Mirrors"; Malet, "Conceptualizations," Shapiro, "Images," Malet, "Kepler's legacy."

more complicated distance problem, for which specific solutions appeared in print only in the final decade of the seventeenth century.

That the relatively slow uptake of the camera in painting was related to this rather poor conceptual grasp of what happens inside the camera obscura is suggested by the timeline. Explicit procedures for how to set up the camera as a copying machine were published only after solutions to the theoretical problem were codified. But once the theoretical problem was fixed, exact instructions on how to get a sharp image on a sheet of paper inside followed soon. 's Gravesande's treatise on the camera obscura was very likely the first to combine both. Although his treatise has been mentioned by various historians, no study of it exists and the existing literature does not draw attention to the fact that 's Gravesande codified a solution to an outstanding practical problem.[9] Here, by 'codified solution', I mean a set of descriptions, quantitative or not, arranged such that, if followed closely, they would allow one to solve the problem at hand. I argue that 's Gravesande's description of a procedure to set up the camera obscura as a copying machine allowed this specific use of the camera to circulate at a much larger scale than before.

Although one might be skeptical of such a link between codifying a solution to a seemingly theoretical problem and the onset of widespread material use,[10] the rest of 's Gravesande's treatise shows how quantification mattered to making the instrument user-friendly. The treatise contains two designs of portable camera obscuras adapted to painting, described in sufficient detail for others to rebuild them. Both instruments, but especially the one depicted in Fig. 1, automatized the procedure of getting the image in focus. The treatise specified how to use the instruments and showed that they corresponded to the quantitative prescripts of geometrical optics. That is, it showed and proved how to bring

None of these studies pays much attention to developments on the camera obscura in the period after Kepler. As Cocquyt, "Instrumental Practices," 86, remarks, during the seventeenth century, "optical rules were not universally applied, but instead depended on particular phenomena [...] imaging in a camera obscura setting, where 'real' images are being produced, was treated differently from imaging in telescopes."

9 Both Delsaute, "Camera Obscura," 114 and Steadman, *Vermeer's Camera*, 136–137 refer to the novelty of the instrument designed by 's Gravesande (see Fig. 1) without addressing the specific instructions given. Andersen, *Geometry*, 341–342 draws attention to geometrical demonstrations given by 's Gravesande and calls him "the first to go into any detail about how the instrument functions relative to a particular perspective projection" but neither discusses his advice on setting up the machine, which comprises the bulk of the text.

10 Such skepticism is expressed, for example, in the recent but already seminal Smith, *Lived Experience*. See, on page 4, "artists and artisans in early modern Europe did not need writing to produce things and make knowledge"; and page 8, "writing was not necessary to transmit [...] information from one generation or region to another." Even if I agree with Smith on the possibility of transmission without writing, my argument is not about circulation *per se*, but instead about the scale of circulation.

an image in focus in just a few steps. Whoever had such a machine built could hence proceed to copy an image without a need for a theoretical or an empirical understanding of the distances between the lens, the sheet of paper, and the object. That is, by following this description, one could greatly reduce the amount of empirical experience needed to operate the camera obscura.[11]

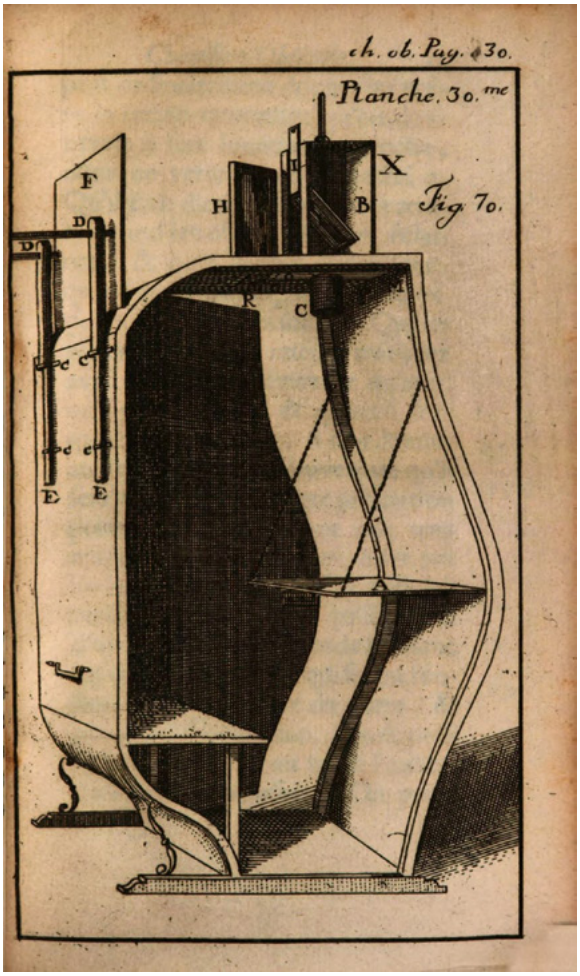


Fig. 1 – The less wieldy but more precise of 's Gravesande's camera obscuras, set up to copy engravings. The engraving to be copied is placed at F, a lens and mirror are placed inside the tube C and box X, and a sheet of paper on table A. An image of the engraving placed at F appears in focus, and in equal size on the sheet of paper, and can be directly copied. 's Gravesande, *Essai*, plate 30.

[11] Perhaps surprisingly for readers living in a world in which even barely adequate inventions are monetized, 's Gravesande made the design of his instrument freely available so others could rebuild it. See section 8 below for more details on his *modus operandi* with regard to instruments. A recent reconstruction of 's Gravesande's machine is discussed in Steadman, "*Canaletto's Camera*," 151–152: "[our replica of 's Gravesande's] camera works […] It is quite feasible to use the instrument to make 'Canaletto-like' sketches. It is not difficult to trace or to maintain focus."

To be sure, the point of this article is not to argue that it was impossible to use the camera obscura for painting before 's Gravesande. As noted above, various painters did use the instrument before. Among those who wrote on the camera, its "ease" of use had even become somewhat of a rhetorical topos, as we will see. 's Gravesande was aware of painters' techniques and acknowledged that he had received advice from a painter for his *Essai de perspective* (1711), a treatise on perspective geometry to which his text on the camera obscura was appended.[12] Neither do I want to argue that 's Gravesande was singlehandedly responsible for the uptake of the camera obscura as a copying machine in the eighteenth century. Uptake certainly depended on more than the availability of codified knowledge alone. Many other factors mattered, not least how an instrument such as the camera obscura fitted into existing painting practices and aesthetic attitudes.[13] As I asserted above, however, the timeline does suggest a connection between the presentation of the camera obscura as a user-friendly machine and its circulation among practicing painters. Textual and material evidence for use of the camera in painting is very sparse before 1700 but grows rapidly from about the 1720s onwards. As John Hammond stated long ago: "during the eighteenth century many instrument makers were producing [the camera obscura] and advertising it for sketching. The apparatus appears to have been a normal piece of equipment for travellers and amateur artists."[14]

My argument on circulation is based on the assumption that using the camera obscura for painting or drawing was made much easier when user-friendly descriptions of the instrument became available. That is, I argue such codification changed the scale on which circulation took place. Whether that be true or not, this article shows (1) that no such user-friendly descriptions were available before 1711, (2) that the first such description

[12] 's Gravesande, *Essai*, [xviii–xix]: "j'ai eu le bonheur de rencontrer un habile Peintre […] je lui suis redevable de plusieurs observations, auxquelles sans lui je n'aurois peut-être jamais pensé"; this painter remains unnamed.

