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Leonardo and the Camera Obscura

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1. Introduction

Enthusiasts who credit Leonardo with the invention of the camera obscura are mistaken.[1] Knowledge of the instrument can be traced back at least until the ninth century A.D.[2] By the latter thirteenth century, Pecham was studying the instrument with respect to physics of light, while his contemporary, William of St. Cloud,[3] explored its uses in the observation of eclipses in astronomy.

If Leonardo's studies of the camera obscura stand in a well established tradition, they remain important for at least three reasons. One is their sheer quantity: there are no less than 270 diagrams of camera obscuras in Leonardo's notebooks. Second, he uses it to demonstrate a wide range of optical principles: inversion of images, non-interference, images all in all, intensity of light and shade and contrary motion. A third reason for their importance is the method they reveal. Whereas his mediaeval predecessors had considered only isolated examples, Leonardo explores a series of cases, systematically altering the shape and number of apertures, as a result of which he makes analogies with the eye. This essay[4] outlines the range of his camera obscura studies and the systematic approach these involve.

2. Astronomical context

Leonardo's earliest extant reference to a pinhole aperture, in Triv. 6v (1487-1490), involves a «way of seeing the sun eclipsed without hurting the eye». Here the aperture serves to screen off excessive light and the sun is still seen directly. On CA 270vb (c. 1490) he describes a camera obscura in which the sun or moon is seen indirectly. The instrument consists of a box with an aperture in a thin sheet of iron at one end and a thin piece of cardboard at the other end, onto which the image is projected. He illustrates such a box on CA 126ra, CA 125vb and CU 789. Elsewhere, on A 64v, A 61v, (1492) and CA 243ra (1510-1515) he specifically considers the shape of the moon's image.

Late Mediaeval authors such as Levi ben Gerson had used the camera obscura to determine the sun's diameters.[5] Leonardo also considers this problem on A 20v (1492), CA 225rb (1497-1500), BM 174v (1500-1505), Leic. 1r (1506-1509) and CA 243rb (1510-1515). He also treats the problem of the sun shining through openings in clouds as an equivalent of the camera obscura principle on CA 297va (1497-1500) and CU476 (1510-1515). Even so astronomy and meteorology remain peripheral to Leonardo's interest in the instrument, which stems primarily from analogies between its functions and those of the eye. Whence the camera obscura serves to demonstrate a number of characteristics of vision.

3. Inversion of images

One of these is that images are inverted inside the pupil, As early as 1489-1490 Leonardo uses a camera obscura to demonstrate this on W 19147v (KIP 22v). He discusses this inversion principle again on C 6r (1490) and CA 125vb (1492), mentions it again on BM 232v (1490-1495) and illustrates it in sketches without text on Forst. III 29v (1490-1495), BM 17Ov (1492), CA 126ra (1492) and CA 155rde (1492-1497).

A decade passes before he broaches the problem again on CA 345vb (1505-1508) and discusses it in detail in the Ms. D (1508). In one passage on D lOr he simply demonstrates how a camera obscura inverts and reverses images. In a second passage on D 8r he specifically uses the camera obscura to demonstrate «how the species of objects received by the eye intersect inside the albugineous humour». The problem of inversion is mentioned again on W 1915Ov (KIP 118va, 1508-1510) and CA 241vc (1508-1510).

4. Non-interference

The non-interference of images within the eye is another visual phenomenon which he demonstrates with the camera obscura. On A 93r (1492), for instance, he shows how red, white and yellow lights can intersect without mixing with one another. On CA 256rc (c. 1492) he makes similar demonstrations with a) red, green and yellow, and b) red, white and green lights. Accompanying these are a number of draft notes on the problem.

More than fifteen years later he returns to this theme on W19112r (KIP 118r, 1508-1510), this time using yellow and blue lights. On CU 789 (1508-1510), he makes a more complex demonstration showing how light from a candle and from the air produce different colours on an interposed object. He had used a similar demonstration on CD 797 (1508-1510) to establish that the colour of shadows participates with the colour of surrounding objects. .