[13] See Kemp, *Science of art*, 190 on the camera obscura and early modern views on the imitation of nature. One reason contemporaries of 's Gravesande gave against the use of the camera obscura was the claim that the image on the sheet presented an "unnatural perspective." As a commentator on 's Gravesande, Jombert, *Methode*, 139, put it: "la maniere dont nous voyons les objets de la nature dans la chambre obscure, est différente de celle dont nous les voyons naturellement […] L'effect en est à la vérité plus piquant, mais il est faux." As this comment appears in the middle of an abridged, pirated edition of 's Gravesande's treatise, it has been mistakenly attributed to 's Gravesande himself by some historians, starting with Hyatt Mayor, "The photographic eye."

[14] Hammond, *Camera Obscura*, 40, see 20–103 for Hammond's wider assessment of its spread. Like Hammond, studies such as Lüthy, "Hockney's Secret Knowledge," and Wenczel, "Camera Obscura" have found no evidence for a wide use of the camera in art before the mid-eighteenth century. Lefèvre, "Camera Obscura," 5, asserts that "there is not one example of a camera obscura or even a single part of one that dates from the 17th century."

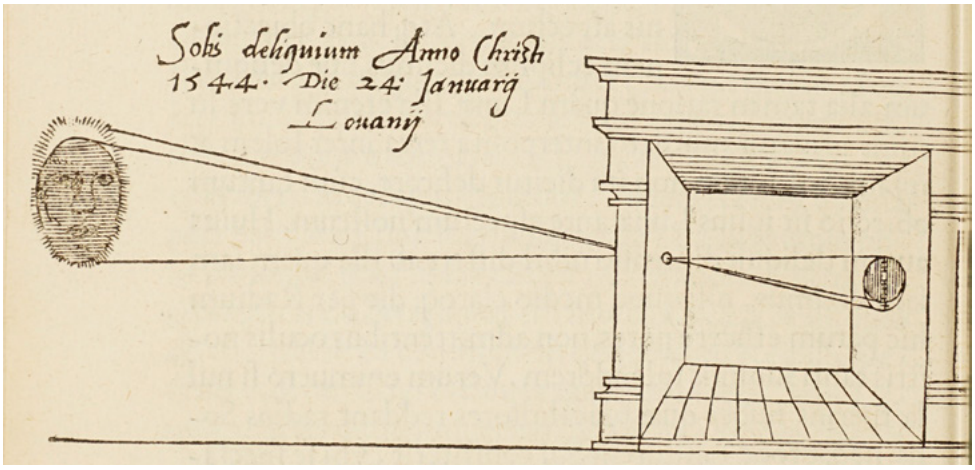


Fig. 2 – The earliest printed illustration of the use of a camera obscura in astronomy, by Gemma Frisius, *De radio astronomico*, 31v.

was directly based on a geometrical codification of the camera's functioning, and (3) that throughout the period here considered, the codification of material use was intertwined with conceptual advances in geometrical optics.

Section 2 of the article looks at the camera obscura itself and discusses what part of the geometry of lenses and light matters to its use in painting. In section 3, I look at the earliest textual source on that use, a mathematical book from 1568, and show its lack of conceptualization of the camera obscura. Sections 4–7 present the historical evidence for my core argument about the overlap between developments in the codification of the functioning of the camera and in descriptions of how to use it for painting. In section 8 I return to 's Gravesande's camera to show why it is plausible that his specific description of the camera indeed impacted the circulation of its use for painting. In the conclusion, I consider what the case of the camera obscura tells us about the relations between mathematical theory, material practice, and technological innovation in early modern science more generally.

2. Focusing the object: the conundrum of the camera obscura

In its simplest form, the camera obscura is a "dark room" in which, in present-day terms, an image of an external object or set of external objects is projected by rays of light falling through an aperture. The image appears inverted on a wall or sheet opposite to the aperture. Camera obscura-like phenomena can and do appear accidentally under strong sunlight and mentions of this phenomenon can be found in texts from ancient China

and Greece.[15] Deliberately blacked-out rooms with a small hole in one wall were used in Renaissance astronomy to observe solar eclipses safely. This technique was described by Leonardo da Vinci (1452–1519) and depicted in print by Gemma Frisius (1508–1555).[16] Projecting images of eclipse, in which the object to be represented was the sun itself, was a well-established and straightforward practice by that time (see Fig. 2).

The camera obscura as a painting device, however, is more complex. It does not project the sun directly but rather specific objects lit by the sun. Even when such objects are brightly lit, the image inside is usually rather mute, unless a convex lens is placed just behind the aperture to refract the rays of light. If handled well, this lens will make the projected image much brighter and sharper than the simple pinhole camera does. However, speaking from personal experience, setting up a camera obscura with a lens such that it projects a traceable image is not a straightforward matter.[17] To get a bright and focused image, one has to find the appropriate orientation for the camera obscura and closely control the distances between the objects, lens, and image, and possibly those of mirrors that correct for the inversion of the image. Present-day optics uses the "thin lens approximation" to find those distances: $1/f = 1/o + 1/i$. Here, o is the distance between the external object and the lens; i is the distance between the place at which the projected image of the object is "in focus" and the lens; and f is the "focal length" of the lens, a constant depending on the properties of the lens in use. For a given o and f, the formula thus gives the distance at which the projected image will be in focus: the place where a sheet of paper should be placed. Alternatively, given the distances of the object and the screen to the lens, the formula gives the focal length of the lens needed to focus the image.

The object distance and the image distance are concrete and measurable, and relatively unambiguous. The focal length, however, is more complicated. It is the key property of a convex lens and depends on its curvature and refractive index. Even in present-day settings, focal length, and the directly associated focal points, are regularly measured by empirical approximation instead of calculated, for example by opticians who want to check the optical power of a pair of glasses. Operationally, this is best done in the special case in which rays of light fall onto the lens parallel. That is the case when the object to be depicted is sufficiently far away. In that case, the $1/o$ term decreases towards zero and can be ignored. Thus, for a far-away object, f and i in the formula above will be approximately equal: the image distance equals the focal length.

This equality between image distance and focal length, which only holds in the specific

[15] Hammond, *Camera Obscura*, 1–5.

[16] See e.g. Steadman, *Vermeer's Camera*, 4–7.

[17] Although I am far from an expert, I have tried to set up camera obscuras with different lenses and in different places and struggled a great deal with finding appropriate components and setting the distances between them. I thank Tiemen Cocquyt, for the discussion and for showing me what concretely matters in setting up a camera obscura.

case of far-away objects, is vital to understanding troubles of historical actors with expressing clearly how a camera obscura functioned. The equality occurs particularly when the camera is used for astronomical purposes: when the object is the sun, rays of light fall in parallel and the "focal length" and the distance from the lens at which the projected image is "in focus," are equal. This is why the distance problem is more complicated for the camera obscura than for the telescope: if one wants the camera to represent, say, a tree or a person a few meters removed from the lens, one cannot ignore the $1/o$ term. However, for Renaissance and early modern treatises on the camera obscura, it was not those cases but instead the astronomical case that tended to be the most important. Hence the 'standard' explanation of optical artifacts was one in which there was no need for a distinction between the image distance and the focal length.

Indeed, such a distinction is absent in historical texts. These texts tended to use the word "focus" to describe the place at which an image was best represented. But in expressing the distance between that place and the lens, they tended to use the same terms irrespective of whether a camera obscura or a telescope was used. They thus lumped what are now called the image distance and focal length. Effects of this lumping persist in present-day popular use. In optics, "focus" remains a technical term: a focus is defined as a *place* at which light rays from the same point of origin converge. But, in casual use, it can also refer to a *distance*: either a focal length or the image distance. Furthermore, as the Latin term for fireplace, "focus" historically had specific connotations not directly relevant to projected images. It was applied to burning mirrors before glass lenses were available, and also was a specific geometrical term: the foci are specific points of reference in the construction of curves such as ellipses and parabolas. Thus, "focus" in general meant the place where lines, whether of heat, of light, or purely mathematical, converged.[18]

More generally, terms such as 'camera obscura', 'image', 'focus', and 'projection', were all moving targets in the period considered. What is more, they were often moved by questions and issues other than that of using a camera obscura for painting. The problem of finding a clear representation of a nearby external object was not the most pressing problem to those concerned with the science of optics or optical instruments. Nevertheless, as we will see, many authors believed it was a question worth addressing. During the seventeenth century, writers on the camera became increasingly convinced that it was a problem that could be solved in geometrical terms. That is, they believed that it was a problem to which the solution could be codified in mathematical terms.

[18] On such use of "focus" in the work of Kepler, Cavalieri, and others, see Shapiro, "Images." The metaphor of "focusing on," now almost as common in academic writing as phrases such as "the way in which," of course has the same root. To avoid confusion, I try to avoid such metaphorical use of the term focus here.

3. *The false start of the conceptualization of the camera obscura*

The oldest published text that describes how to use the camera obscura for painting is Daniele Barbaro's *La pratica della perspettiva* (1568),[19] a text remarkably similar to 's Gravesande's later work on perspective. Barbaro (1514–1570) aimed to provide a compendium on mathematical perspective "of great use to painters, sculptors and architects."[20] Barbaro appended his description of the camera obscura, a term he did not use, at the end of his book, under the header "natural ways to put [things] into perspective." It seems he considered the camera to be an addition or alternative to the geometrical perspective constructions the book was dedicated to. Those mathematical techniques contrast with his lengthy and ambiguous description of the "most beautiful experience around perspective" he had with the camera:[21]

> If you want to see how nature poses the things […] you will make a hole in the shutter of a window of the room from where you want to look, as large as the glass of an eyeglass is. And grab an eyeglass of an old person, that is to say one that has some body in the middle [i.e. a convex lens] and is not concave like the eyeglasses of young people who are short-sighted. And set this glass into the fitted hole, then close all the windows and the doors of the room, such that there is no light apart from what comes from the glass. Then take a sheet of paper and set it opposite the glass at such a distance that you minutely see all that is outside of the house on the sheet. This happens more distinctly at a particular distance. This [distance] you will find by moving the sheet towards or away from the glass, until you find the convenient site. Here you will see the forms on the paper as they are […] For this experience it is required that there be a clear and fair sun, because the light of the sun has great force in drawing out the visible species, as you will experience to your great delight. In this experience you will make a selection of the glasses that work best. If you want to cover the glass so much that you leave a little bit of the circumference in the middle, such that it be clear and exposed, you will see an even more vivid effect thereof. Thus seeing on the paper the outlines of the things, you can with a brush mark on the paper the whole perspective that will appear on it […].[22]

[19] Girolamo Cardano and Giambattista Della Porta are often mentioned to have described a camera obscura with a lens in 1550 and 1558 respectively. Della Porta in fact wrote about mirrors. Cardano referred to a lens in a closed room, but asserted it created "dull images" and did not mention copying them. See e.g. Waterhouse, "Notes," 274, Kemp, *Science of art*, 189, Steadman, *Vermeer's Camera*, 8, and Ilardi, *Renaissance vision*, 220.

[20] See the title page of Barbaro, *Perspettiva*. Andersen, *Geometry*, 152–158, asserts Barbaro's book was largely derivative.

[21] Barbaro, *Perspettiva*, 192, "modi naturali di mettere in perspettiva"; "una bellissima isperienza d'intorno alla Perspettiva."

[22] Ibid., 192–193. "Se vuoi vedere come la natura pone le cose […] farai uno bucco nello scuro

Thus, Barbaro introduced the idea of painting with the camera to the learned world. Given the way he described it and the absence of any claim to invention, it seems likely that he described a practice he had carried out himself, or at the least witnessed. If that is correct, Barbaro's text provides evidence of circulation of the camera as a painting tool. But it does not provide any evidence on the scale of this circulation. Besides the idea of painting with the camera, Barbaro also introduced the main problem: that of finding the distance at which the image – a term he did not use – is seen clearly on the sheet. Barbaro, however, did not give any details on where to move the sheet to distinctly see "the things."

In fact, Barbaro did not provide any clear guidance on making "the outlines of the things" on the screen "more distinct." Instead of codifying solutions to specific issues – as he did give for mathematical perspective problems – for the camera obscura, he advised trial-and-error methods. His readers would have to vary the distance between the lens and the screen and try out varying eyeglasses themselves, until something convenient was found. Barbaro's advice to use convex lenses and to cover part of the lens – with what would later be called a diaphragm – is sound but left unexplained.[23]

Clearly, readers who had experience with both lenses and perspective paintings would be able to set up the instrument. But those who lacked knowledge of optics would probably have found little help in Barbaro's text. Not only was Barbaro unhelpful on distances, he also failed to mention various nuisances with the setup he described. Most importantly, the projection inside his camera obscura will have appeared inverted both left to right and upside down. This could be solved by additional mirrors or lenses but Barbaro did not mention those. Besides that, Barbaro's text did not talk about how to control the com-

d'una finestra della stanza di dove vuoi vedere, tanto grande quanto è il vetro d'un occhiale. Et piglia un occhiale da vecchio, cioè che habbia alquanto di corpo nel mezzo, & non sia côcavo, come gli occhiali da giovani, che hanno la vista curta. & incassa questo vetro nel bucco assaggiato, serra poi tutte le finestre, & le porte della stāza. siche non vi sia luce alcuna, se non quella, che viene dal vetro, piglia poi uno foglio di carta, et ponlo incontra il vetro tanto discosto, che tu veda minutamente sopra'l foglio tutto quelle che è fuori di casa, ilche si fà in una determinata distanza più distintamente. ilche troverai accostando, overo discostando il foglio al vetro, finche ritrovi il sito conveniente. Qui vi vederai le forme nella carta come sono […] A questa isperienza bisogna, che ci sia il Sole chiaro & bello, perche la luce del Sole ha grande forza in cavare le specie visibili, come con tuo piacere ne farai la isperienza, nella quale farai scielta di quelli vetri, che fanno meglio, & se vorrai coprire il vetro tanto, che vi lasci una poca di circonferenza nel mezzo, che sia chiara è scoperta, ne vederai anchora piu vivo effetto. Vedendo adunque nella carta i lineamenti delle cose, tu puoi con uno penello segnare sopra la carta tutta la Perspettiva, che apparerà in quella […]." I have rendered "u" as "v" wherever appropriate. Existing translations in Waterhouse, "Notes," Dupré, "Galileo," 246, and Ilardi, *Renaissance vision*, 220 are more liberal in using terms such as "lens" or "image," which I avoid because I want to draw attention to the lack of conceptual clarity in Barbaro's text.

23 On the importance of diaphragms, especially to compensate for defects in lenses, see Cocquyt, "Instrumental Practices," 54–57.

position: his camera obscura would not simply let one "minutely see all that is outside of the house." But objects at different distances appear with different clarity and distinctness, depending not only on those distances themselves but also on the refracting capacities of the lens in use. Given this largely vague description, we should in my view be skeptical about whether Barbaro's text would have helped to spread the use of the camera obscura for painting.

4. Conceptualizing optical instruments and projection

Barbaro did not explain well what happened inside the camera. Nowhere in his text did Barbaro talk about controlling the image's size, depth, or focus. In fact, he did not use concepts such as 'image' or 'focus' to describe the convergence of rays after passing the lens, nor did he use terms such as 'picture', 'image', or 'representation' to conceptualize what appeared on his screen. In other words, he used no technical vocabulary to codify the process of projection from the lens onto the sheet. But such terms started to develop in the decades after Barbaro's work.