He pursues both the themes of colour participating and the noninterference of images on W 19150v (KIP 118v, 1508-1510). On the recto of the same folio (KIP 118r) he discusses further the phenomenon of non-interference under the heading «Of the nature of the rays in which images of bodies are composed and their situations».

5. Images all in all

On W 1915Ov (KIP 118v 1508-1510), Leonardo also demonstrates that images are all in all and all in every part *(tutto in tutto e tutto in ogni parte).* In one diagram he shows how three light sources, passing through one aperture, produce three individual images. In a second diagram, he shows how three light sources, passing through two apertures, produce six images, the implication being that since images are projected wherever one makes an aperture, they must be spread everywhere throughout the air. This idea had been playing on his mind for a number of years. Draft demonstrations are found on CA 373rb and A 9v (1492), CA 155rd (1497-1500) and CA 238rb, vb (1505-1508).

Scholars have noted that the «all in all» concept had mediaeval precedents.[6] There were also classical ones. For instance, Leonardo credits Anaxagoras as a source for the «all in all» phrase[7]. Nicolaus of Cusa had also cited Anaxagoras in this respect and used the phrase to illustrate the nature of God, a phrase which Leonardo's friend, Luca Pacioli subsequently takes up in his *Divina proportione.* In this context it is all the more striking that one of Leonardo's demonstrations of the all in all principle on CA 345rb should have an excursus on metaphysics ending with the claim that «it is this which guides human discourse to divine things». In this case the camera obscura seems to have provided a visible demonstration of an invisible God.

6. Intensity of light, shade or image

While arguing that images are everywhere in both the camera obscura and the eye, Leonardo is also convinced that they can vary their intensity. On C 14v (c. 1490) he discusses this problem and illustrates it with two diagrams. He mentions it again on CA 256rc (1492). Later, on a single folio, CA 238rb (1505-1508), he uses the camera obscura to demonstrate 1) that images are inverted; 2) that they are all in all and all in every part, and 3) that they vary in their intensity.

On C 12v (1490) in connection with his studies of light and shade he illustrates how a light source in front of two opaque bodies produces concentric rings of light of differing intensities. The accompanying text is closely related to a draft on BM 101r (1490-1495), possibly not in Leonardo's hand. Such demonstrations of concentric rings caused by opaque bodies in the open air are paralleled by further demonstrations involving camera obscuras. For instance, on CA 262v (1497-1500) he draws sunlight entering through an aperture which is intersected at various distances, a theme which he pursues on CA 262ra (1497-1500) with a further diagram above which he drafts a general claim: «The solar ray which penetrates inside the apertures *(of the eye)* of houses, in each degree of its length changes quality as quantity.» Here it is noteworthy that he writes «apertures of the eye» which he then crosses out to write «apertures of houses». The camera obscura analogy is constantly on his mind. It is not surprising therefore that he should discuss different kinds of pupils elsewhere on the page.

7. Contrary motion

Because camera obscuras invert images, the images of moving objects in these instruments have a motion contrary to the movement of the actual object. Leonardo considers this problem on C 3r (1490-1491), on CA 337rb (c. 1490) in a series of sketches without text, mentions it on BM 171 v (1492) and draws further sketches without text on CA 133va (1492-1500). Approximately a decade later, on W 19149r (KIP 118r, 1508-1510) he demonstrates this principle by moving the edges of the aperture. In this same passage he also broaches the problems of images all in all and all in every part, of rectilinear propagation and aperture size.

He examines the principles of contrary motion in more detail on CA 277vc (1508-1510). Here his approach is experimental and systematic. He begins with a stick situated in a high position in front of a nearby wall which casts a shadow low down on the far wall. The stick is then moved downward and its shadow moves upwards. In a third situation when the stick is between the two walls, the stick and its shadow both move in the same direction. In a fourth situation the stick is flush with the wall. These situations he describes in the accompanying text. He returns to this problem on E 2v (1513-1514) in a passage entitled «On shadow and its movement».