Barbaro's text was not devoid of theoretical concepts altogether. In describing what was visible of the objects outside, he used "visual species," which "the light of sun" "draws out" or "extracts." The term species came from perspectivist optics, a field of natural philosophy which had as its main subject the explanation of human sight and visual cognition. In the medieval optics of the likes of Roger Bacon and Vitello, "species" referred to the entity that supposedly established a connection between the perceived objects and the perceiver, that is, between the object and the eye. Perspectivist optics comprised certain geometrical construction techniques to explain vision. But it was not concerned with codifying mathematical perspective techniques that comprised the main body of Barbaro's book, and neither did it include images projected by convex lenses or concave mirrors.[24]

Such artifacts as convex eyeglasses circulated widely in Italy by the middle of the fifteenth century,[25] which makes it likely that projections were experienced, at the least accidentally. Yet not much survives in terms of systematic investigations of their functioning before the time of Barbaro. The first clear attempts to do so overlap with Barbaro's both in time and in their conceptual approach. Authors such as Francesco Maurolico (1494–1575), Giovanni Battista Benedetti (1530–1590), and Giambattista Della Porta (1535–1615) took over elements from medieval perspectivist optics specifically to analyze the functioning of optical instruments such as mirrors, lenses, and combinations of

[24] On *species*, see for instance Smith, *From Sight to Light*, and Pantin, "Simulachrum." See Dupré, "Kepler's optics" on strains between the practices of mathematical perspective and perspectivist optics.

[25] On the circulation of lenses, see Ilardi, *Renaissance vision*. On developments in and control of lens quality, see Cocquyt, "Instrumental Practices."

them. Thus, they drew on the same theory of vision from which Barbaro took the concept of "species."[26]

An early example of such appropriation was Ettore Ausonio's (ca. 1520-ca. 1570) short discussion of the properties of a spherical concave mirror, which dates from around 1560. Ausonio was a practicing physician, alchemist, and maker of instruments such as astrolabes, dials, and burning mirrors. As Sven Dupré points out, Ausonio's interest in perspectivist optics was closely related to the practice of making such instruments, more than to the perspectivists' central topic of perception. For the spherical mirror, Ausonio took advantage of the "cathetus rule," a geometrical construction used by the perspectivists to determine where, after reflection in mirrors, the "imago" would be perceived by the human eye. Ausonio used the same rule to find the "point of inversion" of spherical mirrors. This point of inversion is the place where, if the eye approached it, the image would turn upside down. Ausonio, however, also identified this point with the place where a spherical mirror would produce combustion. This issue of combustion was not proper to perspectivist optics, which means that Ausonio appropriated, in a strong sense, elements from perspectivist optics: he took a specific technique out of its theoretical toolkit and applied it to a problem outside of the field.[27]

The concept of the point of inversion and its relation to combustion became of major importance to Della Porta's studies of optical artifacts such as mirrors and lenses. Della Porta was the author of the *Magia naturalis* (1558, 2nd, more relevant edition, 1589), a book concerned with a broad collection of natural experiments and phenomena. As Arianna Borrelli has argued with respect to his optics, Della Porta "devote[d] himself to the observation, description, and formalization of effects without having to introduce any overarching explanatory notions."[28] That is, like Ausonio, Della Porta was interested in producing phenomena with instruments, independently of developing a broader theory of perception. For lenses and glass spheres, one of Della Porta's most important insights was that combustion and the point of inversion were not always at the same location. Della Porta found that the location of the point of inversion changes when the perceiver or object moves, while the burning point does not.[29] Thus, Della Porta's discussion showed that Ausonio had confused a location that depended on the relative positions of the observer and object, with a fixed point that was determined by the material setting.

[26] On Maurolico, see Dupré, "Galileo," 256–260, on Benedetti, see Goulding, "Binocular vision," on Della Porta, see below.

[27] This section on Ausonio is based on Dupré, "Ausonio's Mirrors," 145–180, Dupré, "Kepler's optics," 515–517.

[28] Borrelli, "Thinking with optical objects," 49. In Della Porta, *Magiae naturalis*, see book XVII, chapter X for the lenses and chapter XIII for the sphere, see Borrelli, "Thinking with optical objects," 44–45 for commentary.

[29] Zik and Hon, "Della Porta."

However, Della Porta's own attempts to find the location of points at which projections appear in focus suffered from similar issues. He, too, used the cathetus rule to construct the location of the "imago." This geometrical construction technique relied on drawing various straight lines. First, it connects the eye and the object to be seen via the mirror, assuming equal angles of incidence and reflection. Second, it constructs the "cathetus line," which is the line drawn from the object to the mirror, hitting the surface of the mirror perpendicularly. The rule states that the image, "imago," is located behind the mirror, at the intersection of this cathetus line and the continuation of the reflected line that reaches the eye.[30] The construction gives the same results as modern approaches for plane mirrors and solutions that are empirically adequate for some situations involving curved mirrors. Yet the solutions for refraction are generally not. For a lens, specifically, refraction takes place at both its surfaces, which would require a much more complicated construction. Della Porta was aware of this problem but chose to draw the cathetus line perpendicular to one of the two refracting surfaces. These solutions are not satisfactory, which Della Porta was undoubtedly aware of. Yet he lacked any other technique to locate the points he wanted to find, making the flawed technique the best he had.[31]

The cases of Ausonio and Della Porta show that rules taken from perspectivist optics could treat various cases of reflection reasonably well but had little to offer on refraction. Much of that had to do with the specific terms and aims of perspectivist optics. This is exemplified by its term "imago," widely used by Della Porta and others. In perspectivist optics, the term imago was the image of an object as processed and perceived in the human mind. As A. Mark Smith asserts, in perspectivist optics, "all images [were] psychologically constructed."[32] Perspectivist optics was meant to explain the appearance of images such as those seen through a mirror, images of which the location changes when the perceiver moves. It was not suited to deal with burning points or projected images, which are independent of the location of the observer.

Della Porta's description of how to get a sharp image inside the camera obscura evinces this point. Della Porta stated that one must "place a white paper opposite the opening, and adapt the people to the light, bringing them closer, [or] further away, until the Sun carries a perfect image on the presented sheet," a picture that he stated could be traced by someone "knowledgeable of painting." Like Barbaro, Della Porta advised trial-and-error methods to find the distance between the objects and the lens needed to produce a good

30 On the cathetus rule, see e.g. Smith, *From Sight to Light*, 59–62. On its problems, see Goulding, "Binocular vision," 500–512, Borrelli, "The eye," 305–308.

31 Borrelli, "Thinking with optical objects," 55–59.

32 Smith, *From Sight to Light*, 318. Dupré, "Inside the *Camera Obscura*," 222, affirms that "[a]lthough projected images were empirically familiar [...], they were conceptually alien to the medieval perspectivist tradition," see also Borrelli, "Thinking with optical objects," 43–46.

image, without guidance.[33] The point of my argument is that Della Porta could not have given a more codified solution to the location of a projected image exactly *because* the techniques he used were suitable only for finding certain classes of perceived images, and not for finding the location of projected images.

5. Kepler on perceived and projected images

Images perceived through a mirror are materially different from projected images. Present-day optics refers to them as "virtual images" and "real images," respectively. Real images are images formed by rays converging to a specific place: these real images, usually created by a convex lens, can be projected in that specific place, or perceived near that place by an observer. Virtual images, on the other hand, are formed by rays seemingly diverging from a specific place. These virtual images are usually perceived as lying behind a mirror, and cannot be projected on a surface.

This distinction is often attributed to Johannes Kepler (1571–1630). In his *Ad Vitellionem paralipomena* (1604), and building on the work of Della Porta, Kepler distinguished between "pictures" and "images."[34] Although the title suggests Kepler's book was a commentary on Vitello's perspectivist optics, Kepler had much wider aims. As the imperial mathematician in Prague, he prepared horoscopes for Rudolf II and continued Tycho Brahe's astronomical work, for which he searched for observational precision in astronomy. This shows in the *Paralipomena*. Besides a discussion of perception, the book gave seminal treatments of light rays and of the effect of the camera obscura, both aimed at improving astronomical observation.[35]

Kepler defined the "image [*imago*]" as something created by a human mind. He stated that "the image is per se nothing, we could say imagination."[36] The "picture [*pictura*]," on the other hand, he defined as "the figures of objects that really exist on paper or upon another surface."[37] What made these figures "really exist," according to Kepler, was that they were created by the convergence of rays of light. As Dupré puts it, "unlike images, which

[33] Della Porta, *Magiae naturalis*, 266: "Oppones foramini papyrum albam, ac tandiu homines ad lumen accommodabis, appropinquabis, elongabis, dum perfectam imaginem Sol in obiectam tabulam referat, picturae gnarus colores superponendo ubi sunt in tabula."

[34] Kepler's distinction does not map exactly to the modern distinction, as is forcefully argued in Malet, "Keplerian illusions," see also Borrelli, "The eye," for a recent discussion.

[35] On Kepler's importance to developments in optics more generally, see, e.g., Smith, *From Sight to Light*, on Kepler's intellectual context and aims, see Chen-Morris, *Measuring shadows*.

[36] Kepler, *Optics*, 77; id. *Ad Vitellionem*, 60.

[37] Kepler, *Optics*, 210; id. *Ad Vitellionem*, 193 "figurae rerum vere in papyro existentes, seu pariete, picturae dicantur."

were products of the imagination, pictures were made by rays of light only."[38] Kepler asserted that, at the place where rays of sunlight converge after refraction, the "illumination is strongest, so much so that gunpowder in cold water is ignited when the sun is intensely hot."[39] Thus, Kepler stressed the material dimension of these "pictures," and the phenomena that they could create.

For Kepler, pictures also played a major role in explaining human vision. According to Kepler, the cause of vision was the formation of a picture on the retina in the back of the eye, where rays of light converged after passing the pupil and refracting on the crystalline lens of the human eye: that is, exactly analogous with what happens in the camera obscura.[40] The picture thus described the causes of human visual perception. But how humans perceived things would not be determined exclusively by this geometry, and this is where images came in. According to Kepler, the mind assessed the location of the image by an act of interpretation, particularly via a triangulation process that usually involved binocular perception.[41] Given that this was a mind-dependent process, it was prone to human errors, he argued. For Kepler, the image was therefore not a faithful representation of the location of the object. As Antoni Malet has put it, "to Kepler those images are illusions resulting from deceived vision."[42] This entailed that the locations of the "image" and of the "pictura" were not the same. The picture was determined fully by the geometry of refraction and light rays. But, Kepler argued, at the place where a projected picture could appear, the eye would see great confusion, and no direct perception of this picture was possible.[43]

Thus, even if it did play a role in Kepler's explanation of perception, the picture was separated from the interpretive act of perception. It was based on the intersection of light rays alone and was to be constructed following the geometry of light rays and refraction. This made the concept of picture suitable to the study of effects produced by optical instruments in a way that perspectivist optics was not. That his notion of the picture was adapted to studying the camera obscura was not a coincidence: Kepler had started his new conceptualization of optics from that very instrument. Thus, Kepler's new optical theory could do work towards both the specific theoretical aims of perspec-

38 Dupré, "Inside the *Camera Obscura*," 243.

39 Kepler, *Optics*, 211; id. *Ad Vitellionem*, 194.

40 Kepler, *Optics*, 222–223; id. *Ad Vitellionem*, 207–208. For the importance of the camera obscura to Kepler, and its implications, see Chen-Morris, *Measuring shadows*.

41 On Kepler and triangulation, see Malet, "Keplerian illusions," Goulding, "Binocular vision."

42 Malet, "Keplerian illusions," 4.

43 Dupré, "Inside the *Camera Obscura*," 239; Kepler, *Optics*, 191; id. *Ad Vitellionem*, 178. As Borrelli, "The eye," 309–310 stresses, Kepler's picture would only appear if a material surface was present at its location. No perception of the picture was possible without such a surface, which makes the picture qualitatively different from the modern notion of real image.

tivist optics and the specific instrumental aims of the likes of Ausonio and Della Porta.[44]

There is direct evidence that Kepler himself used the camera obscura for drawing In a letter to Francis Bacon, an English visitor, Henry Wotton, described how Kepler had used the camera to draw landscapes. It can be gathered from the letter that Kepler used a tent, a "convex glass" and a "concave glass" – likely a mirror – to do so. Kepler's setup of the camera obscura might well have looked like the one 's Gravesande's published 91 years later.[45] Yet no clear description of a camera obscura by Kepler exists. He did, however, give various "cautions" on how to use the camera for painting, which do reveal his material skills with the instrument. For a pinhole camera without a lens, he stated that a larger hole gives a brighter but less sharp picture. For the distance of the sheet of paper, he similarly stated the picture would get sharper but dimmer when the sheet was moved further from the hole.[46] For a camera with a lens, he gave less detail, mentioning that there was an inverse relation between the distance of the object and that of the image: "The place of the picture of nearby things is farther from the glass; and of distant things, nearer," stating that this followed from the theoretical propositions about light rays that he gave before.[47]

Surely, this advice would have helped those without experience only a little more than the advice of Barbaro or Della Porta. Yet Kepler's advice is qualitatively different. Rather than advising trial and error without any guidance, Kepler did state a rule of thumb and backed it up with theory. But it is still a far cry from a codification of problems related to setting up a camera for painting. This was probably not for a lack of trying. Kepler dealt at length with lenses in his second major optical work, the *Dioptrice* (1611). After hearing of Galileo's success with the telescope, Kepler set out immediately to give a theoretical account of how the instrument could make faraway objects appear larger, a phenomenon contemporaries found equally spectacular and puzzling.[48] The *Dioptrice* contains many propositions on the convergence of rays after passing thin equiconvex lenses, such as are used both in the telescope and in the camera obscura. But Kepler had no general way to construct the "punctum concursus," what is called a focal point in present-day optics. As Malet describes, Kepler "only had a largely qualitative knowledge of the location of focal points."[49] For combinations of a lens with another optical artifact, such as needed for a

[44] On reading Kepler as bringing together elements from perspectivist optics and from the more instrumental optics, see Dupré, "Inside the *Camera Obscura*," Dupré, "Kepler's optics."

[45] For this letter, sent by Henry Wotton to Francis Bacon in 1620, see e.g. Chen-Morris, *Measuring shadows*, 98, Steadman, *Vermeer's Camera*, 11–12; on 137–138 Steadman draws attention to the possible likeness to 's Gravesande's camera.

[46] Kepler, *Optics*, 68–69; id. *Ad Vitellionem*, 53.

[47] Kepler, *Optics*, 212; id. *Ad Vitellionem*, 195.

[48] See, e.g., Cocquyt, "Like water," on Isaac Beeckman's struggle to find a mechanism that could explain the telescope's magnification, for which he drew on Kepler's *Dioptrice*.

[49] Malet, "Kepler and the Telescope," 109. See Kepler, *Dioptrice*, 12–15 for a couple of particular

telescope and a camera that corrects for inversion, Kepler had no mathematical codifications.[50] As in Della Porta's case, Kepler's limited description of how to use the instrument for painting can be linked to the absence of a technique to find the distance at which images or pictures would appear after refraction.