8. Size of aperture

Leonardo's interest in the effects on vision of changing pupil size in humans, cats and various types of owls, helps account for his concern with different sizes of apertures. On CA 373rb (1490-1495) he makes two preliminary diagrams without text. He develops these in two diagrams on CA 256rc (1492) drawing a thin and a thick wall, alongside which he writes: «Among apertures of equal... size that which is in a larger wall will render a darker... and smaller percussion». On H 227 inf. (fol. 47v - 48r) he again compares the effects of thick and thin walls. On A 2r (1492) he draws a relatively thin wall and considers changing intensities of light inside a camera obscura. He draws a related diagram on A 85r (1492) and then redraws both those of A 2r and A 85r on CA 262v (1497-1500), this time without an accompanying text.

About a decade later on W 19152v (KIP 118v, 1508-1510) he returns to this theme, opening with a general claim: «Images which pass through apertures into a dark place intersect their sides that much nearer to the aperture to the extent that this aperture is of lesser width.» Accompanying this he draws three diagrams which deal with both the problem of image formation in a camera obscura and physics of light and shade. The connection between these problems and vision, here implicit, are made clearer on CA 385vc where he develops these diagrams and nearby, also draws figures relating directly to vision.

9. Shape of aperture

The shape of apertures was a problem of long standing: when light passes through an aperture does the resulting light image resemble the shape of a) the aperture, or b) the light source? This question was raised twice in the *Problemata* attributed to Aristotle.[8] In the eleventh century (A.D.), Alhazen mentioned the problem of light passing through apertures.[9] Witelo, in the thirteenth century, briefly considered light passing through square, round and angular apertures.[10] His younger contemporary, Pecham, devoted two of his longest propositions to the properties of images passing through triangular apertures.[11] A diagram by Leonardo on A 82v (1492) is clearly related to Pecham.

The basic principle pertaining to apertures and images, as is well known today,[12] is that when light source, aperture and projection plane are all close together, the projected image has the shape of the aperture. When these variables are at a greater distance from one another, the projected image takes on the shape of the light source.

Leonardo does not know the formula this involves, nor does he articulate concisely the general principle. Even so his studies of the problem bear note. Whereas his predecessors had considered only isolated cases, he studies a series of cases systematically, including triangles, squares, slits and cross-shaped apertures. Each of these will be considered in turn.

In the case of triangular apertures Leonardo does not consider the limiting case where the proximity of the light source, aperture and projection produces a triangular image; However, on CA 236ra (1508-1510) he considers in some detail a situation where the triangular image begins to become curved. As the distance between the variables increases, each point of the triangular aperture generates a circle in the form of the light source resulting in a triangular configuration of three circles. This he illustrates on CA 277va (1508-1510). He illustrates a next stage where circles have begun to overlap on C 1Ov (1490-1491) and successive stages on Forst III 29v (1493) and H 227 inf. (fol. 5Ov - 51r) where the distance is greater and the circles overlap to a greater extent.

He makes similar studies of objects passing through square apertures. Here again it is the case that when the light source, square aperture and projection plane are close to one another the image takes on the squareness of the aperture. As the distance between those variables increases the image appears first as a square with four circles at each of its edges (H 227v inf., fol. 48r - 48v), then as four overlapping circles (CA 135va, 1492) and finally as a single circle (H 227v inf., 48r - 50v). If these changes from a square to a circular image be reversed, they provide a visual demonstration of the problem of quadrature of the circle.

On H 227 inf. 49v, 51r - 51 v, CA 135va (1492) and A 64v (1492) Leonardo also makes a series of demonstrations involving both single and double slit-shaped apertures. Having positioned slits above and beside one another, he explores the next logical combination in which the two slits intersect one another to form a cross-shaped aperture. On C 9r (1490-1491) he illustrates and describes a case where light source, aperture and projection plane are near one another with the result that the image resembles .the aperture. On CA 135va (1492) he illustrates how, with greater distance, the ends of the cross acquire rounded shapes which evolve into overlapping circles. On H 227 inf. 49v - 50r these circles overlap more. On C 1Ov, with still greater distance these resolve themselves into a single circle. He has thus illustrated six stages in the transformation from a cruciform shape to a circle. .