6. The location of the image in the camera obscura post-Kepler

Kepler's optical work became seminal in various ways. It led to renewed philosophical debates on what happened inside the camera, on rays of light, species, images, and the nature of optical phenomena more generally.[51] His concepts of image and picture were also picked up. Together with his techniques to construct the location of images, they became part of the standard technical equipment of geometrical optics in the seventeenth century. Much optical theorization focused on the same issue to which Kepler had dedicated his *Dioptrice*: the functioning of the telescope.[52]

Telescopes contained a combination of at least a lens plus an additional lens or curved mirror. One of these optical artifacts would be held as close as possible to the eye for observation. Much theory related to finding the distance between the two optical pieces needed to allow the observer to see a clear image, as well as to the magnification specific setups could achieve. Kepler himself had not used his concept of picture to understand what happened if one looked through a telescope, seeing this as an act of perception instead.[53] Yet his *Dioptrice* made clear that the perceived image, too, had a location that could be constructed geometrically. Moreover, getting this image location right made a material difference when dealing with an instrument such as the telescope: a telescope in which the distance between the optical elements is off, is simply a bad telescope.

Even if it did not have particular solutions, Kepler's work did offer a geometrical algorithm to find these distances between the optical parts and the human eye: it had to be done by tracing rays of light. Throughout the seventeenth century, the problem of image location was attacked by many mathematicians, including René Descartes (1596–1650), Christiaan Huygens (1629–1695), and Isaac Newton (1642–1727).[54] Within geometrical

solutions. On focal points in the *Dioptrice*, see also Malet, "Keplerian illusions."

50 Malet, "Keplerian illusions," 5–6, Shapiro, "Optical Lectures," 127.

51 On seventeenth-century debates on the nature of projected images, see Pantin, "Simulachrum."

52 On geometrical optics and the telescope in the seventeenth century, see e.g. Dijksterhuis, *Lenses*, 24–51, Malet, "Conceptualizations," Malet, "Kepler's legacy," Shapiro, "Images," Borrelli, "The eye." Cocquyt, "Like water," 122, however, shows how Isaac Beeckman and his acquaintances used a simple camera obscura in the 1630s to gauge the quality of telescope lenses, thus connecting the camera obscura to ongoing developments.

53 On Kepler's understanding of the telescope, see Malet, "Conceptualizations."

54 On their work in geometrical optics, see, e.g., Shapiro, "Images."

optics, authors increasingly came to reduce the explanation of specific optical phenomena to finding the path of light rays. They also developed increasingly advanced mathematical techniques for solving specific problems. Their central issue became a more abstract mathematical problem: to locate the point at which rays of light converge after any type of reflection or refraction, independent of material constraints. It was at that point of convergence that Kepler's projected picture could be made visible. However, it also came to be considered the point at which an observer would perceive Kepler's image, if the eye was moved a little behind it, relative to the point of refraction or reflection. Although a distinction between perceived and projected images was still present, by the 1660s and 1670s, James Gregory, Isaac Barrow, and Isaac Newton defined the two types of images as being geometrically the same, making their notion of image fully dependent on light-ray tracing.[55]

Thus, the central problem of optics was widely considered as one to be solved by geometrical construction techniques.[56] Several results with important consequences for understanding the camera obscura came about during the century. In his *Dioptrique* (1637), Descartes found the sine law for refraction. This gave him an exact measure for how far refracted rays are inclined towards the normal, a question on which Kepler could give empirically adequate answers only for small angles of incidence.[57] However, it also led to a more complicated mathematics. Descartes found that spherical lenses could not focus rays of light perfectly but that a perfect focus, in which all rays of light originating from the same spot converge to a single point again after refraction, could only be achieved with lenses of specific but more complex curvatures, for example with a lens of a hyperbolic shape. But such a shape proved near impossible to achieve in lens grinding.[58]

Descartes's *Dioptrique* was a general treatise on optics, perception, and light rays, much in the sense of Kepler's *Paralipomena*. It also contained a description of how to set up a camera obscura for painting, running over two pages. Descartes stated that, once the camera with a lens was put in place, one must consider that

> [...] having the sheet at a certain determined distance, the images appear very distinctly, and that, if we move it a bit further away or towards the glass, they begin to be less [distinct]; [...] if we place the glass a little beyond the hole in one way or another, the sheet must also be moved closer or further away from [the glass]; and that [the image] depends partly on the shape of the glass, and partly also on the distance of the objects: for if we leave the object in the same place, the less curved the surfaces of the glass are, the further the sheet must be

[55] On Gregory, see Malet, "James Gregorie," on Barrow, Shapiro, "*Optical Lectures*."

[56] Although the geometrical approach to optics was widespread, other approaches continued to exist. Athanasius Kircher, for example, considered optics from a much wider perspective, which included metaphysical and religious dimensions, see e.g., Vermeir, "Kircher."

[57] Malet, "Kepler's legacy," 289.

[58] Dijksterhuis, *Lenses*, 13–16; Dijksterhuis, "Constructive thinking."

> moved away from it […] And that the larger the glass is, the clearer and brighter the images appear.[59]

In this advice, Descartes mentioned various elements key to setting up a camera obscura correctly, such as the relation between the curvature of the lens and the distance at which the image will appear and the importance of lens size. However, his advice is still qualitative. Thus, notwithstanding further progress in optical geometry, descriptions of the use of the camera for painting remained much the same. In his *La perspective curieuse* (1652), a book of mathematical perspective techniques aimed at painters, much like Barbaro's, Jean-François Niceron described the camera obscura as "an optical experience that perfectly teaches perspective." Yet he did not apply any of his mathematical apparatus to it. He advised that "we must remove the sheet from the hole, until we find the point or the place most proper from representing the images." His advice, too, echoed Barbaro's by then century-old work.[60]

7. From the geometrical conceptualization of the image to the camera

In the 1660s, as Malet asserts, "the crucial notion of image formation in optical instruments appeared [and] provided new ways of analyzing the properties of optical instruments."[61] This new crucial notion was put forward by Isaac Barrow, the professor of mathematics at Cambridge, who however discussed neither instruments nor configurations of lenses. Barrow's solutions were highly mathematical and decoupled from material use. Although Barrow's geometrical construction techniques would in principle have been sufficient to locate the image of a telescope and the camera obscura, Barrow seems to have had little interest in building optical instruments himself.[62]

This was patently different for Newton, Barrow's student and successor at Cambridge. As is well known, Newton came up with a new design for a reflecting telescope in the late 1660s. A different design for a reflecting telescope, which, as the name suggests, switches the usual convex lens for a concave mirror, had been suggested in print by Gregory in 1663, and

[59] Descartes, *Dioptrique*, 46–49: "[…] a certaine distance determinée a laquelle tenant le linge, les images paroissent fort distinctes, & que pour peu qu'on l'esloigne, ou qu'on l'aproche d'auantage du verre, elles commencent à l'estre moins; […] si lon met le verre vn peu au delà du trou de part ou d'autre, le linge en doit aussi estre d'autant aproché ou reculé; Et qu'elle depend en partie de la figure de ce verre, & en partie aussy de l'esloignement des obiets: Car en laissant l'obiet en mesme lieu, moins les superficies du verre sont courbées, plus le linge en doit estre esloigné […] Et que plus [le verre] est grand, plus [les images] paroissent claires & illuminées."

[60] Niceron, *Perspective*, 21–22.

[61] Malet, "Kepler's legacy," 300.

[62] Shapiro, "Images," 304–307, especially 306, where Barrow is quoted as having included only "that part of optics which is more properly mathematical."

was known to Newton.[63] For both Gregory and Newton, telescope design was closely connected to conceptual work in geometrical optics. Building on Gregory's and Barrow's earlier work, Newton's *Optical Lectures* of 1670–1672 contained many new contributions to that geometrical optics. However, these lectures remained unpublished and virtually unknown until after Newton's death. His first publication to deal with similar matters was his much later *Opticks* (1704), in which Newton discussed and applied his geometrical techniques for finding image locations, such as those in the camera obscura, with ease (see Fig. 3).[64]

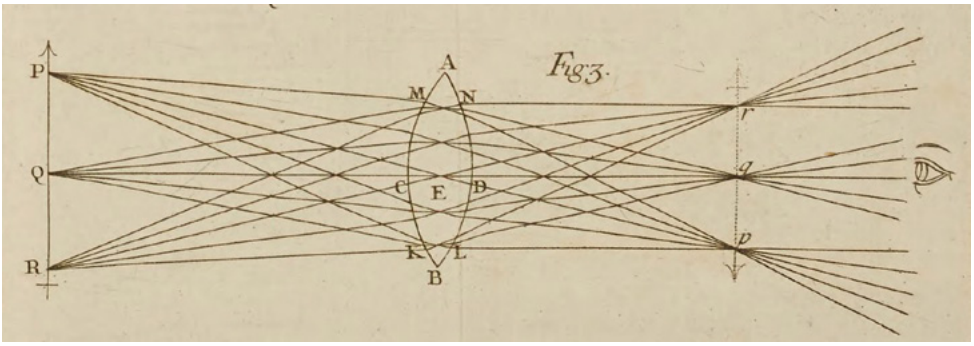


Fig. 3 – Newton's diagram for explaining the location of the image rqp of object PQR after refraction of rays of light in the convex lens, given at the beginning of Newton, *Opticks*, plate 1, fig. 3.

Work by Barrow and Gregory was available in the 1660s, however, especially to English savants. They knew about the camera obscura, too. Robert Hooke presented the instrument to the Royal Society at various meetings and wrote two short notes on it. In 1668, his "A Contrivance to make the Picture of any thing appear on a Wall" appeared. In it, Hooke gave a description of how to set up the camera obscura, stating that "Between this Object, and the Place where tis to be represented, there is to be placed a broad Convex-glass, ground of such a convexity, as that it may represent the Obiect distinct on the said place; which any one, that hath any insight in the Opticks, may easily direct."[65] Hooke did nothing to codify the central problems of the camera and even seemed to imply that it could easily be used. We may speculate that, given his own expertise with instruments, mathematics, and drawing, he did not see what others might possibly find confusing about

[63] Malet, "James Gregorie," 140–143 describes how Newton dog-eared the pages of Gregory's *Optica promota* in which a reflecting telescope was described.
[64] Shapiro, "Images," 307–308.
[65] Hooke, "Contrivance," 743.

painting with the camera.[66]

Yet if this was the case, he was wrong. Although Hooke carried out more experiments with a camera obscura, evidence indicates that he convinced very few others to use a similar instrument.[67] This was the case notwithstanding various other presentations, including one of 1694 in which Hooke had glowing praise for the instrument and listed all kinds of things that could be depicted with it. But even there he was no more specific on how to make sure that the image in the camera obscura was in focus: his description did not make it a user-friendly machine.[68] Only one image of Hooke's camera obscura has been printed (Fig. 4), which was of even less use. It makes the camera look like an oversized helmet, not a workable tool.



Fig. 4 – Hooke's camera obscura, as posthumously depicted in Derham, *Experiments*, 295.

66 On Hooke's mathematical skills, see e.g. Guicciardini, "Invisibility and impact."

67 See Hunter, "Mr. Hooke," on his work with the camera. Hunter, page 313 suggests that John Evelyn might have had a camera obscura similar to Hooke's by 1705.

68 Derham, *Experiments*, 292–296.

As far as I can ascertain, work that attacked the problem of the location of the image in the camera obscura with geometrical construction techniques appeared only in publication in the 1690s. Explanations for this must remain speculative, but the difficulty of the mathematics involved in early solutions might very well have played a role. As Alan Shapiro has detailed, Barrow had provided solutions for the "relative image" – equivalent to the present-day "image location" – of any lens. This included lenses which had little bearing on problems one would face working with material optical instruments. Barrow did so with extensive tables of categories and subcategories of lenses; Shapiro calls the solution "excessively complex and cumbersome."[69]

In his 1692 *Dioptrica Nova*, William Molyneux instead discussed image locations for more concrete types of lenses and mirrors, as well as the camera obscura and telescope. In contrast to the more theoretical work of Barrow and Gregory, whom he cited, Molyneux explicitly discussed the image location for projected images as a separate topic, as is made clear in the subtitle of his work, "A Treatise […] Wherein the Various Effects and Appearances of Spherick Glasses, both Convex and Concave, Single and Combined, in Telescopes and Microscopes […] are Explained."[70]

For the camera obscura, Molyneux concentrated on what happened in various particular setups of the camera obscura. This included the one needed for painting: with light projected into a room by a single equiconvex lens, and rays converging to a place inside that room. He distinguished between cases of "Distant Objects" and "Nigh Objects," explaining that the first gave rays falling parallel on the lens, whereas in the second case, diverging rays fall on the lens.[71] This second case, that of nearby objects, is of course the one that is most relevant when using the camera obscura for painting. And it is for that case that Molyneux explicitly codified a solution to the distance problem. He called the place where rays of light coming from a nearby object would converge the "respective focus." This he kept separate from the "focus" simple, "absolute focus," or "focal length" which was the distance from the lens at which rays from far-away objects would converge. He provided a solution for finding the "respective focus" in terms of the "focus" simple. This solution, the first codification of the problem of image distance in the camera obscura, is mathematically equivalent to the modern thin-lens equation.[72]

It remains unclear what inspired Molyneux to go into more detail on particular projections, as few detailed studies on Molyneux's work exist. He dedicated his book to the Royal Society of London, on which he had based the Dublin Philosophical Society that

69 Shapiro, "*Optical Lectures*," 151.

70 Molyneux, *Dioptrica*.

71 Ibid., 41.

72 Ibid., 42, see Prop. V. If respective focus is *i*, and the focal length is *f*, Molyneux's solution, given in proportional terms, is $o\text{-}f : f :: o : i$, which can be reduced to the equation given above in section 2.

he had founded in 1683. Spreading natural philosophy was certainly one of his aims. But Molyneux also held various political positions in Ireland, including that of Surveyor General of Fortifications and Buildings.[73] As such, looking at buildings through telescopes and making precise sketches of their outlines were material practices Molyneux was most likely quite familiar with.

In the twelve years that separated Molyneux's *Dioptrica Nova* and Newton's *Opticks*, various other solutions to distance problems of thin equiconvex lenses, the common type needed for the camera obscura appeared in print. These can all be reduced to the present-day thin lens approximation.[74] At the turn of the eighteenth century, codified solutions to the key distance problem in the camera obscura, solutions that are still accepted in the present, thus became available. Yet Molyneux's treatment remained the one most relevant to the problem of painting. None of these treatments returned to practical descriptions of how to build a camera obscura for the practice of painting. After stating his solution, Molyneux himself went into more complex matters instead: first a lengthy demonstration and after that solutions for optical constructions of less relevance to that practice.[75]

8. The codification and circulation of 's Gravesande's camera obscura

The step from a codified solution to the geometrical problem to a description of practice is very much present in 's Gravesande's treatise. Published as an appendix to his *Essai de perspective*, in smart duodecimo format, the treatise on the camera obscura covers 36 short pages. It starts with four pages on theory, introducing terminology such as "focus." Pages 5–11 describe the machine here depicted in figure 1 in painstaking detail, and pages 11–32 cover how to use the machine for various purposes, including "representing objects in their natural disposition," mirrored left to right, depicting a countryside, and "representing paintings or engravings" so that they can be copied directly. Each of these gets a separate section and is followed by a short geometrical proof. All proofs rely on the techniques developed in the decades before 's Gravesande.[76] The proof for engravings contains a statement about geometrical proportions between "the focus of the glass," "the height

[73] Molyneux is well known for his contacts with Locke but otherwise understudied. See the dated Simms, *Molyneux*, for biographical detail.