In addition to analysing the properties of light passing through triangles, squares, slits, double slits and cruciform apertures, he also considers octagonal ones on C 7v (1490-

1491) and CA 187ra (c. 1492). On CA 256rc (c. 1492), he drafts a summary of these results under the heading:

> Of the nature of apertures:
> An aperture is composed of a number of sides and that which has fewer will demonstrate the truth of things less.
> The aperture which has more [sides] is better and maximally when the parts of the sides are equidistant from the centre of the aperture.

10. Number of apertures

On CA 187ra (1492) he not only mentions an eight-sided aperture, but also eight pinhole apertures equidistantly arranged in a circle. This is no coincidence. Just as he studies multi-sided apertures, so too does he explore comparable properties of multiple pinhole apertures. For instance, on CA 277va (1508-1510), where he outlines his new plan for arranging his work on light and shade, he sketches the images cast by one, two, three and four pinhole apertures. He develops these sketches on CA 177rb, 177ve and 241rd (1508-1510).

Not content to stop at four apertures, on CA 187ra (1492) he explicitly describes the use of eight apertures and on CA 385vc (1510-1515) carefully draws eight apertures and the eight circles these produce. On the same folio he sketches two cases with 18 apertures. On CA 241vc (1508-1510) he draws 24 apertures and then shows how, at a greater distance, these produce 24 interlacing circles.

On CA 229vb (1505-1508) he develops this theme, beginning with a rough sketch showing two circles inscribed in a larger one, probably caused by two apertures. He next draws four apertures and the four circles they produce, then further examples which are multiples of four: a sketch of 16 apertures with a hint of the circles they produce; twelve points on a half circle which would amount to 24 apertures in all; a case with 28 apertures and eight circles spanning a quarter of the circumference of a circle containing 32 apertures.

On this same folio he also explores multiple shadows produced by a St. Andrews's cross. Further notes on this theme occur on CA 37ra, 177rb, 177ve, 229rb and 241rcd. He is therefore making an implicit comparison between a) light passing through multiple sided apertures (triangles, squares, slits, crosses and octagons); b) light passing through multiple pinhole apertures (1, 2, 3, 4, 8, 16, 24, 32) and c) the multiple shadows produced by a St. Andrew's cross (cf. chart 1). In effect he is making systematic experiments concerning properties of light and shade with respect to apertures and occlusions.

Codex	Multiple pinhole apertures	Multiple-sided apertures	Multiple shadows
CA 177rb	4		4
CA 177ve	4		6
CA 241rcd	1, 2, 3, 4		2, 4
CA 241 vc	24		1 (on multiple surfaces)
CA 229rb, vb	4, 16, 24, 32		2, 4, 6
CA 277va	1, 2, 3, 4	3	1
CA 37ra	1 (in various degrees)		2, 4, 6
CA 385vc	8, 18		1, 2, 3
CA 187ra	8	2,3,4,8	2, 3, 4, 8

Chart 1. Links between Leonardo's works on multiple apertures, multiple-sided apertures and multiple shadows.

11. Apertures and interposed bodies

He also studies these factors in combination, exploring the properties of apertures together with opaque bodies of various shapes. On CA 187va (c. 1490), for instance, he makes draft sketches to show what happens when light, passing through a slit shaped opening encounters a spherical object. These drafts he crosses out, turns the sheet ninety degrees and draws two further sketches showing how light, having passed through a slit, encounters a spherical object and produces a combination of simple and mixed shadow. On CA 187ra (1492) and on A 89v (1492) he redraws this sketch and then develops it into a beautiful diagram without text on A 89r (1492).

On CA 187ra we have further evidence of Leonardo's delight in playing with variables. Having shown what happens when a slit shaped light encounters a spherical opaque body, he considers what occurs when a spherical light encounters a slit-shaped opaque body. He also lets light pass first through a round, then through a slit-shaped aperture and contrasts this with light which passes through a slit-shape and then through a round aperture. Next he replaces this slit shape with a cruciform aperture.

More than fifteen years later he develops this theme on CA 207ra (1508-1510) where he is concerned with making the image of a crucifix enter a room. He takes a blank surface on which he marks a crucifix. Opposite this surface he positions an aperture in the outer wall of a room. The sunlight is reflected from the surface, passes through the aperture and casts an image of the crucifix into the room.[13] On F 28v (1508) Leonardo considers the problem of cruciform images in an unexpected context:

> The ray of the sun, having passed through bubbles of the surface of the water send to the bottom of this water an image of this bubble that has the form of a cross. I have not yet investigated the cause but I believe that it is because of other little bubbles which are joined to this larger bubble.

Alongside he shows how four smaller bubbles surrounding a larger bubble could generate a cruciform image. He makes a further note on CA 236rd (1508-1510) but appears not to have pursued the problem as he had hoped.

He does, however, return to the problems of slit-shaped apertures and opaque bodies on CA 258va (1508-1510). Here he begins with light passing through a slit-shaped aperture, which encounters a narrow, opaque body and casts a shadow on the ground at ninety degrees to this. Next he considers situations where a) this shadow is cast at more than ninety degrees and b) the converse which involves moving an interposed stick through various degrees of obliquity. Finally, he explores a case where a slit-shaped aperture, thin opaque body and the resulting shadow are all in the same plane, which he examines in more detail on CU 630 (TPL 627, 1508-1510).

He also studies more complex combinations of apertures and opaque bodies. On C 9v (1490-1491) he draws a light source, the rays of which meet an opaque body and cast a shadow which passes through an aperture. On the far side of this aperture are two further light sources which cast rays intersecting this shadow. On W 12352v (c. 1494) he sketches another diagram of a luminous body, the rays of which meet an opaque body and cause shadows which then pour through an aperture. This he develops on CA 236rc (1508-1510).

Meanwhile he has been exploring more complex variants of this situation. In a first diagram, a light source is left and drawn and an opaque object casts its shadow through two apertures onto a wall. In a second diagram there are again two apertures, but these now have an opaque body in front of them and smaller body behind them. A third diagram shows the same basic elements, but the relative sizes of the opaque bodies are changed. Further treatment of these problems is found on CA 133va (1497-1500) and CA 238vb,rb (1505-1508).

12. Spectrum of boundaries

Leonardo's studies of camera obscuras in combination with opaque bodies lead him to abandon his early assumptions concerning clearly defined boundaries and to emphasize instead a spectrum of gradations between light and shade, using at least seven claims supported by demonstrations: 1) that derived shade has less power to the extent that is more distant from its primitive shade (CA 258va and CD 707, both 1508-1510); 2) conversely, that derived shade has more power when closer to its source (CA 144va, 1492; CD 730, 699 and 704, and CA 258va, all 1508-1510). He explores 3) to what extent one can speak of uniformity of derived shade (CA 258va, 1508-1510).

He shows 4) that primitive and derived shade mix with distance (CA 256rc, CA 144va and A 92v, all 1492; CD 636, 1505-1510; CD 699,1508-1510 and CA 371rb, 1510-1515). He demonstrates 5) how primitive and derived shade are joined together (CD 677 and 708, 1508-1510); 6) where shade is greater (Forst. III 87v, c. 1493: H 66 [18]r, January 1494; CA 297va, 1497-1500; CA 190rb and 230rb, 1505-1508; CA 37ra, CA 258va and CU 669, all 1508-1510) and establishes 7) where primitive and derived shade are not joined (CA 258va and CA 195va, both 1508-1510). The last of these demonstrations CA 175va serves as a starting point for an explanation involving the perception of backgrounds:

> Why black painted bordering on white colours does not show itself as blacker than where it borders on black, nor white show itself more white bordering on black. This claim is striking because he had made a number of experiments to establish the contrary, namely, that white on a black background appears whiter and black on a white background appears darker.

Parallel with the above demonstrations is a further series which omits the interposed opaque sphere and reduces to its essentials the problem of gradations within the camera obscura (CA 345rb and CA 19Orb, 1505-1508). The accompanying text on CA 19Orb gives instructions to turn the page to CA 190vb which contains various diagrams relating both to camera obscuras and to the inversion of images within the eye. Even so the analogy between physics of light/shade in a camera obscura and physics of vision here remains.implicit.

13. Camera obscuras and the eye

On D 10v (1508) this analogy is developed. In the margin Leonardo draws a camera obscura with various gradations of light and shade. This he marks «first». He then draws an eye with various rays being inverted at the pupil which he marks «second».