[74] These include Picard (1693), Halley (1693), Hartsoeker (1694), and Huygens, whose early optical works were published posthumously in 1703, see Shapiro, "*Optical Lectures*," 151, and Dijksterhuis, "Constructive thinking," 75.

[75] Molyneux, *Dioptrica*, 43–46 for the demonstration, 46–50 for cases in which the rays do not focus after passing the lens, that is, in modern terms, situations in which no real image is produced inside the camera.

[76] 's Gravesande, "Usage," 11: "Représenter les objets dans leur disposition naturelle," 25: "Représenter des Tableaux ou des Taille-douces."

of the Machine above the table," and "the distance of the glass to the painting" – in present-day terms: the focal length, the image distance, and the object distance. This statement is equivalent to Molyneux's, and to the modern thin-lens approximation.[77] Thus 's Gravesande codified the distances at which images were in focus and described the entire procedure of building a camera obscura and setting it up for painting.

's Gravesande's description was user-friendly and allowed his readers to rebuild the instrument. This would leave him without direct monetary gain from the design and raises questions about his motives. 's Gravesande himself stated that his aim was simply helping others to construct this machine and particularly to "save others the fatigue" involved in getting everything right,[78] and it seems indeed he made no money out of the machine. But this is not to say that 's Gravesande did not benefit at all. The book put him in touch with leading mathematicians of the time, including Johan Bernoulli, and helped his career take off.[79]

The details of his career may mitigate skepticism about whether 's Gravesande was truthful about his rather generous interest in helping others. In 1717, 's Gravesande was appointed to a professorship in mathematics and astronomy at Leiden University, on the strength of his previous mathematical work. He went on to design many other instruments for teaching and research purposes. Many of these instruments were described and depicted in his widely popular *Physices elementa mathematica*. Here, too, 's Gravesande gave detailed depictions and descriptions of the instruments that would allow others to rebuild them.[80] Most of these instruments were built for him by the instrument-maker Jan van Musschenbroek. Van Musschenbroek built and sold additional copies of these machines without patenting them.[81] 's Gravesande's instrumentarium included various other optical instruments, such as a magic lantern, a heliostat, and a large set of convex and concave mirrors. Many became standards in eighteenth-century cabinets of scientific instruments, spreading 's Gravesande's work and fame.[82]

The camera obscura was not included in the *Physices elementa mathematica*. But it was discussed in print many other times. A review of 's Gravesande's treatise of perspective of

77 's Gravesande, "Usage," 26–27.

78 Ibid., [ii-iii], "dans la construction méchannique d'une machine propre à faciliter le dessein, on ne pouvoit pas prévoir plusieurs choses que l'expérience seule peut apprendre […] Comme on avoit fait tout ce chemin là, on a crû devoir en épargner la fatigue aux autres." On building the machine, see also my comment in note 11.

79 Van Besouw, "Impeccable credentials."

80 On the book, its aims, and its instruments, see Van Besouw, "'s Gravesande."

81 De Clercq, *Musschenbroek workshop*.

82 On 's Gravesande's magic lantern and later copies of it by figures such as Pieter van Musschenbroek and Jean-Antoine Nollet, see Hankins and Silverman, *Instruments*, 49–54, especially page 50: "['s Gravesande's magic lantern] became the model for all [magic] lanterns during the subsequent century and was surpassed only […] in 1820."

1711 concentrated particularly on the two camera obscuras, and 's Gravesande was approached by the German savant Zacharias von Uffenbach in 1723 to further explain the working of the specific machines.[83] A reprint of the original text appeared in 1717 and a translation into English in 1724. The entry on the camera obscura in an English Dictionary of 1726 noted that "Gravesande […] has given the Description and Use of two Machines" and that they were "the best that have as yet been made."[84] In 1738, Robert Smith gave a description of the camera obscura that looks much like 's Gravesande's in his *Compleat System of Opticks*. By then, the instrument was widespread, or at least so asserted Smith: he described the machine as "[T]he portable *camera obscura* […] commonly sold in the shops."[85]

Without further evidence of what happened between 1711 and 1738, the argument that 's Gravesande had an impact on the wider circulation of the machine must remain somewhat "post hoc, ergo propter hoc." Yet I believe these citations point to plausible mechanisms by which 's Gravesande's treatise might have reached people willing and able to build camera obscuras for themselves, and to use them for painting.

9. Conclusion

This article has focused on one seeming historical paradox: that the camera obscura circulated as a popular artists' tool only after having been around for a couple of centuries. This paradox starts to disappear when we look in detail into how and when its use was codified. Descriptions of the camera obscura remained vague on key issues for over a century. Throughout the seventeenth century it was possible to use the camera for painting, but only if one was willing to invest time in learning how to do so by trial and error. This cost of learning was reduced substantially when user-friendly descriptions such as 's Gravesande's became available. Hence, the presence of codified description of the camera could enhance circulation, and might plausibly have done so.

The case of the camera obscura offers more general lessons for the role of codification in technological innovation, and the circulation of technical inventions. Although 's Gravesande's case might seem to be a clear case of "applying theory" to a "practical problem," the longer history refutes the idea that innovation takes place as a simple ap-

[83] Le Clerc, "Essay." For the correspondence, see Niedersächsische Staats- und Universitätsbibliothek Göttingen, 2 Cod. Ms. Uffenbach 20: Bd. I, 522–532. See also the mention in Jombert, *Methode* (1755), which reproduces part of 's Gravesande's treatise. Many more such mentions of 's Gravesande are present in dictionaries and encyclopedic works until at least the early nineteenth century.

[84] Stone, *A New Mathematical Dictionary*, "Camera Obscura."

[85] Smith, *System*, 386.

plication of theoretical, propositional, or conceptual knowledge.[86] Rather than talking about the circulation of unspecific "practical knowledge," we would do well to focus on the practices actually being described, and possibly codified. For much of the history of the camera obscura, the material dimension came first. From Barbaro at least up until Descartes, material practices with the camera obscura were the direct source of conceptual developments. All of those who wrote on the camera obscura were "practitioners": they all showed awareness of the complexities of setting up experiments in the camera, and in dealing with lenses.

Theoretical developments in optics were inseparable from material, empirical manipulation until after Kepler. Only when Kepler had provided an algorithm for further work, did one specific part of optics start to develop in more isolation from material practice: the geometrical problem of image location.[87] But after the key problem of image location was settled in the 1660s, theory was not "applied" back to instrumental practice directly. 's Gravesande's contribution was to derive solutions to very specific problems in the camera from the general solutions, and to find ways to materialize these solutions so that these problems would not appear if the camera obscura was set up for specific painting purposes. 's Gravesande did not simply apply theory. He found a way to *reconstruct* geometrical techniques to give specific answers to questions that practitioners faced when trying to use the instrument.

[86] For a critical historical take on the idea that innovation takes place through applying theory to practical problems, see Godin, *Models of Innovation*.

[87] Many other parts of optics still depended very much on material issues. As Cocquyt, "Instrumental Practices," 9 remarks: "throughout the seventeenth century, the import of optical instruments was continually redefined through their embeddedness in evolving conceptual frameworks, and their adaptation to changing user practices."

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