On this folio he also explores the perceptual problem of boundaries of paintings. On CA 195va (c. 1510), another folio where the analogy between camera obscura and eye is made explicit, he draws further sketches of camera obscuras with five, seven and nine gradations of shade, now attempting to quantify a hitherto qualitative problem.

14. Conclusions

Although it is well known that Leonardo worked with camera obscuras the extent of this work has not previously been examined. This paper has outlined the context of his c. 270 diagrams which he devoted specifically to the camera obscura. We have seen that his interest in the instrument stems in part from the astronomical tradition. His main interest in the camera obscura is to demonstrate a number of basic principles of light and shade which bear on the visual process: the inversion of images; that images passing through an aperture do not interfere with one another; that images are all in all and all in every part, that pinhole apertures produce different intensities of light and shade and that inverted images demonstrate a contrary motion.

Mediaeval optical writers had been concerned with isolated cases of light sources passing through triangular and other apertures. Leonardo studies the problem more systematically in the case of a variety of shapes. He also studies situations with 1, 2, 3, 4, 8, 16, 24, 28 and 32 pinhole apertures, as well as more complex situations involving apertures and interposed bodies in combination. These studies lead to examination of gradations of light and shade relevant to visual perception: why, for instance, the eye cannot see clearly the boundaries of nearby objects.

The great importance of these detailed studies of the camera obscura is that they bring various principles relating to light, shade and vision into the realm of physics. Optics is no longer a problem for philosophical discussion; it is now a branch of science requiring experimental demonstration. Leonardo's work prepares the way for Kepler's publication of these ideas a century later in his *Paralipomenon ad Vitellionem* (1604).

Notes

[1] See, for instance, E.L. Erdmann, «Rundschau» *Prometheus*, Berlin, vol. X, n. 481, 1899, p. 205.

[2] See G. Pauschmann, «Zur Geschichte der linsenlosen Abbildung», *Archiv für Geschichteder Naturwissenschaften* und *der Technik*, Leipzig, 9, 1922, pp. 86-103.

[3] «Guillaume de St. Cloud, Astronome», *Histoire littéraire de la France*, Paris, tom. XXV, 1869, p. 73.

[4] This essay constitutes an abridged version of Volume two, Part two, chapter three of the author's *Leonardo Studies* which deals with all the notes on optics and astronomy. There, the illustrations alluded to in this essay will be reproduced in full.

[5] Maximilian Curtze, «~Die Dunkelkammer. Eine Untersuchung über die Vorgeschichte derselben, *Himmel und Erde. Illustrierle naturwissenshaftliche Monatsschrift*, Berlin, Jg. XIII, 1901, pp. 226-232.

[6] Martin Kemp, «Leonardo and the Visual Pyramid», *Journal of the Warburg and Courtlaud Institutes*, London, Vol. XL, 1977, pp. 128-149.

[7] CA 38Sv. Cited in Richter, Vol. 2, n. 1472.

[8] Aristotle, Ross edition, Oxford, 1927, Vol. 7, *Problemata*, 911b 3-S; 912b 11-14

[9] Alhazen, *Opticae...*, Risner edition, 1S72, p. 17; Bk I, 29.

[10] Witelo, *Opticae...*, Risner edition 1S72, pp. 74-7S: Bk II, 36-38.

[11] J. Pecham; *Perspectiva communis*, 00. D.C. Lindberg, Madison: University of Wisconsin Press, 1970, Part I. Prop. S, 7. See also D.C. Lindberg, «The Theory of Pinhole Images in the Fourteenth Century», *Archive for History of Exact Sciences*, Berlin, vol. 6, no. 4, 1970, pp. 299-32S.

[12] See: W. Minnaert, *The Nature of Light and Colour in the Open Air*, trans. H.M. Kremer Priest, New York: Dover Publications, 19S4, pp. 2-3.

[13] This passage has also been interpreted as being «a curious mistake in perspective». See: Carlo Pedretti, *The Literary Works of Leonardo da Vinci... Commentary*. Oxford: Phaidon, 1977, Vol. 1, p. 137.